

# User Guide for Ecopath with Ecosim (EwE)

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# Introduction



The Ecopath with Ecosim (EwE) approach and modelling framework is designed for straightforward construction, parameterization and analysis of mass-balance trophic models of aquatic and terrestrial ecosystems. Focus is on using the models for fisheries management, and a suite of tools are included for this aim. This User Guide describes how to use the Ecopath software system, while background information and theory is available in an accompanying textbook.

The Ecopath mass-balance modelling system is built on an approach initially presented by J.J. Polovina for estimating biomass and food consumption of the elements (species or groups of species) of an aquatic ecosystem. Subsequently it was combined with various approaches from theoretical ecology, notably those proposed by R.E. Ulanowicz, for the analysis of flows between the elements of ecosystems. However, the system has been developed much further, including for direct use in fisheries management and for addressing environmental questions including climate change through the inclusion of the temporal dynamic model, Ecosim, the spatial dynamic model, Ecospace, and the Ecotracer model for tracking persistent compounds. EwE is now used increasingly in multi-disciplinary settings, including for a wider range of application as illustrated below.

# Using EwE

Understanding the influence of man-made structures on the ecosystem functions of the North Sea (UNDINE)



**ICES Journal of Marine Science**  
An ecosystem approach for studying the impact of offshore wind farms: a French case study  
Jean-Philippe Frey, Aurere Raoux, and Jean-Claude Dauvin

**Analyzing Coastal and Marine Changes - Offshore Wind Farming as a Case Study - Zukunft Küste - Coastal Futures Synthesis Report**  
Marco Langer, Benjamin Nuchter, Sarah Germe, Kira Goe, Johannes Kriener, Benjamin Schmalz & Rüdiger Wüstenberg

**ROBERTS BANK TERMINAL 2 PROJECT ENVIRONMENTAL IMPACT STATEMENT EXECUTIVE SUMMARY**  
Ecological Modelling

**Evaluating the fishery and ecological consequences of the proposed North Sea multi-annual plan**  
Steven Mackinson, Mark Pietsch, Clement Garcia, Christopher Lyttim

**The European Landing Obligation**  
Reducing Discards in Complex, Multi-Species and Multi-Jurisdictional Fisheries  
3. Spatial MSE for the NPF: Evaluating Trade-offs  
Della Management Fish and Shellfish Ecosystem Model

**Evaluating conservation and fisheries management strategies by linking spatial prioritization software and ecosystem and fisheries modelling tools**  
Kristian Metcalfe, Sandrine Yaz, Georg H. Engelhart, Maria Ching Vilanova, Robert J. Smith, and Steven Mackinson

**Spatial ecosystem modelling of marine renewable energy installations: Gauging the utility of Eospace**  
Trade-offs between conservation and socio-economic objectives in managing a tropical marine ecosystem

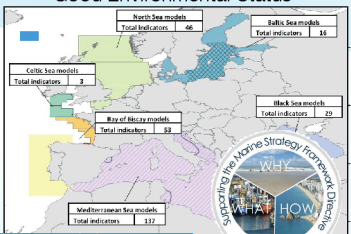
**Towards an Ecosystem Approach to Assess the Impacts of Marine Renewable Energy**  
Jean-Philippe Frey, Aurere Raoux, Nathalie Niquil, and Jean-Claude Dauvin

**How will fisheries management measures contribute towards the attainment of Good Environmental Status for the North Sea ecosystem?**  
Christopher Philip Lyttim, Steven Mackinson

**Good Environmental Status**

**Chapter 27 Preparing for the Inevitable: Ecological and Indigenous Community Impacts of Oil Spill-Related Mortality in the United States' Arctic Marine Ecosystem**

**Assessing ecological and fisheries implications of the EU landing obligation in Eastern Mediterranean**  
Dimitris K. Moustakidis, A. K. Kostasidou, T. Kostasidou



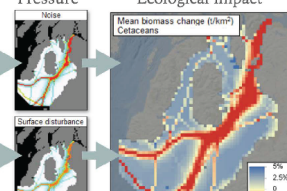
**UK Oil Sector To Spend \$19 Billion On North Sea Decommissioning**  
Assessing cumulative socio-ecological impacts of offshore wind farm development in the Bay of Seine (English Channel)

**Modellbasierte Bewertung der Auswirkungen von Offshore-Windkraftanlagen auf die ökologische Integrität der Nordsee**  
Science and Policy for People and Nature  
Ecological impact

**Chapter 4 State of the Art in Simulating Future Changes in Ecosystem Services**  
Trade-offs between supportive and provisioning ecosystem services of forage species in marine food webs

**JRC TECHNICAL REPORTS**  
**Towards an integrated water modelling toolbox**

**Using the Ecopath with Ecosim Modeling Approach to Understand the Effects of Watershed-based Management Actions in Coastal Ecosystems**  
James M. Woodruff, Ole G. Madsen, Villy Christensen & Howard Townsend



**Using the Ecopath approach for environmental impact assessment—A case study analysis**  
Sarah Fretzer A. W.

The development of EwE is coordinated by the [Ecopath International Research and Development Consortium](#) through the [Ecopath International Initiative](#) in Barcelona.

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## Adaption

This book is adapted from the unpublished EwE User Guide (2008) by Christensen V, C Walters,

D Pauly, R Forrest. Ecopath with Ecosim unless otherwise noted under the chapter “Adaption” heading.

## Citation

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# Disclaimers

The user guide provided herewith pertains to Ecopath with Ecosim (EwE), an open-source ecosystem modeling software tool. It is essential to recognize the limitations and boundaries associated with both this document and the software itself.

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In conclusion, this user guide endeavors to enhance user comprehension of EwE. However, users must exercise caution, diligence, and consider seeking professional guidance when suitable. The use of EwE signifies users’ acknowledgment and acceptance of the terms of this disclaimer.

For the most precise and current information, please consult the official EwE documentation and community resources.

EwE is a collaborative result of the open-source community's contributions and dedication. We appreciate your understanding, contributions, and feedback.

On behalf of the Ecopath International Initiative & the Ecopath Research and Development Consortium,

**Villy Christensen & Jeroen Steenbeek**

09 August 2023

This text was generated in part with GPT-3, OpenAI's large-scale language-generation model. Upon generating draft language, the editors reviewed, edited, and revised the language to their own liking and takes ultimate responsibility for the content.

# WORKING WITH EWE

# Getting Started

## How to Obtain the Ecopath with Ecosim Software

The setup programme for Ecopath with Ecosim 6 (EwE6) can be downloaded from [www.ecopath.org](http://www.ecopath.org). Simply download the setup file and follow the prompts.

## Software Support, Copyright and Liability

The software is copyrighted but not copy-protected. You may freely copy and distribute the program as long as this is not done commercially.

## Installing and Running Ecopath with Ecosim

Installation is done via a customized third-party setup program. Simply click on the link to the setup programme on the Ecopath website ([www.ecopath.org](http://www.ecopath.org)) and choose Run. Some browsers will give a warning that the software is from an unknown publisher, click Run if you get this warning. Then follow the prompts to for installing the software.

When installing, note that there are options for installing plug-in (utilities providing extra capabilities) – check those you want installed.

Currently EwE6 will only run only on the Windows platforms. For Mac/Linux versions we recommend the Parallel virtualization software, it provides a straightforward and easy-to-use-and-maintain approach for running EwE smoothly. Unfortunately, it is not free.

We are working to raise funds for a new version of EwE (7), and are committed to making that version platform independent.

If you have any other problems with installation, please contact us through the user support section of [www.ecopath.org](http://www.ecopath.org).

## Previous Versions

Any model built using a version of EwE5 later than version 1.67 can be converted to EwE6 format using the Ecopath database conversion wizard.

# ECOPATH

# Ecopath Input

The first task in building an ecosystem model is to clearly [define the question\(s\)](#) that the model is to answer. Once this is in place, it becomes much clearer what the model structure should be like. Assuming that is done, you can go ahead with the practical aspects of getting your model defined in EwE. That's what this chapter deals with.

Before entering data, you are encouraged to read the introductory material on the mass balance approach to ecosystem modelling for information about how the input parameters are used in the model.

Be aware that generally, leaving an input blank on a data entry form implies it is unknown. For some required parameters defaults are supplied and leaving such in place means accepting the default values. This is for instance the case for biomass accumulation, detritus import, landings, discards, migrations and prices (for all of which the default value is 0). You should be aware that opting for default values is as much a modelling decision as setting values – default values will not necessarily be appropriate for your model. But one upside is that you generally don't have to explain the EwE default values when publishing your model.

## Model Parameters

The *Ecopath > Input > Model parameters* form is used to define some basic settings and record basic information about your model.

## Model

This descriptive part is for recording some basic information, including the model area (in km<sup>2</sup>). All model stock sizes and flow rates are expressed per unit area (km<sup>-2</sup>), and stock and flow calculations in Ecopath, Ecosim, Ecospace and Ecotracer are all expressed per that unit area. There is, however, one exception. The value chain analysis works with quantities, so it, e.g., sums of how much the landings (in t km<sup>-2</sup> year<sup>-1</sup>) are for the ecosystem in question and then multiplies this with the model area (km<sup>-2</sup>) to get the quantity (t year<sup>-1</sup>). The value chain will then work with these quantities for all calculations. It makes sense, once the seafood is landed, the quantity is what matters, not how big the area was it came from or what the densities were in that area.

The spatial extent (N, S, W and E) can also be entered here. If this is done, the area will be known in Ecospace where it is used to calculate the cell dimensions considering the model latitude.

## Classification

If values are selected here from the drop down listings, the information can be used by the ecosystem model collection in [Ecobase](#). Related, when you have published an Ecopath model, you are strongly encouraged to submit it to Ecobase. This can be done from the menu *File > Export model > To Ecobase*. Ecobase models are available at [www.ecobase.ecopath.org](http://www.ecobase.ecopath.org) and can also be downloaded directly from *File > Import model > From Ecobase*.

## Basic Input

We provide only a cursory introduction and explanations for the various input fields as many are self-explanatory.

## Define Groups

You must define whether a functional group is a primary producer, consumer or detritus by checking the appropriate box.

- Primary producers (producers) obtain all of their energy from photosynthesis. By definition, their trophic level is 1.
- Consumers obtain their energy by consuming other organisms. They have trophic level > 1.
- You must enter at least one detritus group and you can have as many detritus groups as you like. Detritus groups must be placed after all living groups (i.e., they must have a higher group number than the last living group). You must also specify where the surplus detritus (left over after feeding by detritivores) will go using the *Ecopath > input > Detritus fate* form.

## Define Multi-Stanza Groups

The *Edit groups* form allows you to create groups representing life history stages or stanzas for species that have complex trophic ontogeny.

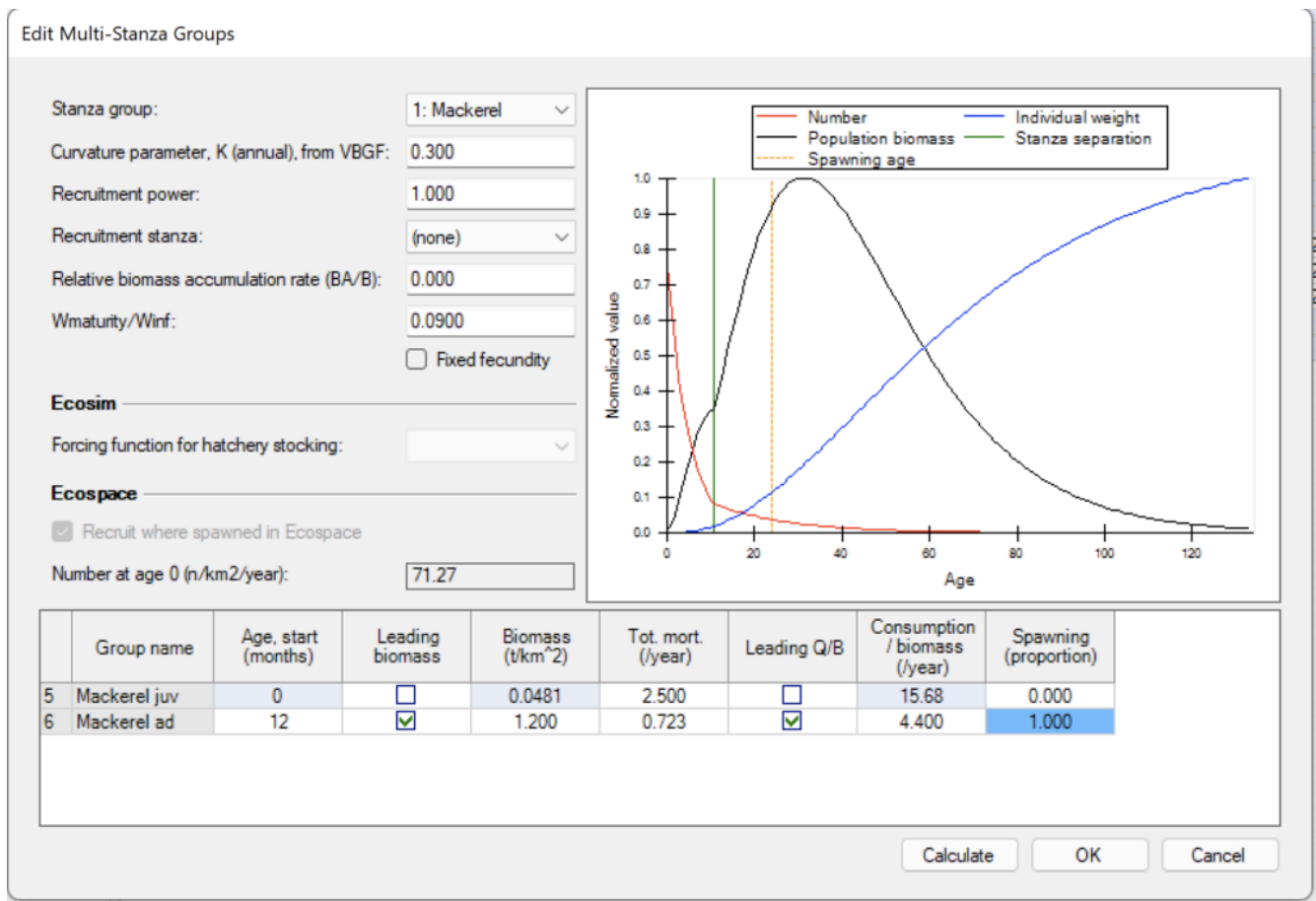
To define a multi-stanza group, add the stanzas as separate groups using the Insert button. Note that each stanza must have a unique group name (e.g., Juvenile cod; Adult cod). Name the multi-stanza group as a whole (e.g., Cod) in the Multi-stanza group name column. Once you have created a multi-stanza group name, it is added to a pull-down menu in the Multi-stanza group name column. Enter the start-age of each stanza in months in the Stanza age (in months) column. Note that your youngest stanza must have a start-age of zero months. If you do not have an age-zero stanza, Ecopath will set the youngest stanza's start age to zero (a message box will inform you of this). After defining a multi-stanza group(s), you must set the values of additional parameters for the group(s).

## Edit Multi-Stanza Groups

Multi-stanza groups represent life history stages or stanzas for species that have complex trophic ontogeny. Mortality rates ( $M_0$ , predation, fishing) and diet composition are assumed to be similar for individuals within each stanza (e.g., larvae having high mortality and feeding on zooplankton, juveniles having lower mortality and feeding on benthic insects, adults having still lower mortality and feeding on fish). For Ecosim and Ecospace it is advised to split groups of special interest into multi-stanza groups as this makes their dynamics more realistic, provides insights on stock-recruitment relationships, and allows consideration of stanza-specific habitat use.

Once you have defined a multi-stanza group(s) you must go to the *Ecopath > Input > Basic Input > Edit multi-stanza* form to set the parameters needed to calculate the biomass and numbers in each age category.

You must enter baseline estimates of total mortality rate  $Z$  (i.e.,  $P/B$ ) and diet composition for each stanza, and biomass and consumption/biomass ratio ( $Q/B$ ) for one 'leading' stanza only (can be any stanza). Biomass and consumption are then computed for the other stanzas, assuming a stable age distribution.



**Figure 1** – Ecopath > Input > Basic input > Edit multi-stanza form used for parameterizing multi-stanza groups. Input includes a (leading) biomass for one stanza, and a (leading) Q/B for one stanza. The remaining biomasses and Q/B are then calculated to ensure consistency. Setting the spawning (proportion) to 0 ensures that the stanza will not spawn even if the stanza reaches Wmaturity.

## Curvature Parameter, K

Set the von Bertalanffy growth rate. Note that it is assumed that body growth for the species as a whole follows a von Bertalanffy growth curve with weight proportional to length-cubed.

## Recruitment Power

This parameter is used by Ecosim and sets the degree of density dependence in juvenile survival for juveniles outside the modelled area. Set a low value, (e.g., 0.1-0.5) for this parameter if the juveniles for a group spend some time 'outside' the system in a nursery area where they are subject to density-dependent juvenile mortality rate, (e.g., juvenile Pacific salmon abundance may

be limited by freshwater nursery habitat, so that numbers recruiting to a coastal oceanic area can be practically independent of adult abundance in the oceanic area, especially if juvenile production is 'enhanced' by hatchery systems).

Note that you should not need to change other basic parameters defining trophic ontogeny for split groups. When it is the very early juvenile stage that is spent in some rearing habitat outside your modelled area (e.g. a stream or coastal lagoon), you may model the effect of limiting factors within that rearing habitat just by adjusting the recruitment power parameter, without bothering to account factors such as 'Import' of food to the juvenile biomass while juveniles are in the rearing area (cumulative effect of such trophic development are automatically calculated when scaling the juvenile body sizes within Ecosim based on Ecopath juvenile pool biomass). You can also use a low recruitment power parameter to make juvenile recruitment 'flat' with respect to modelled adult biomass due to recruitment of juveniles from some adult population 'egg source' outside the modelled area.

## Recruitment Stanza

Is used only for coupled stanza groups, where, e.g., males and females are modelled as separate stanza groups, ([see linked stanza recruitment](#)). In that case one can let the recruitment of males be a function of the abundance of spawning females. We've used that to model crabs where fisheries only retains males.

## Relative Biomass Accumulation Rate (BA/B)

The BA/B term represents effect on the numbers at age of the population growth rate, (e.g., the cohort born one year ago should be smaller by the factor  $\exp(-a \text{ BA/B})$  than the cohort born  $a$  years ago.

$$W_{\text{maturity}}/W_{\text{inf}}$$

Set the mean weight at maturity relative to  $w_{\infty}$ . Note that it is assumed that body growth for the species as a whole follows a von Bertalanffy growth curve with weight proportional to length-cubed.

## Forcing Function Number for Hatchery Stocking

Multi-stanza populations can be designated as hatchery populations, and hatchery production can be varied over time in Ecosim using time forcing functions. To turn off natural reproduction select the hatchery forcing function from the pull-down menu in the Forcing function number for hatchery stocking box. For this, you must already have a forcing time series loaded in Ecosim. Forcing functions to represent historical changes in stocking rates can be entered via the same CSV files as used to set up historical fishing and model fitting scenarios. Enter stocking rates as values relative to the stocking rate of 1.0 assumed for the Ecopath base year.

At each simulation time step, the base recruitment for the population (calculated from Ecopath input parameters) will be multiplied by the current time value for the designated forcing function. If it is desired to simulate stocking of older fish (e.g., 18 months), the first stanza for the population should be set to have this duration, the mortality rate ( $Z$  or  $P/B$ ) for the stanza should be set to 0.001, and the diet for the stanza should be set to 1.0 imported (i.e., no feeding in the modelled ecosystem).

## Fixed Fecundity

Some types of organism (e.g., marine mammals or some sharks) may have a fixed number of young each year, regardless of adult bodyweight. Checking the *Fixed fecundity* check box fixes the number of recruits.

## Biomass

You must enter estimated absolute biomass (in appropriate units) for one 'leading' stanza.

## Z (Production/Biomass)

You must enter estimated total mortality rates for each stanza.

## Consumption/Biomass

You must enter estimated consumption/biomass (Q/B) for one 'leading' stanza.

## Habitat Area

This is the fraction of the total area in which the group occurs, that is, the fraction of the total area to which the biomass in habitat area pertains. Default is that the habitat area is 1, i.e. that the group occurs in the total area.

## Biomass in Habitat Area

The average biomass per unit area in the habitat area where the group occurs. It is assumed that an average value can be used to represent the biomass of each group. Appropriate units should be used, (e.g.,  $\text{t km}^{-2}$ ) for the biomasses. Entry of biomasses is optional for living groups, but biomass(es) should be entered for the detritus group(s). However, if biomasses are unknown for all living groups and there are no exports from any of the groups, it is necessary to enter at least one biomass estimate, preferably of a top predator. (But in such a hypothetical case: what is the purpose of that model?)

Biomasses should be entered relative to the habitat area where the group occurs. An example: assume a species for instance has a biomass of  $1 \text{ t km}^{-2}$  in its habitat area, and the habitat area is  $100 \text{ km}^2$ , while the total area in your model is  $1000 \text{ km}^2$ . You could then enter a habitat area of 0.1 and a biomass in habitat area of  $1 \text{ t km}^{-2}$  as the biomass for the group in your model.

## Biomass

This is the Biomass in habitat area x Habitat area.

## Production/Biomass

Enter the Production/Biomass (P/B) ratio for each group using consistent units, e.g., per year. The P/B ratio is equivalent to the instantaneous rate of total mortality (Z) used in fisheries assessments

<sup>1</sup>(Allen 1971). Entry of P/B ratios is optional, but should as a rule be entered – don't leave it to estimation using the mass-balancing routine.

Production includes fishery yield (considered export in network analysis) plus predation plus net migration plus biomass change plus other mortality; or as expressed in the second Ecopath Master Equation,

$$P/B = Z = F + M2 + BA + E + M0 \quad (1)$$

Estimation of P/B is discussed in the [EwE textbook](#)

## Consumption/Biomass

Consumption/biomass (Q/B) ratios are entered using the same units as for P/B. Entry of consumption/biomass ratios is optional, but it is strongly advised to enter P/B for all groups, not to let it be estimated by the mass-balance routine.

The Q/B input box will be blocked (blue colour) for primary producers. If your model unit is carbon, you can however, click the blue input box, and enter a Q/B value, which will be used to calculate respiration for the group.

Estimation of Q/B is discussed in the [EwE textbook](#)

## Ecotrophic Efficiency

The ecotrophic efficiency (EE) is the fraction of the production that your model describe the fate of in the system, i.e. that is passed up the food web, used for biomass accumulation, migration or export (such as fished). Ecotrophic efficiency is difficult to measure directly. It varies between 0 and 1 and can be expected to approach 1 for groups with considerable predation pressure. The part of the production that is not included in the EE is often called 'other mortality'. EE is dimensionless, and the entry of EE values is optional.

The ecotrophic efficiency of a detritus group is defined as the ratio between the flow out of a detritus box to the flow into the same box. EE for detritus cannot be entered, it is always calculated.

## Other Mortality

Corresponds to 1-EE, if the other mortality is entered, EE will be blocked and *vice versa*.

## Production/Consumption

The ratio between production (P) and consumption (Q) and is a dimensionless parameter. P/Q corresponds to what may be called the gross food conversion efficiency (*g*). This ratio is by default considered constant in Ecosim where Q is estimated and P deduced.

There are physiological constraints for the P/Q ratio, which in most cases will range from 0.05 to 0.3. Exceptions are top predators, e.g., marine mammals, which can have lower P/Q values, and small fast-growing fish larvae or nauplii or bacteria, which can have higher P/Q values (up to around 0.5). The value of the ratio is checked during the mass-balance routine, and warnings are given if production exceeds consumption (as can occur in organisms with symbiotic algae, such as corals and giant clams), or if the production exceeds half the consumption (which may be acceptable for bacteria, small nauplii and fish larvae, but usually not for other groups).

P/Q can only be entered if P/B and/or Q/B is left blank. If P/Q is entered along with, e.g., P/B, then Q/B will be calculated as  $Q/B = (P/B) / (P/Q)$ .

## Unassimilated Consumption

An estimate of the fraction of the food that is not assimilated must be entered if the currency of your model is energy-related. Following Winberg<sup>2</sup>, a default value of 0.2 is suggested for carnivorous fish groups if other estimates are not available. Thus, 80% of the consumption is assumed to be physiologically useful while the non-assimilated food (consisting of faeces) is directed to the detritus. For herbivores, the proportion not assimilated may be considerably higher, e.g., up to 0.4 in zooplankton.

If the currency is a nutrient, there is no respiration, and the fraction of the food that is not assimilated is calculated as  $(1 - \text{production} / \text{consumption})$ . In this case, it is not possible to input the fraction of the food that is not assimilated.

The parameter for unassimilated food is dimensionless, it is entered as a proportion. A routine checks whether the sum of gross efficiency plus proportion of food not assimilated exceeds 1, and

displays a warning if so. Then, a new and consistent proportion for the non-assimilated food must be entered.

## Detritus Import

If there is import of detritus to the system, enter the quantity as a rate with a unit of, e.g.,  $\text{t km}^{-2} \text{ year}^{-1}$ .

## Diet Composition

In Ecopath predation links together the different groups in the model and diet composition must be entered for all consumer groups. While quantitative information on diet composition overall is sparse, there is a considerable amount of information in FishBase and SeaLifeBase. Unfortunately, much of the available information on diet compositions is expressed on a ‘percent occurrence’ basis or as ‘dominance’, both of which are of little use for quantification of diets, though there is a correlation with the preferable forms where diet inputs represent weight, volume or energy content of the preys<sup>3</sup>.

At the *Ecopath* > *Input* > *Diet composition* form enter diet composition for all consumers, column by column (i.e., predators are represented by column and their prey by row). The diet compositions of each group should sum to 1. For guidance, the current sum of the fractions representing the food composition is summed at the second-but-last row (*Sum*). The last row (*1 – Sum*) shows the proportion of prey still to be entered. You can use the *Sum to one* button at the top of the Diet composition screen to raise a diet to unity. If diets do not sum to unity when you start basic estimation (i.e., try to balance the model) you will be given the option of having the software do the raising for you, or to return to the diet to do it yourself.

In Ecopath ‘import’ to a system is the consumption of preys that are not a part of the system as it is defined (for example for species that spend parts of the year feeding outside the area of the model, e.g., gulls feeding on fields during harvest time).

Note that import is different from migration Migration, which is a production term. Import is treated as a ‘prey’ in the diet composition, and should be entered as a fraction of the total diet. See the section on *Dealing with open system problems* in the chapter on *Defining the ecosystem* in the EwE textbook for more information on how to treat groups that feed both within and outside of the modelled area.

A warning about zero order cycles, i.e., groups that feed on themselves ('cannibalism'). Avoid situations where the fraction of the food of a group taken from that same group exceeds ~0.1. This may occur when adults feed on their own juveniles. In such cases, it is advised to split the box into groups representing predator and prey stanzas, e.g., in adults and juveniles. This will not only reduce or eliminate a zero-order cycle, and the bothersome computational problems usually associated with such cycles, but also lead to groups with better-defined characteristics (because adults usually have much lower production and consumption rates than those of juveniles).

## Detritus Fate

At the *Ecopath > Input > Detritus fate* form you must, if there is more than one detritus group in the system, specify where the detritus left over after the detritivores have covered their food intake is to be directed. Surplus detritus can be directed to the same detritus group (equivalent to 'biomass accumulation') or to other groups, by entering the appropriate fractions directed to each detritus groups. If these fractions sum to less than 1, the remaining part of the surplus detritus will be exported out of the system.

## Other Production

Other production refers to production represented in *Ecopath* by migration and biomass accumulation. Migration is not the same as import – emigration and immigration are production factors, while import is food consumption.

If B, P/B, Q/B and EE are entered for a group, a prompt will appear during parameterization asking if you want to estimate biomass accumulation. If you answer no to this, a new prompt will ask if you want to estimate net migration. If you answer yes, the program will estimate net migration.

The net migration is calculated as emigration less immigration. This means that net migration will be negative if there is more coming into the system than leaving it. This may seem contradictory but it should be remembered that a negative mortality can yield an increase in population. If the net migration is positive (immigration > emigration), but not entered, the main effect will depend on the previous entries:

- if the production had been entered, the fraction of production directed toward the detritus will be overestimated; or
- if production was to be estimated, this estimate will be underestimated.

## Immigration

Migration into the area covered by the model. Must be entered as a non-negative value. Unit is a flow, e.g.,  $\text{t km}^{-2} \text{ year}^{-1}$ .

## Emigration

Migration out of the area. Must be entered as a non-negative value. Unit is a flow, e.g.,  $\text{t km}^{-2} \text{ year}^{-1}$ .

## Emigration Rate

Emigration can also be presented as the proportion of the population emigrating from the system in a year (unit is  $\text{year}^{-1}$ ). The immigration rate can be entered by setting the emigration rate to a negative value.

## Biomass Accumulation

Ecopath is not a steady-state model. If the biomass for a group is known, e.g., at the beginning of the year and at the beginning of the next year, the biomass accumulation (BA) can be calculated as the difference between these biomasses. BA is a production term that can be entered for all living groups (default is 0), but is calculated for detritus groups. BA is a flow term, with a rate unit of, e.g.,  $\text{t km}^{-2} \text{ year}^{-1}$ . The default value for BA is zero indicating no biomass accumulation. A negative value signifies biomass depletion (biomass decreased during period modelled).

If B, P/B, Q/B and EE are entered for a group, a prompt will ask during parameterization if you want to estimate BA. If you answer yes to this question the BA will be calculated, overruling any BA you may have entered.

If you have a BA in your Ecopath model, Ecosim and Ecospace will pick up these values and it will set both models on a trajectory when a model run starts. A negative BA value may for instance inform Ecosim that the fishing pressure in Ecopath is unsustainable and Ecosim will hence predict a decline over time in the species concerned.

### Biomass accumulation rate

Biomass accumulation can also be represented as a rate relative to the total biomass,  $BA/B$ . The unit is  $(t\ km^{-2}\ year^{-1}) / (t\ km^{-2}) = year^{-1}$ .

## Fishery

At the *Ecopath* > *Input* > *Fishery* > *Fleets* > *Define fleets...* form you must first of all define your fishing fleets, then at the mother *Ecopath* > *Input* > *Fishery* > *Fleets* form set basic fleet cost parameters. Notice that the economic analysis that can be done with these basic cost factors is quite limited in comparison to what can be done with the full value chain analysis in EwE , see *Ecopath* > *Output* > *Tools* > *Value chain*.

## Fixed Cost

Fixed cost is the cost of operating a fleet unit, independent of effort, in the unit time defined in *Ecopath* (typically on an annual basis). The definition of 'fixed' costs depends on the actual situation being modelled. To illustrate this consider some examples:

The Ecospace optimization module, *Ecosed*, allows for effort reduction to nil in connection with simulated increase in protected areas from 0 to 100% of total model area. As the last boats operating in a fleet cannot cover the total 'fixed' costs of the total fleet; they should only bear the 'fixed' costs that are independent of effort. For this type of application use the 'fixed costs' only for costs that are independent of effort at the fleet scale, for instance for the costs of management and monitoring, (and subsidies if there are fixed subsidies to the fleet). Costs that are capacity dependent in this situation should be considered effort-related variable costs instead.

Effort can also be changed in *Ecosim*:

- If the changes are relatively small and intended to represent changes in effort with constant capacity, the fixed costs can be seen to represent all costs that are effort-independent at the boat-level. Examples are costs for management, monitoring, licenses, capitalization, and insurance.
- If the changes are major, the procedure outline for *Ecosed* above should be adopted instead. Hence, consider the fixed costs to be effort-independent at the fleet level.

## Effort Related Cost

Represents costs that are a function of effort. The examples above give some guidance to how these should be defined. Enter the costs as a percentage of the total value of the fishery in the given year. Simulation in Ecosim with changes in fishing effort are entered relative to the base effort, hence if the effort is increased with, e.g., 10% the variable costs are assumed to increase 10% as well, whereas the fixed costs are assumed unchanged.

Ecosim: use *Effort related costs* for all variable costs (e.g., fuel, gear costs and crew wages);

Ecospace: use *Effort related costs* for variable costs that depend on effort, e.g., for gear costs (which mainly depend on how many hours the gears is used), but not for costs that depend on spatial effort allocation, e.g., sailing costs. See next section.

## Sailing Related Cost

For Ecospace applications it is recommended to use two separate forms for variable costs: effort-related and spatially-related (i.e., sailing related). Do not enter sailing related costs if you are only using Ecosim, then use effort related costs for all variable costs.

If you are using Ecospace, use *Effort related costs* for variable costs that depend on effort, e.g., for gear costs. Enter costs that depend directly on spatial effort allocation, e.g., fuel costs and crew wages as *Sailing related costs*.

## Profit

Profit is calculated as percentage of value, calculated from total value less all costs. It cannot be entered directly.

## Total value

The total value is the value of all landings (as entered on subsequent forms). It is displayed here only to indicate that the '100 %' relates to value, not to total costs.

## Landings

Landings and catches are not the same, as discarding is an integral part of most fishing operations. Ecopath calculates:  $\text{Catch} = \text{landings} + \text{discards}$ .

You should therefore enter only the landings here – while any discards should be entered on the discards form. Landings must be expressed as flows, typically in  $\text{t km}^{-2} \text{ year}^{-1}$ . The area to be used should be the total area of your model, not just habitat area, or the area in which the fleet operates. For instance, if you are entering information for a coastal shrimp fishery, the landings (and discards) should be calculated relative to the total area of the model – even if most of it is too deep for trawling.

In a model of an ecosystem exploited by a fishery, the catch is the total extractions over the time period considered in the model, (e.g., a year), for each of the groups modelled. Similarly, in an aquaculture system the ‘catch’ is the harvest from each group over the time period considered, (e.g., a growing season considered representative for a year).

Fishery catches are normally based on landing statistics. This may cause a problem as official statistics are generally on a regional basis, not on an ecosystem basis. This can be of importance when defining the system to be modelled, either as a geographical/political region or as an ecosystem. It is necessary to consider the availability of appropriate catch data when taking such decisions. [Sea Around Us](#) data may be useful if you don't have access to local data or for comparison with local data.

The catches together with other export sum up to the total export. Catches are also used to estimate the fraction of primary production that is utilized in the system (i.e., the ‘gross efficiency of the fishery’).

## Discards

Discarding is (or was) a normal practice in most fisheries, though this has changed with the [EU Landing Obligation](#) regulations. If you do not enter any information, you are assuming that discarding does not take place. If discarding does take place this is worse than guessing! Therefore, it is better to use information from similar fisheries in other areas or perhaps based on interviews with fishers in your area – or from the [Sea Around Us](#) .

Discarding may affect trophic and population dynamics. For example, in shrimp fisheries where the discards include predators on shrimps that may be turned into food for shrimps, an ecosystem model can be used to quantify the ecological role of discarding.

## Discard Mortality

Discard mortality is a mortality rate in the [0,1] range, where by default the assumption is that all discards die.

## Discard Fate

Ecopath needs to be told what to do with the discards you enter as part of the catches. Discards can either go to a detritus group or be exported. Discard fate is entered as a proportion, i.e., a value between and including 0 and 1, representing the fraction of the discards directed to a given detritus group (or exported).

If you are interested in quantifying the ecological impact of discarding it is recommended that you make a special detritus group called, e.g., 'Discarded fish' and direct the discards to this group.

## Off-Vessel Price

Enter the market value (in the specified monetary unit per unit catch) for each group for each gear (fleet). It is generally not important whether the market values are entered in, e.g., €/kg or €/tonnes, as long as the entries are consistent among groups. This is, however, important for Value chain analysis, which are designed to quantify the total socio-economic benefits and costs of ecosystem usage.

The off-vessel prices are fleet-specific on the entry forms, as quality and hence price varies more between fleets than within fleets.

As per EwE version 6.7, negative off-vessel prices can be specified to impose quota penalties.

## Non-Market Price

Shadow price or non-market price represents the value of a resource in the ecosystem, e.g., for non-exploitative uses. Values should be expressed in monetary units per unit biomass. At present it is assumed that there is a linear relationship between the biomass of a resource and its non-market price (if there is any). Hence, for groups with a non-market price it is assumed that a doubling in biomass will lead to a doubling of the resource's non-market value.

# Pedigree

Define pedigree...

**Pedigree**  
 Category: Production / biomass  
 View as: Color

**Assignment**

	Group name	Biomass in habitat area	Production / biomass	Consumption / biomass	Diet	Catch
1	Whales					
2	Seals					
3	Cod					
4	Whiting					
5	Mackerel juv					
6	Mackerel ad					
7	Anchovy ad					
8	Shrimp					
9	Benthos					
10	Zooplankton					
11	Phytoplankton					
12	Anchovy juv					
13	Detritus					

Classifications:

- (none)
- Estimated by Ecopath
- Guesstimate
- From other model
- Empirical relationship
- Similar species, similar system, low precis
- Similar species, same system, low precis
- Same species, similar system, high precis
- Same species, same system, high precis

Figure 2 – Screenshot of pedigree table

## Resources

There is a *Quick guide on how to calculate P/B and Q/B for EwE models* by Daniel Vilas, Marta Coll, Chiara Piroddi, Jeroen Steenbeek, developed for the EC Safenet Project, available at [this link](#).

## Notes

- Allen, K. R. 1971. Relation between production and biomass. J. Fish. Res. Board Can., 28:1573-1581. <https://doi.org/10.1139/f71-23>
- Winberg, G. G., 1956. Rate of metabolism and food requirements of fishes. In: Transl. Fish. Res. Board Can., Translation Series 194. pp. 1-253. <https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/38248.pdf>
- MacDonald, J. S., and Green, R. H. 1983. Redundancy of variables used to describe importance of prey species in fish diets. Can. J. Fish. Aquat. Sci., 40:635-637. <https://doi.org/10.1139/f83-083>

# Linked Stanza Recruitment

JEROEN STEENBEEK

## Background

Occasionally, ecosystem modellers run into issues where gender-split populations need explicit modelling. This can occur when empirical data is only available for male or female specimens, or when males and females of key species have markedly different behaviours. We have made a small modification to the Ecopath with Ecosim (EwE) multi-stanza model <sup>1</sup>, that allows linking recruitment to ensure proportional spawning between two multi-stanza groups, and thus connecting two gender-spilt populations at their foundation.

## Implementation

At the first Ecosim and Ecospace time steps, a base scalar is calculated:

$$a_i = NAge1_i / NAge1_j \quad (1)$$

where  $a$  is the scalar,  $i$  is a multi-stanza group whose recruitment is driven by multi-stanza group  $j$ , and  $NAge1$  is the number of individuals at age 1, e.g., the number of recruits, for multi-stanza groups  $i$  and  $j$ . This base scalar serves to maintain the ratio between the number of gender-split recruits during the simulations.

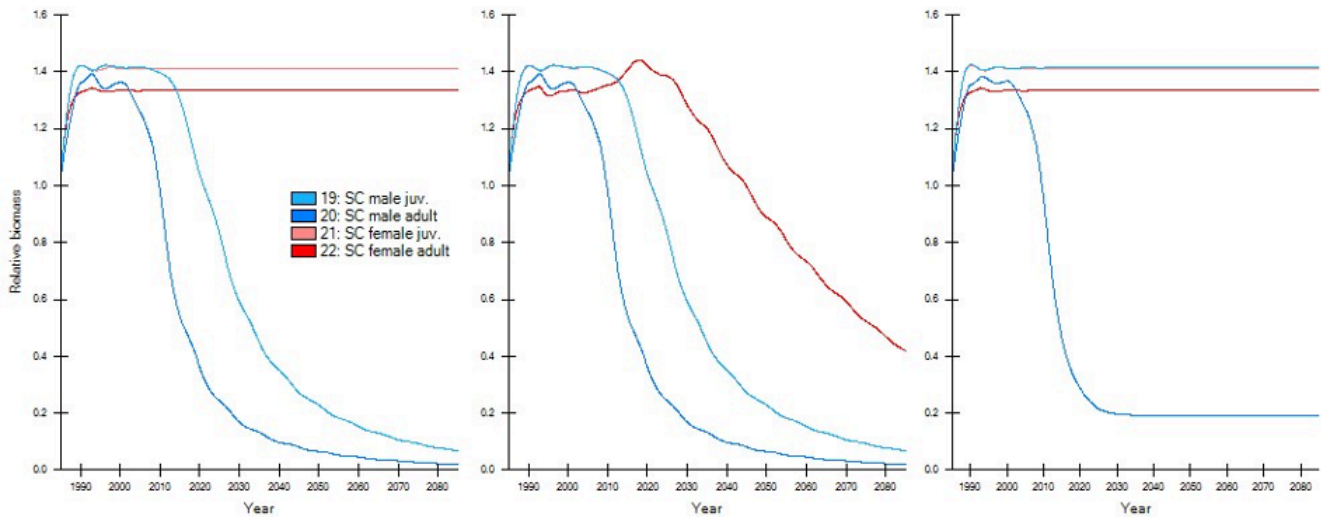
For every consecutive time step, the number of multi-stanza group  $i$  recruits is then set as follows:

$$NAge1_i = a_i \times NAge1_j \quad (2)$$

Changes to the EwE computations were minimal; the most challenging code changes were made in the Ecospace IBM model <sup>2</sup>, where parallel computations was reorganized to ensure that multi-stanza recruitment is calculated in the correct order. Ecospace does not yet calculate recruitment success from spatial overlap of the gender-split stanza; this could be a future refinement if needed.

An example of the impact of linked recruitment is shown in Figure 1. Here, Ecosim is executed for a model that contains separate multi-stanza groups for male and female snow crab *Chionoecetes opilio*. Both multi-stanza groups consist of two life stages each: juveniles and adults. Only the male snow crabs are fished. The model contains no change in environment and fishing other than

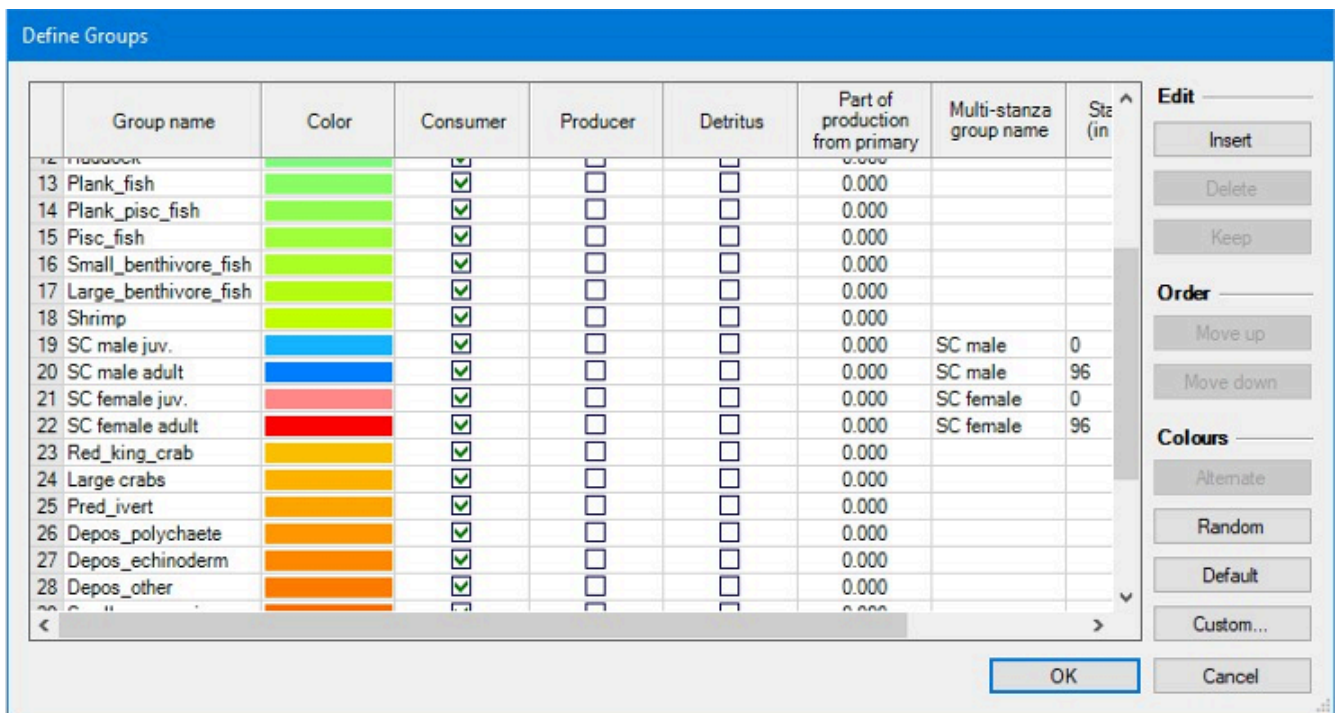
gradually intensifying effort of the snow crab fishery. Figure 1 shows three simulations: in the left panel, multi-stanza recruitment is not linked. In the middle panel, female recruitment is obtained from the male multi-stanza group. In the right panel, male recruitment is obtained from the female multi-stanza group.



**Figure 1** - Three Ecosim simulations with different recruitment linkage configurations for snow crab: no linked recruitment (Left), female recruitment linked to the fished males (Center), and fished male recruitment linked to non-fished females (Right). Note that both juvenile groups are identically parameterized in this specific case, and therefore their biomass estimates exactly overlap in the Center and Right plots.

## Configuring Linked Stanza Recruitment

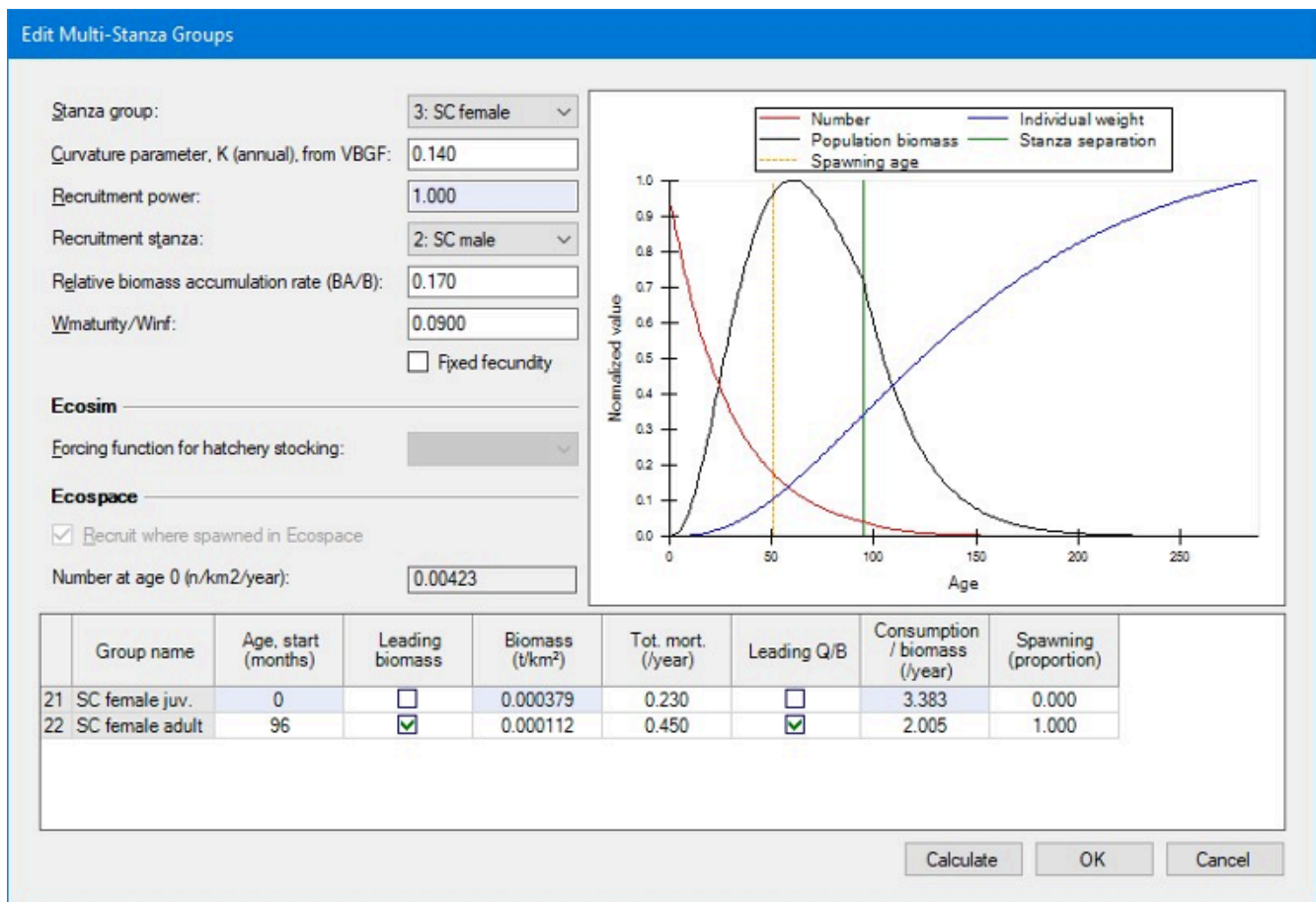
First, define the male and female multi-stanza configurations in the *Define groups* interface (Figure 4).



**Figure 2** - Define gender-split multi-stanza groups

Second, configure the two gender-split multi-stanza groups in the “Edit multi-stanza” interface (not shown here).

Third, link recruitment in the “Edit multi-stanza” interface. In the figure below, female snow crab recruitment is linked to the males. A multi-stanza group whose recruitment is linked will have its recruitment calculations overwritten, and therefore the “Recruitment Power” parameter becomes inactive (Figure 5).



**Figure 3** - Linking the recruitment of a multi-stanza configuration to another multi-stanza.

## Attribution

Linked stanza recruitment was implemented by Jeroen Steenbeek after an idea by Villy Christensen under project [EISA: Ecology and management of the invasive snow crab](#).

## Notes

1. Christensen and Walters, 2004, *op. cit.*
2. Walters, C., Christensen, V., Walters, W., Rose, K., 2010. Representation of multistanza life histories in Ecospace models for spatial organization of ecosystem trophic interaction patterns. [Bulletin of Marine Science](#) 86, 439–459.

# Ecopath Output

It's a fascinating aspect of food web models that one can deduct quite a bit about the ecosystem form and functioning simply from the flows and state variables in the food web, from the ecosystem flow chart. This is different though from what can be deducted from a more complex dynamic model. You could think of it as the difference between analyzing a single picture and watching a movie. It's different things, different questions, all with their value. The value of the food web representation comes from it being simple, well rather simple, it can be complex or messy given enough functional groups. But there are lessons to be drawn from such simple representations.

To get to those lessons, we need indicators. The food web *per se* is indeed quite messy to examine, and we use indicators to make sense of such messiness. The field of network analysis is built around this, what can one deduct from a network such as represented by a food web? EwE to that effect has a network analysis plug-in with the more complex analysis, while a suite of indicators are given in the *Ecopath > Output* forms, which is the topic of this chapter.

Once you have entered sufficient input parameters, you can proceed to the output forms where on the *Ecopath > Output > Basic estimates* form, the missing parameters will be estimated so that mass balance is achieved. Both input (black font) and calculated (blue font) parameters are displayed.

If Ecopath has NOT been balanced already since opening or making changes to the input parameters, selecting any of the output forms will cause Ecopath to attempt to balance the model. Note also that you will not be able to balance your model if the sum of the diet composition for each consumer group does not sum to 1. Return to the *Ecopath > Input > Diet composition* form and fix the problem if this is the case. When you create an Ecopath model and need to mass-balance it, know that uncertainty can be dealt with later. To get started, we need a plausible model, not the correct model (which doesn't exist) but one that can be used for, e.g., making thousands of models based on parameter uncertainty.

Problems in parameter estimation will be shown in the *Status panel*. Two types of message may be displayed in the *Status panel* while you are balancing your model

- Information messages provide feedback on regular events in EwE. Information events are confirmations of things that went well. Examples are opening the model; successful edits; and successful balancing (i.e., parameterization) of the model.
- Warning messages when EwE was not able to complete an action and requires the user to fix a problem, usually with the input data. For example, one of the most important of these is when parameterization fails (i.e., the model failed to balance). When this occurs, you will get

the message “Your model is NOT balanced! Computed Ecotrophic Efficiencies (*EE*) invalid for one or more group(s).” Clicking on the “+” icon next to this message expands the message to show which groups are causing the problem.

## Basic Estimates

Most of the parameters on this screen are input values and therefore discussed in [that section](#) of this guide.

## Trophic Level

Lindeman <sup>1</sup> introduced the concept of trophic levels. In Ecopath, the trophic levels are not necessarily integers (1, 2, 3...) as proposed by Lindeman, but can be fractional (e.g., 1.3, 2.7, etc.) as introduced by Odum and Heald <sup>2</sup>. A routine assigns definitional trophic levels (TL) of 1 to producers and detritus and a trophic level of  $1 + [\text{the weighted average of the preys' trophic level}]$  to consumers.

Following this approach, a consumer eating 40% plants (with TL = 1) and 60% herbivores (with TL = 2) will have a trophic level of  $1 + [0.4 \cdot 1 + 0.6 \cdot 2] = 2.6$ . The fishery is assigned a trophic level corresponding to the average trophic level of the catch, i.e. without adding 1 as is done for ‘ordinary’ predators.

The trophic level is a dimensionless index.

## Key Indices

### Net Migration

The net migration, *E*, is calculated as emigration less immigration. This means that net migration will be negative if there is more coming into the system than leaving it, i.e. it will be a negative production term, which perhaps may balance a higher fishing mortality or an increase in biomass accumulation.

## Flow to Detritus (FlowToDet)

For each group, the flow to the detritus consists of what is egested or excreted (the non-assimilated food) and those elements of the group that die of old age, diseases, etc., (i.e., of sources of 'other mortality', expressed by  $1 - EE$ ). The flow to the detritus, expressed, e.g., in  $t\ km^{-2}\ year^{-1}$ , should be positive for all groups.

### **Estimation of Q/B for Detritivores**

It is not possible to estimate the Q/B ratio for groups that feed exclusively on detritus. For detritus, the production is not defined, and for such detritivores it will be necessary to input Q/B (or P/B and an estimate for gross food conversion efficiency,  $g$ , as  $Q/B = P/B / g$ ).

Remember, it is not a good idea to estimate P/B or Q/B for any group, make them input instead.

## Net Efficiency

The net food conversion efficiency is calculated as the production divided by the assimilated part of the food, i.e.,

$$\text{Net efficiency} = P/B / (Q/B \cdot (1 - U))$$

where P/B is the production / biomass ratio, Q/B is the consumption / biomass ratio, and U is the proportion of the food that is not assimilated (but egested or excreted).

The net efficiency can also be expressed,

$$\text{Net efficiency} = \text{production} / (\text{production} + \text{respiration})$$

The net efficiency is a dimensionless fraction. It is positive and, in nearly all cases, less than 1, the exceptions being groups with intermediate trophic modes, e.g., groups with symbiotic algae. The net efficiency cannot be lower than the gross food conversion efficiency,  $g$ .

## Omnivory Index

The 'omnivory index' was introduced in 1987 (Pauly et al., 1993a) in the initial, unreleased version of the Ecopath II software. This index ( $OI_j$ ) is calculated as the variance of the trophic level of a consumer's ( $j$ ) prey groups ( $i$ ). Thus

$$OI_j = \sum_{i=1}^n (TL_i - (TL_j - 1))^2 \cdot DC_{ji} \quad (1)$$

where,  $TL_i$  is the trophic level of prey  $i$ ,  $TL_j$  is the trophic level of the predator  $j$ , and,  $DC_{ji}$  is the proportion prey  $i$  constitutes to the diet of predator  $j$ .

When the value of the omnivory index is zero, the consumer in question is specialized, i.e., it feeds on a single trophic level. A large value indicates that the consumer feeds on many trophic levels. The omnivory index is dimensionless.

The square root of the omnivory index is the standard error of the trophic level, and a measure of the uncertainty about its precise value due to both omnivory and sampling variability.

## Mortality Rates

The three forms in this node are arguably the most important reference for the user during the model-balancing process, as they can be used to indicate which mortality components are most likely to be causing problems.

## Mortalities

The mortality coefficients form (Figure 1) is one of the most important forms on the Parameterization menu and it is, as a rule, the first that should be checked when balancing a model.

	Group name	Prod/biom or Z	= Fishing mort. rate	+ Predation mort. rate (/year)	+ Biomass accum. rate (/year)	+ Net migration rate (/year)	+ Other mort. rate (/year)	Fishing mort. / total mort.	Proportion natural mort.
1	Whales	0.0500			0.0200		0.0300	0.000	1.000
2	Seals	0.154	0.0739		-0.0500		0.130	0.471	0.529
3	Cod	0.310	0.150	0.129			0.0308	0.484	0.516
4	Whiting	0.581	0.111	0.435			0.0345	0.191	0.809
5	Mackerel	0.723	0.333	0.340			0.0500	0.461	0.539
6	Anchovy	1.149	0.200	0.898			0.0509	0.174	0.826
7	Shrimp	3.000	0.625	1.676			0.699	0.208	0.792
8	Benthos	3.000		1.800			1.200	0.000	1.000
9	Zooplankton	35.00		6.945			28.05	0.000	1.000
10	Phytoplankton	240.0		211.3			28.74	0.000	1.000

**Figure 1** – Mortalities form, Ecopath > Output > Mortality rates > Mortalities. The form neatly lists the second Ecopath Master Equation, with production = fishing + predation + biomass accumulation + net migration + other mortality, with all terms expressed as rates (i.e. relative to biomass, unit year<sup>-1</sup>). This form is the first to check when balancing a model.

## Components of Mortality in Ecopath

Under equilibrium assumptions, each group can be represented by an average organism, with an average weight. This makes it possible to use equations for estimating mortality in numbers, even when dealing with biomass. One such equation is  $N_t = N_0 \cdot e^{-Zt}$  where  $N_0$  is a number of organism at time 0;  $N_t$  is the number of survivors at time  $t$ ; and  $Z$  is the instantaneous rate of mortality (year<sup>-1</sup>).

Under the assumption that  $Z_i$ , the mortality of group  $i$ , is constant for the organisms included in  $i$  it turns out that for a large number of growth functions (including the von Bertalanffy Growth Function, or VBGF)

$$Z_i = (\text{production/biomass})_i = (P/B)_i \quad (2)$$

or instantaneous mortality equals total production over mean biomass<sup>3</sup>.

The mortality coefficient can be split into its components following a well-known procedure, i.e., the second Ecopath Master Equation,

$$Z_i = (P/B)_i = \text{Fishing mortality} + \text{Predation mortality} + \text{Biomass accumulation} + \text{Net migration} + \text{Other mortality}$$

or

$$Z_i = (P/B)_i = F_i + M2_i + BA_i + E_i + M0_i \quad (3)$$

Where for group  $i$ ,

- $F_i$  is the fishing mortality rate;
- $M2_i$  is the predation mortality rate;
- $BA_i$  is the biomass accumulation rate (actually  $BA_i/B_i$ );
- $E_i$  is the net migration rate (emigration less immigration).  $M0_i$  is the other mortality rate.

All are with the unit  $\text{year}^{-1}$  as they are rates ( $\text{t km}^{-2} \text{ year}^{-1}$ ) relative to biomass ( $\text{t km}^{-2}$ ).

In some models, (notably the Multispecies Virtual Population Analysis), the ‘other mortality’ component is split between  $M1$ , i.e., predation by predators not included in the model, and  $M0$ , ‘other mortality’, caused by diseases, senescence, etc. In Ecopath,  $M1$  is included in  $M0$ , as models often are intended to describe the major components of predation mortality explicitly (so  $M1$  is likely to be minimal). Further,  $M0$  is not entered directly, but is computed from the ecotrophic efficiency,  $EE$ .

Ecopath-predicted values for these coefficients are given on the Mortality coefficients form. The mortality coefficients are estimated from the following equations:

$$Z_i = (P/B)_i \quad (4)$$

$$M2_i = \sum_j B_j \cdot (Q/B)_j \cdot DC_{ji} / B_i \quad (5)$$

$$F_i = C_i / B_i \quad (6)$$

$$M0_i = (1 - EE_i) \cdot (P/B)_i \quad (7)$$

where  $(Q/B)_j$  is the consumption/biomass ratio of predator  $j$ ;  $DC_{ji}$  is the proportion prey  $i$  contributes to the diet of predator  $j$ ,  $B_i$  is the average biomass of  $i$ , and  $C_i$  is the catch of  $i$ . The biomass accumulation term,  $BA_i$ , is a basic input term.

## Predation Mortality

The predation mortality of a group  $i$  is the sum of the consumption of  $i$  by all groups (including  $i$ ), divided by the biomass of group  $i$ . Predation mortality is calculated from (7), i.e., it is *not* an input parameter.

When you balance a model, and you have a group that does not balance ( $EE > 1$ ), the first thing to do is to check the *Ecopath > Output > Mortality rates > Mortalities* form (as described above in this chapter) to evaluate if the problem is due to fishing or predation (one of which or both often being the culprit). If it is due to predation, the next step is to check the *Ecopath > Output > Mortality rates > Predation mortality rates* form (Figure 8).

	Prey \ predator	1	2	3	4	5	6	7	8	9
1	Whales									
2	Seals									
3	Cod	0.0240	1.218		0.0930					
4	Whiting	0.0400	2.537	0.215	0.155					
5	Mackerel	0.120				0.220				
6	Anchovy	0.0514		0.111	0.359	0.377				
7	Shrimp		1.142	0.967	0.697					
8	Benthos	0.000434	0.495	0.0350	0.0118			0.0578	1.200	
9	Zooplankton					0.161	4.318		13.47	
10	Phytoplankton								22.14	207.2

**Figure 2** – Predation mortality form (Ecopath > Output > Mortality rates > Predation mortality rates) for Anchovy Bay with seal biomass increased 100 times. The model is not balanced for cod and whiting (highlighted). Make it rule to examine this form, here to find the problem with predation mortality rates (M2) due to seal's erroneously high biomass, but also generally for models to balance to learn who they important predators are for each group. The M2s are rates (year<sup>-1</sup>) that can be summed up by row to give the total M2 by group.

The form will guide you to particular mortality coefficients that are causing problems with balancing. If predation mortality is too high then the form will help you identify which predators that are causing the problem for a particular prey group.

To help you identify possible problem predators, cells with unusually high predation mortalities will be shown with a different-coloured background instead of the usual background (as is the case for seals predation on cod and whiting in Figure 1).

## Consumption

The Ecopath estimates of consumption (food intake) can be found at Ecopath > Output > Consumption. The consumption of a living group is the product of its biomass (B) times its consumption/biomass ratio (Q/B). The food intake is a flow rate expressed, e.g., as t km<sup>-2</sup> year<sup>-1</sup>.

The consumption table also displays all flows to the detritus group(s) even though it is not consumption, (we had to put it somewhere).

# Respiration

The Ecopath estimates of respiration are at  $Ecopath > Output > Respiration$ . The *Respiration* form displays the predicted values for respiration and assimilation of food by all groups.

## Respiration

Respiration includes all non-usable 'model currency' that leaves the box representing a group.

When the currency is energy or carbon, the bulk of the assimilated food will end up as respiration. If, however, a nutrient (e.g. phosphorus or nitrogen) is used as currency, all nutrients that leave the box is re-utilized; in this case, respiration is nil.

Primary producers will not have respiration if the unit is energy based.

Since assimilated food ends up as either production or respiration, only one of these two quantities needs to be estimated, as the other – here respiration – can be calculated as a difference. In Ecopath, this is calculated as the difference between the assimilated part of the consumption and that part of production that is not attributable to primary production (i.e.,  $1 - TM$ ). Thus, for groups with intermediate values of  $TM$ , i.e., for mixed producers/consumers, only that part of the production that is not attributable to primary production is subtracted. For reasons of consistency, in Ecopath, detritus is assumed not to respire, although it would if bacteria were considered part of the detritus, (which is one reason why it is better to create one or more separate groups for the detritus-feeding bacteria if this difficult group is to be considered at all).

The respiration of any living group ( $i$ ) can be expressed as,

$$Resp_i = (1 - U_i) \cdot Q_i - (1 - TM_i) \cdot P_i \quad (8)$$

where  $Resp_i$  is the respiration of group  $i$ ,  $U_i$  is the fraction of  $i$ 's consumption that is not assimilated,  $Q_i$  is the consumption of  $i$ , and  $TM_i$  is the proportion of the production that can be attributed to primary production. If the unit is a nutrient,  $TM_i$  is equal to zero, irrespective of whether the group is an autotroph or not (nutrients are not produced), and,  $P_i$  is the total production of group  $i$ .

Respiration is used, in Ecopath, only for balancing the flows between groups. Thus, it is not possible to enter respiration data. However, known respiration values (i.e., the metabolic rate) of a group can be compared with the output, and the input parameters adjusted to achieve the desired respiration.

Respiration is a non-negative flow expressed, e.g., in  $t\ km^{-2}\ year^{-1}$ . If the currency is a nutrient, (e.g., nitrogen or phosphorus), respiration is zero: nutrients are not respired, but egested or excreted and recycled within systems.

## Assimilation

The part of the food intake that is assimilated is computed for each consumer group from

$$B_i \cdot (Q/B)_i \cdot (1 - U_i) \quad (9)$$

where  $B_i$  is the biomass of group  $i$ ;  $(Q/B)_i$  is the consumption / biomass ratio of group  $i$ ; and  $U_i$  is the part of the consumption that is not assimilated.

The three parameters needed for the estimation are all input parameters. Assimilation is a flow expressed, e.g., in  $t\ km^{-2}\ year^{-1}$ .

## Respiration/Assimilation

The (dimensionless) ratio of respiration to assimilation cannot exceed 1 as respiration cannot exceed assimilation. For top predators, whose production is relatively low, the respiration/assimilation ratio can be expected to be close to 1, while it will tend to be lower, but still positive, for organisms at lower trophic levels.

## Production/Respiration

The (dimensionless) ratio production / respiration express the fate of the assimilated food. Computationally, this ratio can take any positive value, though thermodynamic constraints limit the realized range of this ratio to values lower than 1.

## Respiration/Biomass

The R/B ratio can be seen as an expression of the activity of the group. The higher the activity-level is for a given group, the higher the ratio. The R/B ratio is strongly impacted by the assumed fraction of the food that is not assimilated, see the basic input form. If the ratio is too high, this

may be due to GS being too low. The R/B ratio may be available in the physiological literature for some species/groups.

The ratio respiration / biomass can take any positive value, and has the dimension year<sup>-1</sup>.

## Niche Overlap

Niche overlap indices for Ecopath models are available at three *Ecopath > Output > Niche overlap* forms

For this, a simple niche overlap index is adopted, and it is shown how it can serve as a starting point for the development of a new (predator) niche overlap index incorporating predation. The procedure involved in deriving a predator niche overlap index (from a prey niche overlap index) should be generally applicable, i.e., not limited to the type of index presented below.

Pianka (1973) suggested the use of an overlap index derived from the competition coefficients of the Lotka-Volterra equations. This index,  $O_{jk}$ , which has been used for many descriptions of niche overlap, can be estimated, for two species/groups  $j$  and  $k$ , from

$$O_{jk} = \frac{\sum_{i=1}^n (p_{ji} \cdot p_{ki})}{\sqrt{\sum_{i=1}^n p_{ji}^2 \cdot p_{ki}^2}} \quad (10)$$

where  $P_{ji}$  and  $P_{ki}$  are the proportions of the resource  $i$  used by species  $j$  and  $k$ , respectively. The index is symmetrical and assumes values between 0 and 1. A value of 0 suggests that the two species do not share resources, 1 indicates complete overlap, and intermediate values show partial overlap in resource utilization.

Closer examination of the Pianka overlap index shows it to have an unwanted characteristic and it is therefore slightly modified here. If one of the groups (say  $j$ ) only overlaps with one other group  $k$  then  $P_{ji}$  will be zero for all values of  $i$  but  $i = k$ , where it will reach a value of 1. In such a case, the denominator of (12) will always be 1, and the overlap index will equal  $P_{ki}$ , whereas a value between  $P_{ki}$  and  $P_{ji}$  would be more reasonable. This behaviour is caused by the geometric mean implied in the denominator of (12), and can be circumvented by the use of an arithmetic mean. For this, (12) is changed to

$$O_{jk} = \frac{\sum_{i=1}^n (p_{ji} \cdot p_{ki})}{\sum_{i=1}^n p_{ji}^2 + p_{ki}^2} \quad (11)$$

where the index and all of its terms can be interpreted as above. This version of the Pianka overlap index is used subsequently.

The niche overlap index can be used to describe various kinds of niche partitioning. Here attention will be focused on the trophic aspects. In this case, the  $P_{ki}$  and  $P_{ji}$  in (13) can be interpreted as the fraction prey  $i$  contributes to the diets of  $j$  and  $k$ , respectively.

Using an approach similar to that above, it is possible to quantify the predation on all preys  $m$  and  $n$  by all predators  $l$ , and to derive a ‘predator’ composition, estimated from

$$\bar{X}_{ml} = Q_i P_{lm} / \sum_{l=1}^n (Q_l \cdot P_{lm}) \quad (12)$$

and

$$\bar{X}_{nl} = Q_i P_{ln} / \sum_{l=1}^n (Q_l \cdot P_{ln}) \quad (13)$$

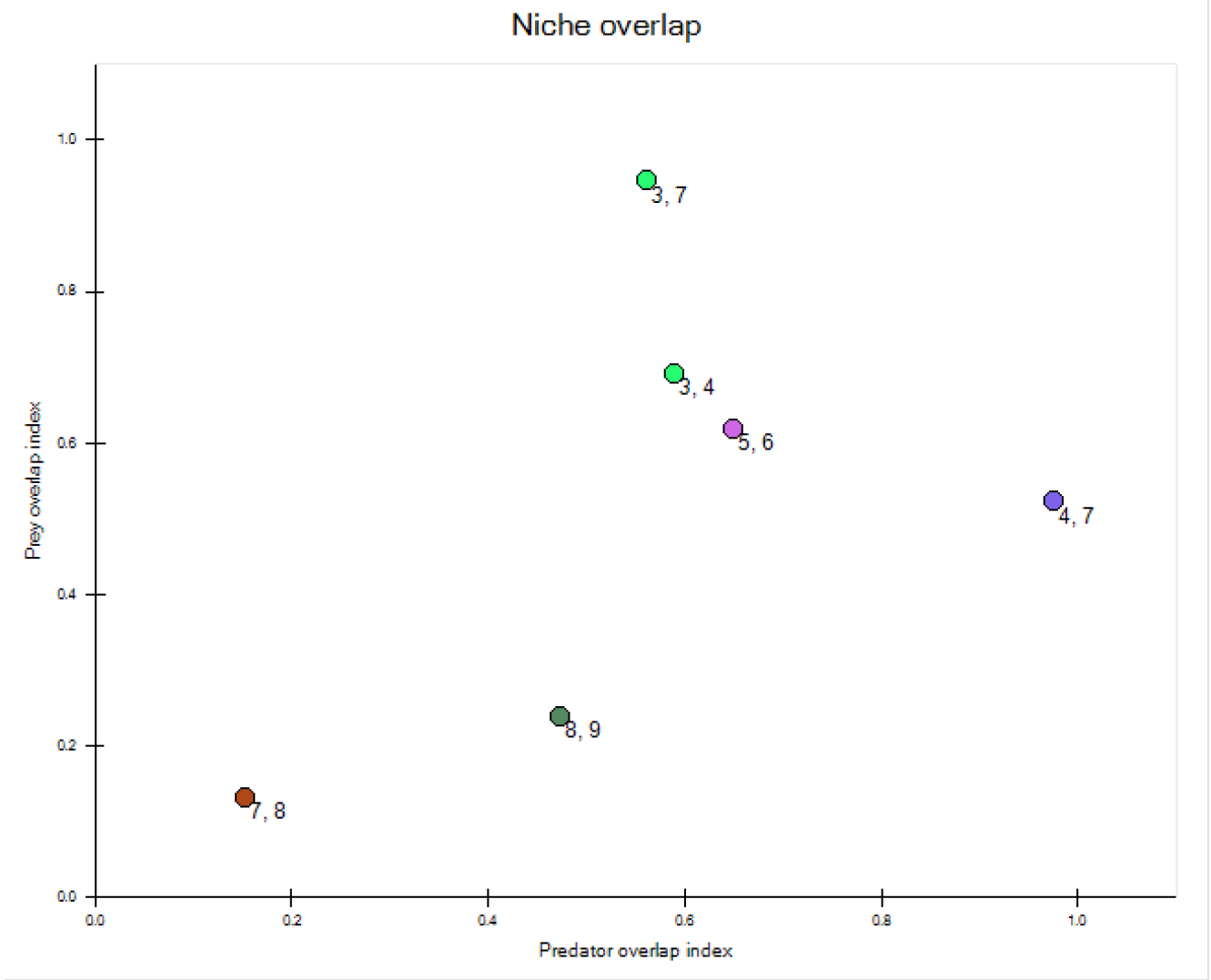
Here  $\bar{X}_{ml}$  can be interpreted as the fraction the predation by  $l$  contributes to the total predation on  $m$ , while  $Q_l$  is the total consumption for predator  $l$ . The predator compositions given above correspond to what Augoustinovic<sup>4</sup> defined, in the context of input-output analysis, as ‘technical coefficients’.

Based on the predator composition a ‘predator overlap index’ ( $P$ ) can be derived as

$$P_{mn} = \sum_{l=1}^n (\bar{X}_{ml} \cdot \bar{X}_{nl}) / (\sum_{l=1}^n (x_{ml}^2 + x_{nl}^2) / 2) \quad (14)$$

the values of this predator overlap index range between 0 and 1 and can be interpreted in the same way as those of the prey overlap index, given in (13).

In the present version, only one type of niche overlap index is incorporated, but both predator and prey niche overlap is given for this index. If of interest, more indices may be included in upcoming versions of EwE.



**Figure 3** – Niche overlap plot for Anchovy Bay model. Here, groups 3 and 4 (cod and whiting) have similar predator and prey overlap indices. The same holds for 5 and 6 (mackerel and anchovy), while 7 and 8 (shrimp and benthos) have little overlap with regards do predators and prey. The niche overlap can be used to identify potential candidate groups for merging in models with (too) many models. Groups with overlap indices < 0.1 are not included in the plot.

## Electivity

The electivity (selection index) describe a predator's preference for prey. It scales from -1 to 1; where -1 indicates total avoidance of a prey; 0 indicates that a prey is taken in proportion to its abundance in the ecosystem; and 1 indicates total preference for a prey. The electivity values are highlighted using a colour scale for the background, scaling from -1 (white) to 1 (red) using shades of red for intermediate values. The electivity index displayed is the standardized forage ration of Chesson<sup>5</sup>(1983), see below.

One of the most widely used indices for selection is the Ivlev electivity index,  $E_i$ <sup>6</sup> defined for a group  $i$  as:

$$E_i = (r_i - P_i)/(r_i + P_i) \quad (15)$$

where  $r_i$  is the relative abundance of a prey in a predator's diet and  $P_i$  is the prey's relative abundance in the ecosystem.  $E_i$  is scaled so that  $E_i = -1$  corresponds to total avoidance of,  $E_i = 0$  represents non-selective feeding on, and  $E_i = 1$  shows exclusive feeding on a given prey  $i$ . Note that within Ecopath,  $r_i$  and  $P_i$  refer to biomass, not numbers.

The Ivlev electivity index while widely used has a major shortcoming, seriously limiting its usefulness as a selection index, it is not independent of prey density. A more versatile approach is to use the standardized forage ratio ( $S_i$ ) as suggested by Chesson<sup>7</sup>. This index is independent of prey availability, and is given by

$$S_i = \frac{r_i/P_i}{\sum_{j=1}^n r_j/P_j} \quad (16)$$

where  $r_i$  and  $P_i$  are defined as above, and  $n$  is the number of groups in the system. The standardized forage ratio as originally presented takes values between 0 and 1, with  $S_i = 0$  representing avoidance and  $S_i = 1$  exclusive feeding. As implemented in EwE, the forage ratio has been transformed (linearly) such as to vary between -1 and 1, so that -1, 0 and 1 can be interpreted as for the Ivlev index.

	Prey \ predator	1	2	3	4	5	6	7	8	9
1	Whales									
2	Seals									
3	Cod	0.0577	0.312		-0.157					
4	Whiting	0.338	0.667	0.258	0.122					
5	Mackerel	0.821				0.607				
6	Anchovy	0.468		-0.108	0.561	0.817				
7	Shrimp		0.277	0.899	0.825					
8	Benthos	-0.817	0.693	0.192	-0.340			1.000	-0.429	
9	Zooplankton					0.458	1.000		-0.0770	
10	Phytoplankton								-0.181	0.961
11	Detritus								0.956	0.333

**Figure 4** – . Electivity plot for the Anchovy Bay ecosystem model. Here, whales have a very strong preference for mackerel (0.821) while benthos is eaten, but a negative preference for benthos (-0.817) indicating that the proportion of benthos in the whale diet is much lower than the proportion of the benthos biomass relative to the total ecosystem biomass .

## Search Rates

A useful feature of the system of linear equations underlying the Ecopath approach ([link](#)) is that it can be used to estimate the Lotka-Volterra mass-action term  $a$ , which has the dimension of a volume searched per unit time by a given predator  $j$  seeking a certain prey  $i$ . Building on the second Ecopath Master Equation

$$B_i \cdot (P/B)_i \cdot EE_i - \sum_j B_j \cdot (Q/B)_j \cdot DC_{ji} - C_i - E_i - BA_i = 0 \quad (17)$$

where  $B$  is biomass,  $P$  production rate,  $EE$  the ecotrophic efficiency,  $C$  the catch rate,  $BA$  the biomass accumulation rate,  $E$  the net migration rate,  $Q$  the consumption rate,  $DC_{ji}$  the proportion  $i$  contributes to the diet of  $j$  (each of the consumers). Separating the biomass accumulation rate,  $BA$ , and re-expressing as a differential equation

$$BA_i = \frac{dB}{dt} = B_i \cdot (P/B)_i \cdot EE_i - \sum_j B_j \cdot (Q/B)_j \cdot DC_{ji} - C_i - E_i = \dots = B_i \cdot (P/B)_i \cdot EE_i - C_i - E_i - \sum_j Q_{ji} \quad (18)$$

where  $Q_{ji}$  expresses the consumption rate for consumer  $j$  of prey  $i$ . We can then solve for  $a_{ji} = Q_{ji}/(B_j B_i)$ , which defines the Lotka-Volterra mass-action term  $a$  as the quotient of the amount of  $i$  consumed by  $j$ , divided by the product of their biomasses.

This mass-action term is a proportionality factor used in Ecosim to estimate consumption rate for consumers, given the changing biomasses of their preys, and their own changing biomasses.

The values of  $a$  depend obviously on the units used, and the biomass units used in Ecopath render difficult a direct interpretation of the numbers in the *Ecopath > Output > Search rates* table. However, they can easily be converted into values of  $a$  applying to single organisms, given that the ratio of the individual prey and predator weights are divided into the values of  $a$  for each pair of prey and predator.

## Fishery

The *Ecopath > Output > Fishery > Catch* form and *Ecopath > Output > Fishery > Value* form summarizes total catch by quantity and value for each fished group by fleet. In connection with the [EU Landing Obligation](#) regulations, considerable capacity to handle discard dynamics have been added to EwE, and part of this are presented in the *Ecopath > Output > Fishery > Discard mortality*, *Ecopath > Output > Fishery > Discard survival* and *Ecopath > Output > Fishery > Computed landings* forms.

## Catch

The *Ecopath < Output < Fishery > Catch* form shows total catch for fished groups by fleet, where

$$\text{Catch} = \text{Landings} + \text{Discards}$$

where landings and discards are entered as inputs at the *Ecopath < Input < Fishery > Landings* and *Discards* forms, respectively. The form also displays the trophic level of each fleet and of the fishery in total. For this, the trophic level is calculated similarly to how the trophic level is calculated for functional groups – as the average trophic level of the catch + 1.

## Value

The *Value form* shows the calculated value for fished groups ( $i$ ) by fleet ( $g$ ), where

$$\text{Value}_{i,g} = \text{Market price}_{i,g} \times \text{Landings}_{i,g}$$

where market price and landings are input from the *Ecopath < Input < Fishery > Off-vessel price* and

*Ecopath < Input < Fishery > Landings* forms, respectively. The market value is with unit monetary value per year.

The non-market value of each resource is also shown in a separate column on the *Ecopath > Output > Fishery > Value* form (if any non-market prices have been defined on the *Ecopath > Input > Fishery > Non-market value* form. The non-market value is calculated for group *i* as

$$\text{Non-market value}_i = \text{Non-market price}_i \times \text{Biomass}_i$$

The non-market value is with unit monetary value per year.

## Discard Mortality

Discard mortality is at the *Ecopath > Output > Fishery > Discard mortality* form and is for group *i* caught by fleet *g* calculated as,

$$\text{Discard mortality}_{i,g} = \text{Discard}_{i,g} \times \text{Discard mortality rate}_{i,g}$$

where the discard and discard mortality rate is obtained from *Ecopath < Input < Fishery > Discards* and *Ecopath < Input < Fishery > Discard mortality rate* respectively. Discard mortality is a flow rate with unit  $\text{t km}^{-2} \text{ year}^{-1}$ .

## Discard Survival

Discard survival is at the *Ecopath > Output > Fishery > Discard survival* form and is for group *i* caught by fleet *g* calculated as,

$$\text{Discard mortality}_{i,g} = \text{Discard}_{i,g} \times (1 - \text{Discard mortality rate}_{i,g})$$

where the discard and discard mortality rate is obtained from *Ecopath < Input < Fishery > Discards* and *Ecopath < Input < Fishery > Discard mortality rate* respectively. Discard survival is a flow rate with unit  $\text{t km}^{-2} \text{ year}^{-1}$ .

## Computed Landings

The computed landings at the *Ecopath > Output > Fishery > Computed landings* form should correspond closely to the input landings at the *Ecopath > Input > Fishery > Landings* form and I am

not sure why the computed landings have been added. The computed landings are flow rates with unit  $\text{t km}^{-2} \text{ year}^{-1}$ .

## Particle size distribution

later gator – REMOVE?

### Notes

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3. Allen 1971, *op. cit.*
4. M. Augustinovics, 'Methods of International and In- tertemporal Composition of Structure,' Contributions to Input-Output Analysis, Vol. I, North-Holland, London, 1970.
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6. Ivlev, V.. (1961). *Experimental Ecology of The Feeding of Fishes*.
7. Chesson. 1983. *op. cit.*

# Ecopath Tools

## Flow Diagram

One of the characteristics of food web models is that all flows and biomasses can be represented in a single graph.

The traditional method of representing trophic flow in ecosystem models, usually by scattering interconnected boxes across a page, both under-utilizes the potential descriptive and explanatory power of graphical representations and makes it difficult to compare different system representations. Often, trophic models are drawn such that the boxes representing organisms low in the food web are placed in the lower part of the graph, along with the plants, while the boxes representing organisms high in the food web are put higher up.

In the flow chart incorporated in Ecopath, explicit use is made of this mode of graphing, i.e., to plot the boxes representing the organisms of an ecosystem such that the horizontal axis of symmetry of each box is aligned with the (functional) trophic level of the box in question. Using trophic level as the Y-axis is not sufficient to define the relative position of the elements of a model, and two approaches may be considered for ordering the boxes along the X-axis:

- arranging the boxes such that they do not overlap, and/or with emphasis on some symmetry, such that the resulting graph is aesthetically pleasing, or,
- arranging the boxes such that the arrows linking the boxes cross each other as little as possible, hence maximizing clarity of the graph.

You might consider (i) and (ii) when constructing flow charts using the flow diagram in this version of Ecopath. The size of each (round) box is proportional to the biomass it represents. This trick is particularly useful in helping to visualize the relative role and impact of the organisms in each box.

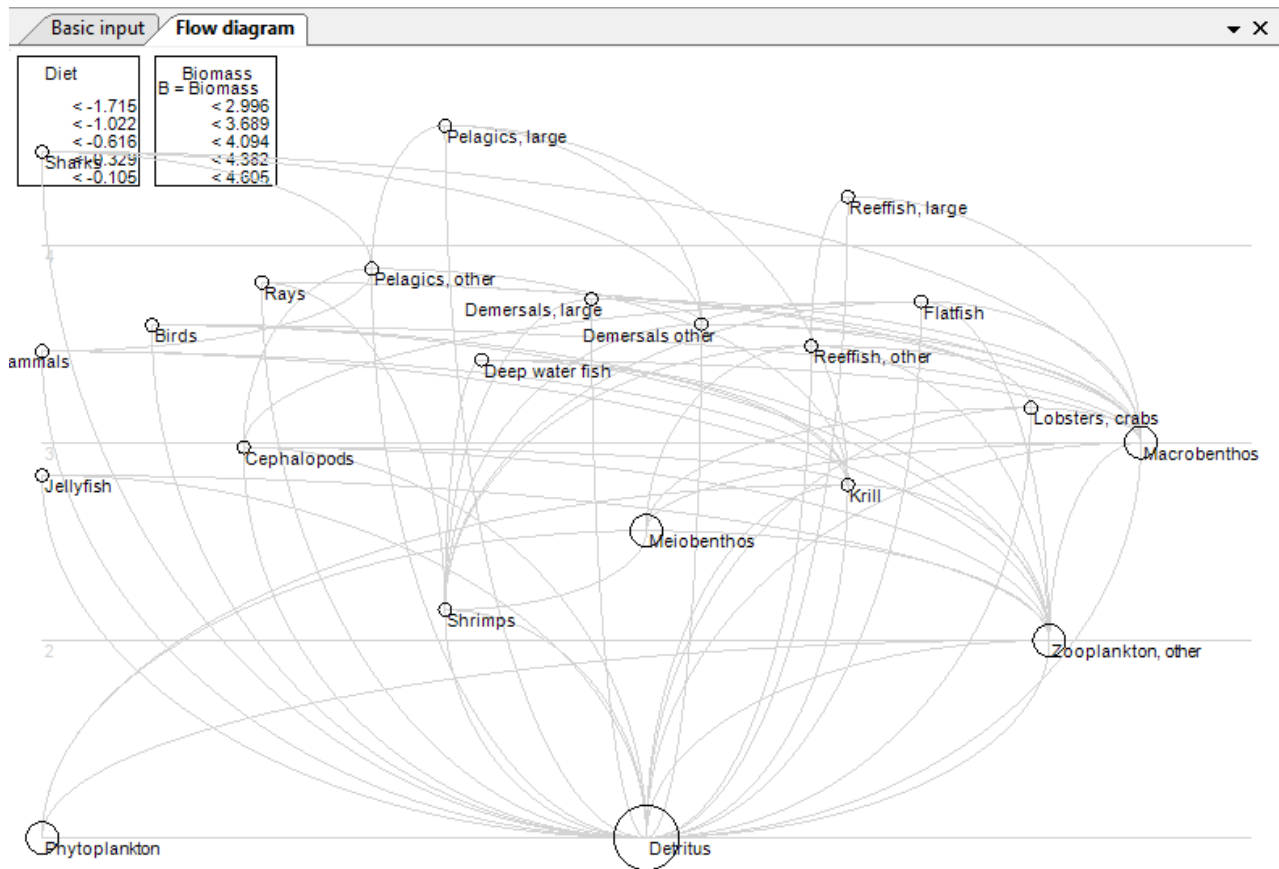
Another rule of construction was incorporated in the flow chart design of Ecopath. Flows entering a box do this on the lower half of the box, while flows exiting a box do it from the upper half. Flows that enter a box can be combined, while flows that leave a box cannot branch, but can be merged with flows exiting other boxes. This ensures compatibility with electronic hardware design, and more importantly, it simplifies the flow chart.

'Cannibalism' or zero-order flows can be shown as arrows originating from the top half of

a box, and moving in an incomplete circle before entering the lower half. The flow chart routine of Ecopath will label all connecting arrows with their respective flows.

EwE6 automatically builds a trophic flow diagram. **Right click on the Flow diagram form and select Settings** to set the colour of the nodes, colours, width and types of lines, the shape of the nodes (square or circular) and whether the nodes are to be scaled or not.

Hover your mouse over a node to see its connections. Trophic levels are shown in the background.

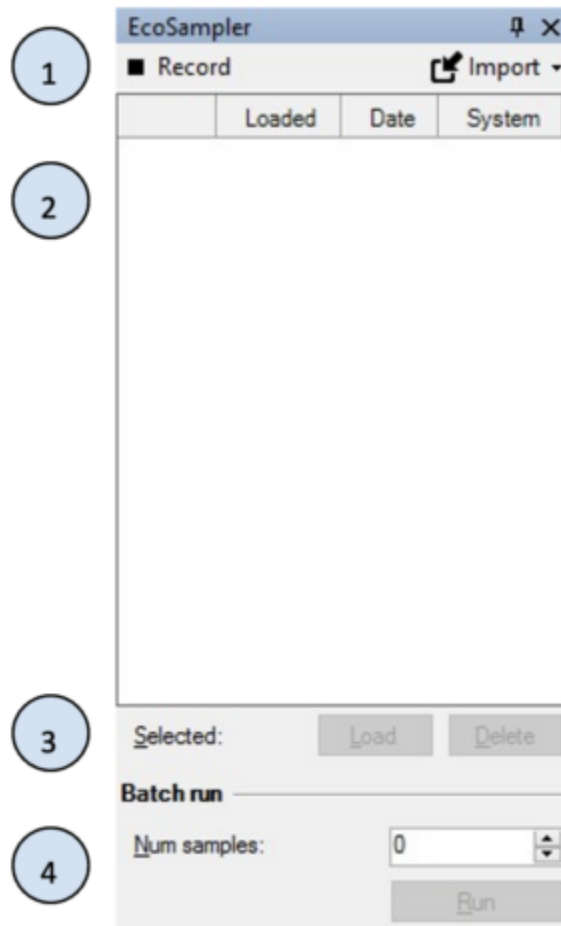


**Figure 1** – Ecopath flow diagram.

# Using Ecosampler

JEROEN STEENBEEK AND MARTA COLL

Ecosampler is a utility for Ecopath with Ecosim (EwE) that records alternate balanced Ecopath parameter sets (referred to as ‘samples’) produced by the EwE Monte Carlo routines. Ecosampler can then run these samples through the EwE core modules Ecopath, Ecosim and Ecospace, and any active plug-in. Any saved model output can then be used to assess the impact of Ecopath input parameter uncertainty onto predictions of any EwE module.



**Figure 1** – The Ecosampler interface upon launch with the main toolbar (1), sample list (2), sample management section (3), and batch run section (4).

## Obtaining the Plug-in

Ecosampler is distributed as part of EwE version 6.6+. For any issues, contact the EwE development team at ewedevteam@gmail.com.

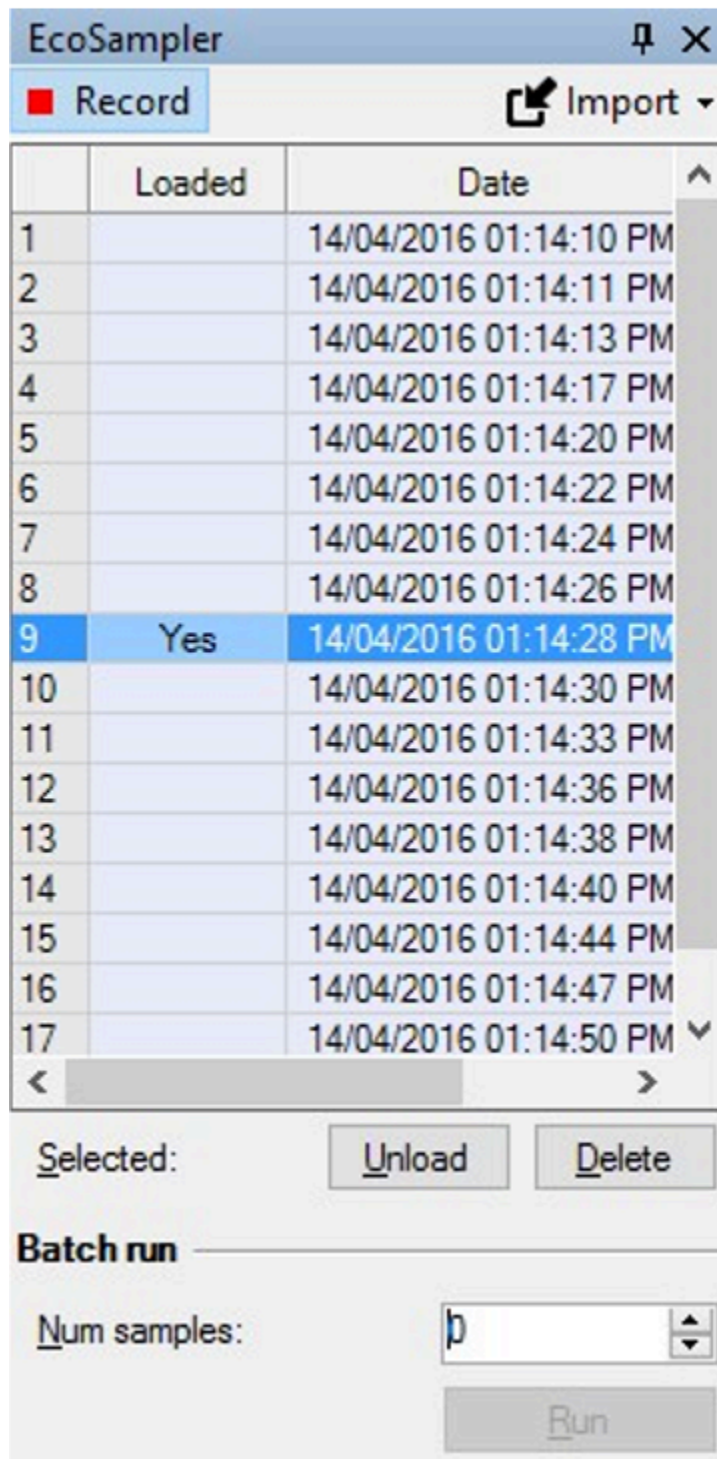
## Interface

The Ecosampler interface is launched by choosing *Navigator > Tools > Ecosampler*. The Ecosampler interface offers the following elements (Figure 1):

1. A toolbar that offers options to turn sample recording on and off, and to import samples stored elsewhere.
2. A overview with the list of recorded samples, and for each sample a sequential number, whether a sample is currently loaded in the EwE user interface, and the data and computer system the sample was recorded on.
3. A sample management section where samples can be loaded, unloaded, and deleted.
4. A batch run section to run a number of samples through EwE and any loaded module and active plug-ins..

## Recording Samples

Ecosampler records samples from the Monte Carlo routine that ships with the EwE desktop software. Toggle the *Record* button (Figure 2) to enable and disable record mode.



**Figure 2** – Ecosampler record mode is on, and many samples have been recorded from Monte Carlo. Sample 9 is loaded in EwE, and the sample can be unloaded or deleted.

To record samples, do the following:

1. Turn recording on in Ecosampler by clicking the inactive *Record* button until its icon turns red, indicating that record mode is active. A black record option indicates that Ecosampler recording is off.
2. Run the Monte Carlo routine built into EwE.

While recording, Ecosampler listens to the execution of Monte Carlo, and intercepts and stores any alternate mass-balanced parameter found by Monte Carlo as a “sample” in the currently loaded model database. The samples immediately appear in the samples list, showing the current date and the name of the computer EwE is executed on.

To stop recording samples, do the following:

1. Turn recording off by clicking the active “Record” button until its icon turns black, indicating that record mode is inactive.

## Managing Samples

A stored sample can be loaded in the EwE interface to assess its validity.

To load a sample, do the following:

1. Select a sample in the samples list
2. Press *Load*.

The sample list will indicate which sample is loaded, and when a loaded sample is selected, the load button text will read *Unload*.

To unload a sample and restore the original Ecopath parameter values, do the following:

1. Select the loaded sample
2. Press *Unload*.

A stored sample can be deleted if it produces unrealistic or outlying behaviour.

To delete a sample, do the following:

1. Select the sample to delete
2. Press *Delete*.

Ecosampler contains a safety feature that prevents users from accidentally overwriting their original parameters with a loaded sample. If a sample is then modified, and then saved, Ecosampler will first restore the original parameters. However, it is possible to save a loaded sample as a new Ecopath base model. To do so, save a model with a loaded sample using the “Save As” function (“Menu > File > Save as...”). This writes the model under a new name, using the sample content as new Ecopath base line inputs.

## Importing Samples

Recording a large number of samples may take considerable time, especially when Monte Carlo is configured to perturb the diet composition matrix and when the chances to randomly find alternate mass-balanced models are slim. In this case, it makes sense to record samples for the same model simultaneously on multiple computers. Once all recording is complete, the Import Samples functionality can then be used to bring all generated samples – generated by the Ecosampler runs in different copies of the EwE model – back into one model.

It is NOT recommended to run multiple copies of Ecosampler on the same computer and the same EwE model. Microsoft Access models are not designed for concurrent writing (e.g., having multiple programs save changes to the same database at the same time). If you wish to run multiple Ecosampler copies on one computer, then each Ecosampler copy MUST operate on its own copy of the EwE model file!

To import models from another model do the following:

1. Click *Import*.
2. Select *From another model*.
3. Browse to the model.
4. Press OK.

The sample list will be updated with samples found in the selected model.

Ecosampler will import samples from any model without any safety checks. It is the ultimate responsibility of the user to check whether the import process makes sense, e.g., whether the import source and destination models are the same.

The import option also provides an option to import samples generated and stored by the Cefas MSE routines. This logic has not been implemented yet.

## Expiring Samples

Samples are alternate mass-balanced configurations for one specific set of values of an Ecopath model. If any Ecopath input parameter is changed by the user and this change is saved, all stored samples in principle become invalid. In this case, Ecosampler will prompt the user whether stored samples should be deleted.

## Running Samples

The second aim of Ecosampler is to run samples through various components of EwE and collect output.

To run Ecosampler samples through EwE, do the following:

1. Load the desired Ecosim and Ecospace scenarios are correctly loaded.
2. Activate desired plug-ins.
3. Enable data auto-saving (*Menu > Tools > Options > File Management*) for every component that you wish to gather output data for.
4. Enter the number of samples to run in the Batch run panel.
5. Press *Run*.

When a batch run is started, Ecosampler will execute the current model configuration as a baseline sample, and will store this in a subfolder *Sample\_baseline* under the default core output path. If Ecopath does not balance, the user is notified, and the batch run is aborted.

If Ecopath did balance, then Ecosampler checks if Ecosim, Ecospace and Ecotracer are loaded. Ecosampler will start processing the list of samples, starting at the first stored sample up to the

end of the list or until the number of requested samples has been processed. It will run each sample in turn.

When running a sample, EcoSampler performs the following steps:

- Append the current core output path with a subfolder *Sample\_[sample number]* for the loaded sample. This reroutes all auto-saving component output to a unique folder per sample;
- Load the sampled parameter set into Ecopath;
- Run Ecopath, and if Ecopath balances for the loaded sample, run Ecosim (if loaded) and Ecospace (if loaded) with Ecotracer enabled (if loaded). Any connected component that is configured to auto-save its output will now do so.

Ecosampler is a simple tool that only reruns the present EwE configuration. Ecosampler has no means to decide which data may need saving, and has no means to control which plug-ins will run. Instead, it relies on the current configuration of the EwE software to take care of this. For instance, if the Ecological Indicators plug-in is set to run with Ecopath and Ecospace, and Ecospace is set to autosave ASCII output maps in Ecospace parameters, these settings will also apply to every sample ran by Ecosampler.

## Using the Ecosampler Output

The output of Ecosampler is an organized series of folders – a baseline output folder and a unique folder per executed sample – under the current EwE output directory, with regular file-based output for the components that were activated. Each sample folder contains the various output files written by EwE components set to automatically write their output to file when Ecosampler was executed.

## Troubleshooting

Ecosampler writes its activities to the Ecopath log file, which can be viewed by choosing *Main Menu > About > View Log File*.

## Further Development

A series of future changes can be foreseen:

- Prompt user when deleting a sample because delete cannot be undone;
- Hide *System* column when there are no samples from another computer;
- Implement a system to rate samples, where the rating may be used for randomly selected samples during batch runs;
- Automatically rate or score samples when they are generated?
- Build to logic to import samples generated by the Cefas MSE plug-in.

Ecosampler was built by [Ecopath International Initiative](#) and has been added to the Ecopath with Ecosim source code repository.

Ecosampler was realized through funding from the European Commission through the Marie Curie Career Integration Grant Fellowships PCIG10-GA- 2011-303534 – to the BIOWEB project. This study is a contribution to the projects SafeNET (EU-DGMARE MARE/2014/41) and MERCES (European Union's Horizon research and innovation programme grant agreement No 689518). X. Corrales was supported by an IOLR scholarship under the DESSIM project (“A Decision Support System for the management of Israel's Mediterranean Exclusive Economic Zone”).

## References

Steenbeek, J., Corrales, X., Platts, M., and Coll, M. 2018. EcoSampler: automating the ability to assess input parameter sensitivity on Ecopath with Ecosim aquatic food web model results. SoftwareX. <https://doi.org/10.1016/j.softx.2018.06.004>.

# ECOSIM

# Density-dependent catchability

In fisheries modelling we usually represent the fishing mortality rate  $F$  as a product of catchability  $q$  times fishing effort  $f$ :

Here the catchability  $q$  represents the mortality rate caused by a unit of fishing effort, or in intuitive terms the proportion of the stock harvested by a unit of fishing effort. A useful way to think about  $q$  is in terms of the spatial or effort response power ganization of fishing: if each unit of effort 'sweeps' an area  $a$  while the stock is distributed over a total area  $A$ , and if effort is randomly distributed within  $A$ , then  $q=a/A$ . There are two problems with this formulation:

- $A$  is generally seen by both fish and fishers as a much smaller area than the map area over which you might display a stock's range (neither fish nor fishing are randomly distributed, so  $A$  is generally much smaller than the map range area for a stock), so we usually cannot predict  $q$  from simple analysis of gear swept area and total range area; and
- almost always, the actual area  $A$  occupied by fish and fishers decreases with decreasing fish abundance, (i.e., the occupied range 'collapses' as stock size decreases) due to fish behaviours like shoaling and also cumulative effects of localized stock depletion events. The second problem is particularly important for fisheries analysis, since it implies that  $q$  increases, sometimes grossly, as  $A$  decreases ( $q = a / A$  increases when  $A$  decreases) whether or not there is a change in fishing technology as represented in the area swept per unit effort.

On entry to Ecosim, Ecopath has provided a base fishing rate  $F_0 = \text{Catch} / (\text{Ecopath biomass})$ . You can specify time scenarios for  $F$  ( $F_t, t > 0$ ) relative to this  $F_0$  by using either the fishing effort 'sketch pad' interface (*Ecosim > Input > Fishing effort*) or by using time reference data files (time series). The Ecosim default is to treat your time series values as relative or absolute fishing rates without reference to changes in  $q$ . But you can also treat the time input values as relative fishing efforts  $f_t$ , where  $f_0 = F_0$  (efforts scaled so base  $q_0 = 1$ ). Then to create density-dependent catchability effects, set a value greater than 1.0 for the  $Q_{\max}/Q_0$  ratio(s) at the *Ecosim > Input > Group info* form.

For example, setting a value of 5 represents assuming that  $q$  can be as much as 5 times higher than the  $q$  that led to the Ecopath base  $F_0$ , if stock size is very low. That is, suppose you set  $Q_{\max}/Q_0 = 5$ , then run a scenario where you shape the relative fishing rate over time (now treated as relative effort) so as to cause a gross stock depletion followed by a return to  $f_t = f_0$ . In this scenario, the 'realized' fishing rate  $F_t$  can be as much as 5 times  $F_0$  even for  $f_t = f_0$ , due to density-dependent decrease in the effective area  $A$  occupied by the depleted stock.

Internally, Ecosim represents the density-dependent effect by calculating time dependent fishing

rate  $F_t$  using the equation  $F_t = f_t QR_o / [1 + (QR_o - 1) B_t / B_o]$ , where  $QR_o = Q_{max}/Q_o$  is your specified catchability increase ratio,  $B_t$  is stock biomass, and  $B_o$  is Ecopath base biomass.

Note that this dependence is applied to the individual group fishing rates rather than the relative efforts by fishing fleets, to represent the idea that decreases in area occupied by a stock ( $A$ ) when biomass  $B_t$  is less than the Ecopath base biomass  $B_o$  are likely to result in concentration of efforts by fishers in general. If you need to represent a differential change in availability of fish to some particular fleet(s) but not others, you will need to develop an Ecospace model that explicitly represents spatial distinctions in where particular gears can operate. Note further that the  $QR$  parameter is not used in Ecospace: we assume random distribution of effort within each Ecospace cell, recognizing that Ecospace can already represent larger-scale range changes and associated changes in the spatial concentration of fishing effort.

In Ecosim scenarios where you do choose to treat the time input fishing information as relative fishing efforts  $f_t$  rather than absolute fishing rates  $F_t$ , you should be quite careful to recognize that catchability often increases quite dramatically for low values of  $B_t/B_o$ .  $QR$  values ( $Q_{max}/Q_o$ ) of 5 to 10 are not uncommon in the fishery literature, especially for shoaling fishes like herring, sardine, and spawning cod. Further, modern fishing technologies like side-scan sonar and GPS are making fishers ever better at concentrating their swept areas  $a$  within the actual areas  $A$  where fish are concentrated (probability of a sweep of area  $a$  not being within the occupied area  $A$  has decreased dramatically). Even where there are not such technological changes, fishers are generally capable of making very good assessments of  $A$  just by combining their own search information with observation of where other fishers are doing well.

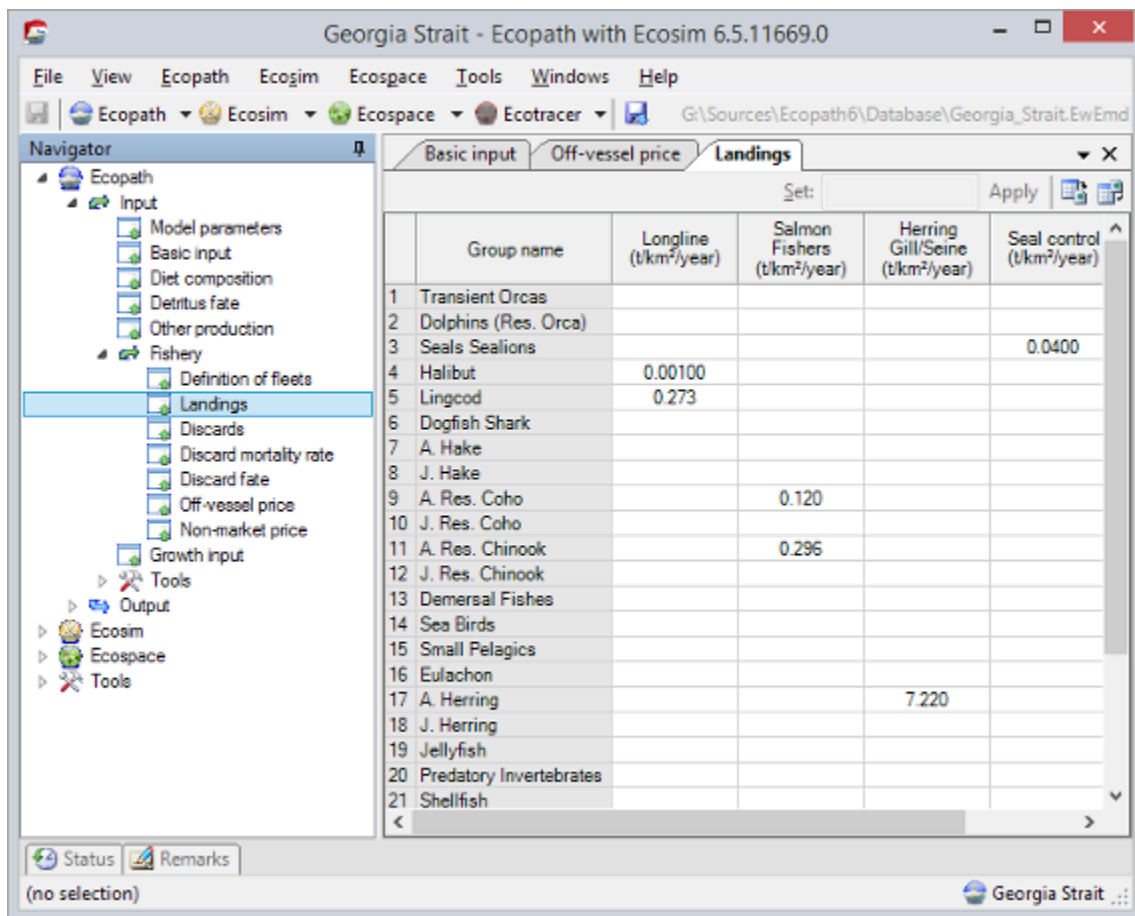
Note that you generally do not want to set  $QR > 1$  for 'reconstruction' scenarios where you have provided historical  $F_t$  estimates based on single-species assessment methods such as virtual population analysis (VPA) or stock synthesis. Presumably these methods have already accounted for density dependent effects on  $q$ , by calculating  $F_t = (\text{historical catch}) / (\text{estimated stock biomass})$  without regard to whether the historical catch was high relative to biomass because of catchability changes or changes in total fishing effort. But you should check the single species assessment method carefully, to insure that the method did not make an inappropriate assumption about stability of  $q$  in its reconstruction of historical biomass, (e.g., was fitted to the data using historical effort data under a constant  $q$  assumption, or was 'tuned' to historical catch per effort data uncorrected for temporal/stock dependent changes in  $q$ ).

# Price Elasticity

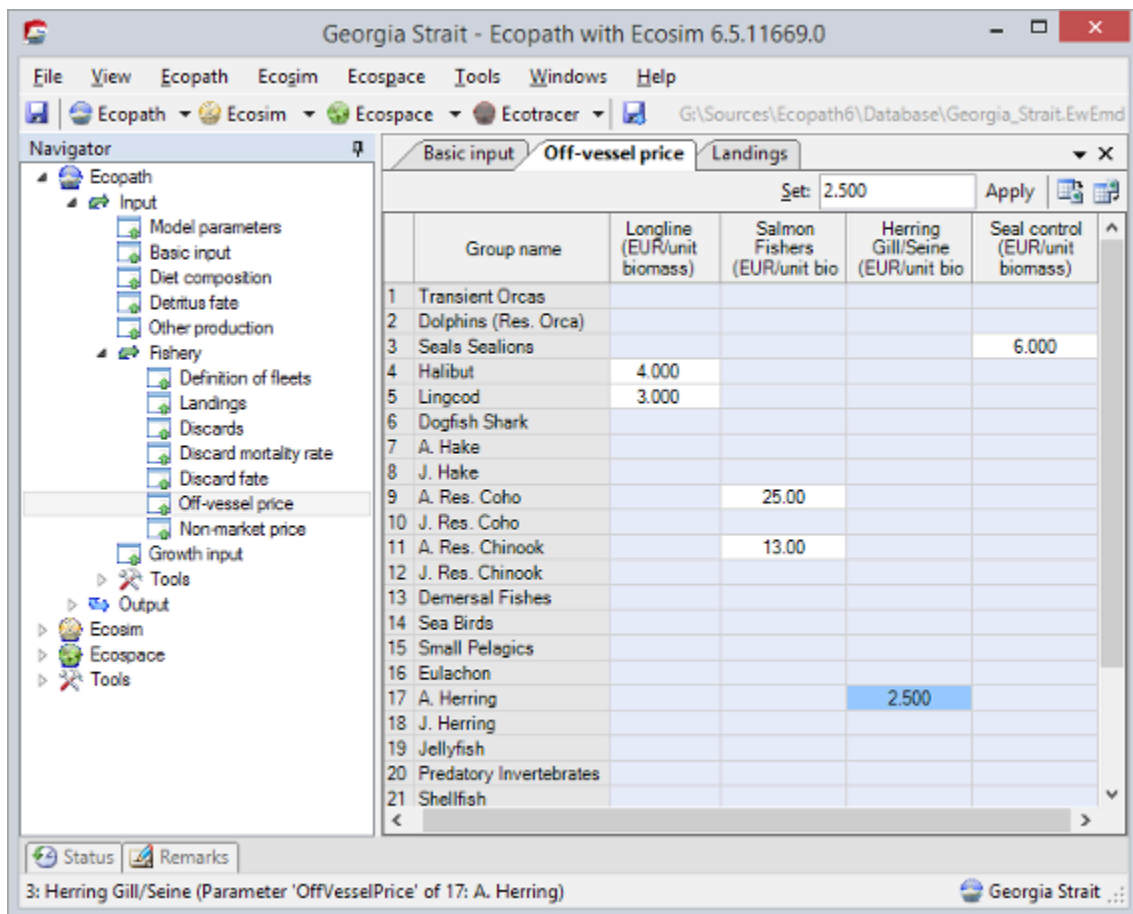
JEROEN STEENBEEK

We have implemented price elasticity in Ecosim as outlined in this chapter. For background descriptions of how EwE is implemented in EwE please see the [Ecosystem Modelling with EwE](#) textbook.

Elasticity is based on landings (Figure 1) and off-vessel price (Figure 2).



**Figure 1** – EwE landings form available at Ecopath < Input < Fishery < Landings.

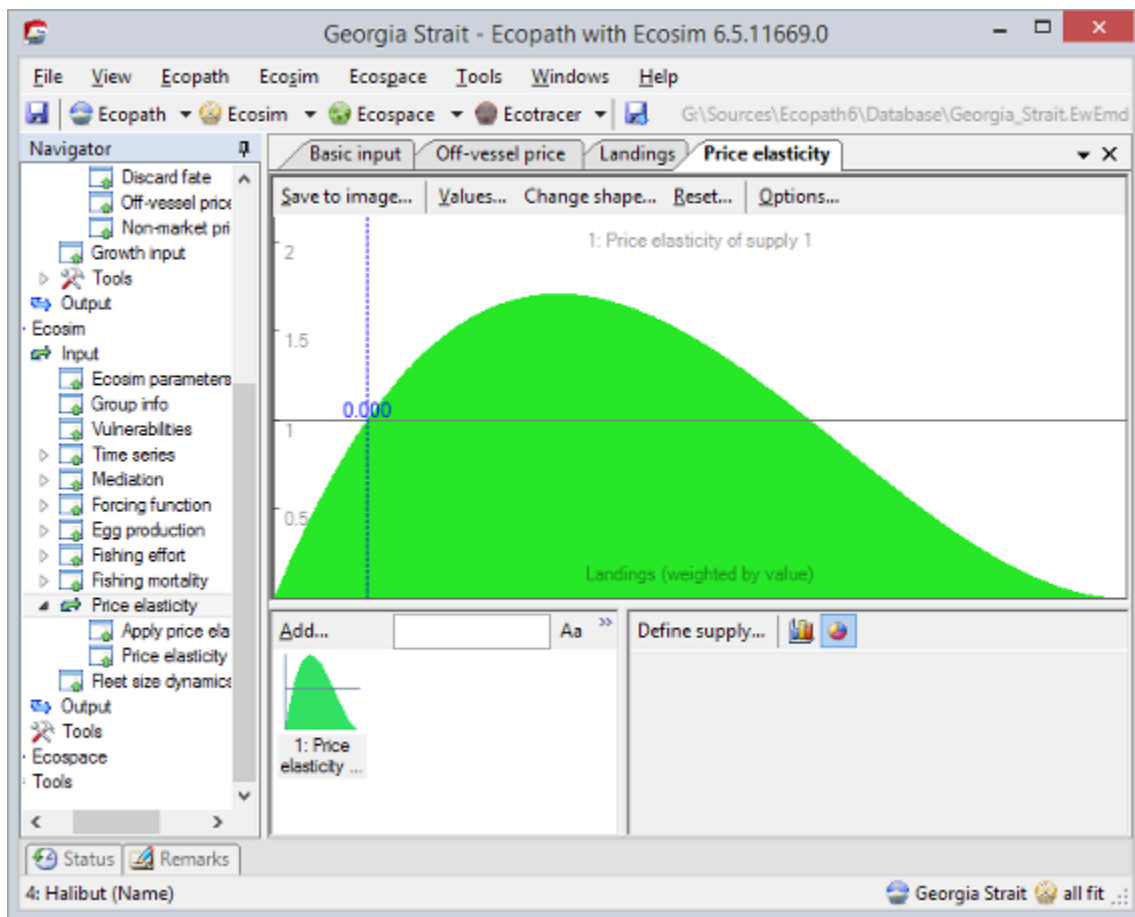


**Figure 2** – EwE off-vessel price, available at Ecopath < Input < Fishery < Off-vessel price.

Users configure price elasticity through the Ecosim > Price Elasticity node in the navigation tree (Figure 3). In this form users define elasticity curves or ‘shapes’, and use these shapes to determine how (combinations of) landings affect the price of a given landing.

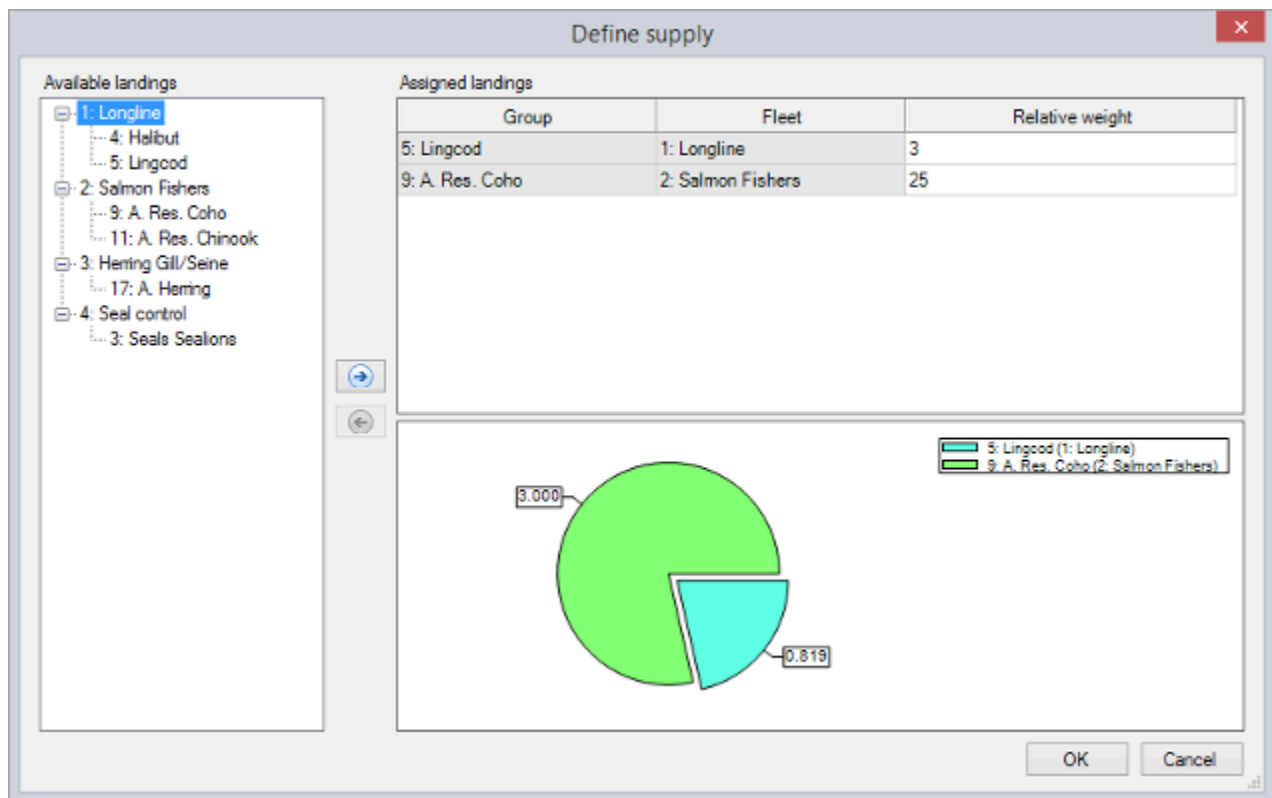
The procedure is as follows:

1. Define one or more price elasticity mediation curves, or bluntly called ‘shapes’ in EwE. As with every shape interface in EwE, users can alter the contour of shapes by sketching with a mouse, by Copy / Pasting values into the *Values* interface, or by selecting a mathematical primitive in the *Change Shape* interface. The result is always stunning (Figure 3). The dashed blue line can be moved with the mouse cursor, and indicates the mediation baseline point – the point where the price equals the Ecopath base value.



**Figure 3** – Ecosim price elasticity interface, available at Ecosim < Input < Price elasticity. The price elasticity is used in Ecosim and inherited by policy optimizations, value chains, MSE, Ecospace, indeed wherever landed value is estimated in EwE.

2. Select the supply to drive the prices via a mediation curve. To do so, select a curve in the price elasticity interface and press *Define Supply*. This opens – surprisingly – the EwE *Define Supply* form (Figure 4). Here, one or more landings (supplies) can be assigned and weighted to drive the prices using the selected curve. Select an available landing and press the arrow that points right. The landing is added as a price driver with a relative weight equal to the off-vessel price of that landing. The weights can be modified. The pie chart shows the weighted landed amounts, and thus provides a graphical overview how each landing contributes to overall price elasticity. The pie segments obtain the colour from the landed group.



**Figure 4** – EwE Define supply interface available at Ecosim < Input < Price elasticity > Define supply.

- Once the *Define supply* form is closed, the main *Price elasticity* form will update to display supply assigned to the selected shape when the shape is selected. The shape itself will display the weighted supply total at the Ecopath mediation base line point (Figure 5, dotted blue line). Now, the supply must be applied to a landing to drive price elasticity. This is done via the *Apply Price Elasticity* node in the navigation tree, which opens the form shown in Figure 6.

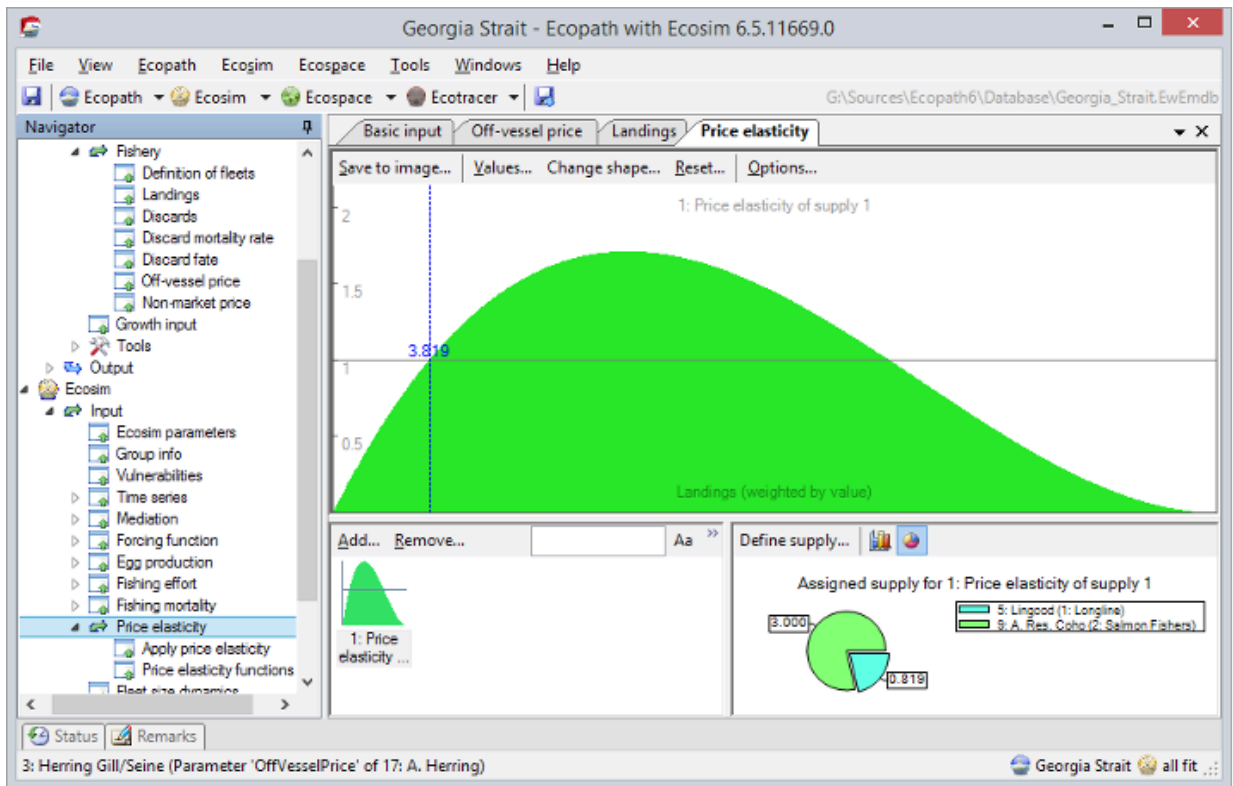
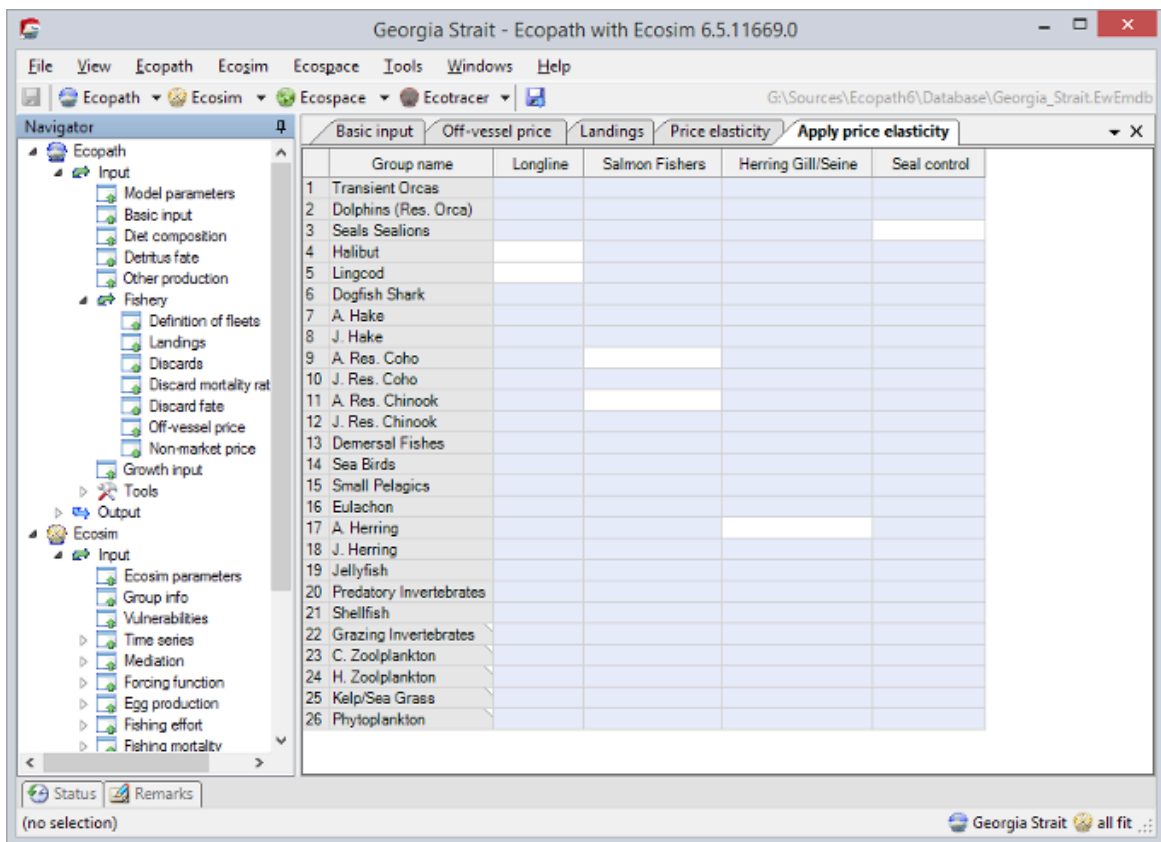


Figure 5 – Defined supply for an elasticity curve.



**Figure 6** – EwE Apply price elasticity interface available at Ecosim > Input > Price elasticity > Apply price elasticity.

- To apply price elasticity to a landing (i.e gear – functional group combination), now click a landing in the Apply price elasticity interface and select a supply curve that was configured in the previous steps.

Elasticity is now applied and used throughout EwE.

Note, however, that EwE does not yet have an explicit way to show how prices change. EwE will need this functionality, both in a plot that shows changing off-vessel prices, and written to CSV file when Ecosim auto-saves information. Let us know if you need it badly ...

# Vulnerability Multiplier Estimator

CARL J. WALTERS

Simple estimator of minimum vulnerability multiplier needed to allow a predator to rebuild by some assumed amount after removal of all fishing effort

The Ecosim vulnerability multiplier interface at Ecosim > Input > Vulnerabilities > Estimate vulnerabilities allows users to obtain an initial estimate of the average prey vulnerability multiplier needed to allow a predator population to recover to some much higher level (e.g., a much higher historical abundance than the Ecopath base abundance) if fishing mortality were removed. This initial estimate is derived by assuming that the predator will not deplete any prey populations when it recovers, i.e. total prey biomass  $B_0$  will remain similar to the Ecopath base value.

Given this assumption about no prey depletion, an approximation for the predator biomass dynamics is given by the simple differential equation

$$dP/dt = gQ - ZP \quad (1)$$

where the food conversion efficiency  $g$  is the ratio of two Ecopath input,  $g = (P/B)/(Q/B) = Z_0/(Q_0/P_0)$ , and the total food consumption rate  $Q$  summed over prey types is predicted from vulnerable prey biomass as  $Q=aVP$  where vulnerable prey biomass  $V$  is given by

$$V = vB/(2v + aP) \quad (2)$$

The vulnerability exchange rate  $v$  is calculated in Ecosim as

$$v = KQ_0/B_0 \quad (3)$$

where  $K$  is the vulnerability multiplier entered by the user,  $Q_0$  is Ecopath base predator consumption, and  $B_0$  is Ecopath base prey biomass (Ecopath base predation rate is  $Q_0/B_0$ , and the maximum predation rate  $v$  is assumed to be a multiple ( $K$ ) of this base predation rate). On entry to Ecosim, the predator rate of effective search  $a$  is estimated from  $K$  and base predator abundance  $P_0$  as

$$a = 2v/[(k - 1)P_0] \quad (4)$$

Note that  $v$  in (3) and  $a$  in (4) both depend on the vulnerability multiplier  $K$ .

In order to derive a simple estimator for the multiplier  $K$ , we simply set  $dP/dt=0$  in (1), while setting  $Z=Z_0-F$  (i.e. set  $Z$  to just the natural mortality rate) and  $P$  equal to the unfished  $P$  or more simply to  $P=RP_0$  where  $R$  is the ratio of the unfished biomass that we want to achieve to the Ecopath

base biomass (e.g.  $R=10$  means we want the predator  $P$  to be able to grow by a factor of 10 if fishing mortality rate  $F$  is set to 0). Setting  $dP/dt=0$  creates the algebraic condition  $eQ=ZP$ . Next, we substitute (2) to (4) into this condition, and solve the resulting equation for  $K$ . A few tedious algebraic steps then result in the Ecosim estimator for  $K$  used in the interface:

$$K = (R - 1)HP_0 / (Q_0/B_0 - HP_0) \quad (5)$$

where  $H=Z/(eB_0)$ . Note again in this equation  $R=P/P_0$ , implying that we need to assume proportionally larger  $K$  values for larger values of  $K$ . This equation can be parameterized in other ways using Ecopath input values, e.g., by noting that  $Q_0$  is estimated in Ecopath as input consumption per biomass ( $Q/B=Q_0/P_0$ ) times  $P_0$ .

Most predators in Ecosim models feed on multiple prey types. The predicted consumption rate  $Q(p)$  of each prey type  $p$  as predator and prey biomasses vary can be expressed using Kerim Aydin's<sup>1</sup> parameterization of the Ecosim consumption rate equation<sup>2</sup>

$$Q(p) = Q_0(p)K(p)[B(p)/B_0(p)][P/P_0]/[K(p) - 1 + P/P_0] \quad (6)$$

Provided the  $K(p)$  are similar for all prey types that contribute significantly to the predator diet and that none show substantial depletion ( $B(p)/B_0(p)$  stays near 1.0 as  $P$  grows, for all  $p$ ), total consumption rate per predator  $\sum pQ(p)/P$  will behave the same (all  $Q(p)$  will increase by the same function of  $P/P_0$ , diet composition will not change) as if there were just one prey type as assumed in the basic derivation above. That is, the really critical assumption for (5) to work is that all important prey types have similar  $K(p)$  and are not depleted (or changed in biomass due to other factors like fishing) as the predator biomass  $P$  recovers from its initial level  $P_0$ .

Note that absent dynamic changes in prey biomasses  $B(p)$  due to factors other than changes in  $P/P_0$ , (5) represents a minimum estimate of  $K$  needed to allow an assumed growth ratio  $R$ . If increases in  $P/P_0$  do cause some decreases in key prey type abundances,  $K$  will need to be set to higher values in order to reach the target  $R$ , and there may in fact be no  $K$  value for which some high assumed  $R$  ( $P_{\text{unfished}}/P_0$ ) can be achieved, i.e. the modeled prey production rates may simply be incapable of supporting such a high assumed unfished predator biomass. This happens for example in models where prey biomasses and net production at the Ecopath base system state are substantially lower (e.g., due to fishing) than the prey biomasses that supported the historically higher  $P_{\text{unfished}}$ .

A more elaborate, iterative approach is typically needed to set by-stanza  $K$ 's for multi-stanza populations represented in Ecosim by an age-structured model rather than a simple biomass rate equation. Typically, fishing mortality rates for multistanza populations are substantial only for the older (larger) fish.  $K$ 's for at least one juvenile stanza are typically set to low values in order to represent density dependent juvenile mortality (stock-recruitment relationship). Biomass of older

fish can then be limited either by food availability or the number of recruits. As a first iterative step, increases in biomass of older fish can be represented by setting high  $K$ 's for older stanzas, so that removal of fishing basically just results in increased biomass-per-recruit (due to increased longevity). If that biomass-per-recruit response is insufficient to predict assumed recovery of biomass of older fish, it will then be necessary as a second iterative step to increase the  $K$ 's for at least one unfished juvenile stanza, in order to allow both increased numerical recruitment and maintenance of juvenile growth rates.

## Notes

1. Aydin, K.Y., 2004. Age structure or functional response? Reconciling the energetics of surplus production between single-species models and ECOSIM. *African Journal of Marine Science*, 26, pp.289-301. <https://doi.org/10.2989/18142320409504062>
2. see also Whitehouse, G.A. and Aydin, K.Y., 2020. Assessing the sensitivity of three Alaska marine food webs to perturbations: an example of Ecosim simulations using Rpath. *Ecological Modelling*, 429, p.109074. <https://doi.org/10.1016/j.ecolmodel.2020.109074>

# Time Series

Time Series Type	Unit	Abbreviation	Type	Pool Code	Pool Code 2	Driver or Reference
Biomass, relative		BiomassRel	0	Group		Reference
Biomass, absolute	t km <sup>-2</sup>	BiomassAbs	1	Group		Reference
Biomass, forced	t km <sup>-2</sup>	BiomassForcing	-1	Group		Driver
Forcing function		TimeForcing	2	Function #		Driver
Fishing effort		FishingEffort	3	Fleet		Driver
Fishing mortality	year <sup>-1</sup>	FishingMortality	4	Group		Driver
Total mortality	year <sup>-1</sup>	TotalMortality	5	Group		Reference
Total mortality, constant	year <sup>-1</sup>	ConstantTotalMortality	-5	Group		Driver
Catches	t km <sup>-2</sup> year <sup>-1</sup>	Catches	6	Group		Reference
Catches, forced	t km <sup>-2</sup> year <sup>-1</sup>	CatchesForcing	-6	Group		Driver
Catches, relative		CatchesRel	61	Group		Reference
Average weight		AverageWeight	7	Multi-stanza group		Reference
Ecotracer, relative concentration <sup>1</sup>		EcotracerConcRel	8	Group		Reference
Ecotracer, absolute concentration <sup>1</sup>		EcotracerConcAbs	9	Group		Reference
Discard proportion, absolute		DiscardProportion	10	Fleet	Group	Driver
Discard mortality rate, absolute	year <sup>-1</sup>	DiscardMortality	11	Fleet	Group	Driver
Landings, absolute	t km <sup>-2</sup> year <sup>-1</sup>	Landings	12	Fleet	Group	Reference
Discards, absolute	t km <sup>-2</sup> year <sup>-1</sup>	Discards	13	Fleet	Group	Reference
Catchabilities <sup>2</sup>		Catchabilities	14	Fleet	Group	Driver

**Table 1 - List of time series types and their abbreviations that can be used in Ecosim along with description. Notice that for reference time series, the CSV file weight can be [0, ∞] while the weight is not used for driver time series (so just set it to 0). Where no unit is indicated, the time series is a relative value (so no unit). Pool code and Pool code 2 should be numbers.**

Time Series Type	Unit	Abbreviation	Type	Pool Code	Pool Code 2	Driver or Reference
Off-vessel price, absolute	\$/t	OffVesselPrice	15	Fleet	Group	Driver
Off-vessel price, relative		OffVesselPriceRel	-15	Fleet	Group	Driver
<sub>3</sub> Effort cost, absolute	%	EffortCost	16	Fleet	Group	Driver
<sub>3</sub> Effort cost multiplier		EffortCostRel	-16	Fleet	Group	Driver
<sub>3</sub> Sailing cost, absolute	%	SailCost	17	Fleet		Driver
Sailing cost multiplier, relative <sup>3</sup>		SailCostRel	-17	Fleet		Driver
Fixed cost, absolute <sup>3</sup>	%	FixedCost	18	Fleet		Driver
<sub>3</sub> Fixed cost multiplier		FixedCostRel	-18	Fleet		Driver
Fishing mortality		FishingMortalityRef	104	Group		Reference
Diet composition <sup>1</sup>		Diet		Group (predator)	Group (prey)	Reference

**Table 1 - List of time series types and their abbreviations that can be used in Ecosim along with description. Notice that for reference time series, the CSV file weight can be  $[0, \infty]$  while the weight is not used for driver time series (so just set it to 0). Where no unit is indicated, the time series is a relative value (so no unit). Pool code and Pool code 2 should be numbers.**

<sup>1</sup> Not yet implemented in EwE

<sup>2</sup> Time series 14 replaces the catch abilities input interface in EwE 6.6

<sup>3</sup> These time series vary the Ecopath > Input > Fleet cost proportions

# Time Series Fitting

Ecosim can incorporate (and indeed benefits from) time series data. For many of the groups to be incorporated in the model the time series data will be available from single species stock assessments. EwE thus builds on the more traditional stock assessment, using much of the information available from these, while integrating to the ecosystem level.

When an Ecosim model is loaded, you can load time series “reference” data on relative and absolute biomasses of various pools over a particular historical period, along with estimates of changes in fishing impacts over that period. After such data have been loaded and applied (using the Time series form), a statistical measure of goodness of fit to these data is generated each time Ecosim is run (using the Run Ecosim form). This goodness of fit measure is a weighted sum of squared deviations (SS) of log biomasses from log predicted biomasses, scaled in the case of relative abundance data by the maximum likelihood estimate of the relative abundance scaling factor  $q$  in the equation  $y = qB$  ( $y$  = relative abundance,  $B$  = absolute abundance).

Each reference data series can be assigned a relative weight using a simple spreadsheet in the search interface, representing a prior assessment by the user about relatively how variable or reliable that type of data is compared to the other reference time series (low weights imply relatively high variance, unreliable data).

The time series fitting uses either fishing effort or fishing mortality data as driving factors for the Ecosim model runs. A statistical measure of goodness of fit to the time series data outlined above is generated each time Ecosim is run. The model allows four types of analysis with the SS measure (see Fit to time series for help with implementing these analyses):

- Determine sensitivity of SS to the critical Ecosim vulnerability parameters by changing each one slightly (1%) then rerunning the model to see how much SS is changed, (i.e., how sensitive the time series predictions ‘supported’ by data are to the vulnerabilities);
- Search for vulnerability estimates that give better “fits” of Ecosim to the time series data (lower SS), with vulnerabilities ‘blocked’ by the user into sets that are expected to be similar;
- Search for time series values of annual relative primary productivity that may represent historical productivity ‘regime shifts’ impacting biomasses throughout the ecosystem;
- Estimate a probability distribution for the null hypothesis that all of the deviations between model and predicted abundances are due to chance alone, i.e. under the hypothesis that there are no real productivity anomalies.

In addition to the nonlinear optimization routines described above the fit to data can also be improved in a feedback-process by examining some of the crucial ecological parameters in the

EwE model (notably total mortality rates and the settings for top-down/bottom-up control). It is important to note here that such fitting does not include any “fiddling-factors” internal to the model, instead the type of question that is addressed after each run is “which species parameters or ecological settings are not set such that the model captures the observed trends over time adequately?”

The inclusion of time series data in EwE facilitates its use for exploring policy options for ecosystem-based management of fisheries. An important preliminary conclusion from applications to various ecosystems is that the model is capable of producing a reasonable fit, (i.e. fits that can be compared to those obtained using single species models) for all available time series related to the ecological resources of an ecosystem in one go. This indicates a capability or at least a potential to replicate the known history of the ecosystems. In turn this lends some confidence to how the model can be used for policy exploration. It is also indicated that the fitting of time series in Ecosim may be used not just for identification of ecosystem effects of fishing but also to address questions of environmental impact at the ecosystem level (as well as for individual groups of course).

# Hints for time series fitting

If a model can't reproduce the past, how credible is it that it can predict the future?

If it can reproduce the past, maybe one can a bit less skeptical about its ability to predict the future?

A critical step in development of credible models for policy analysis is to show that they can at least reproduce observed historical responses to disturbances such as fishing.

This demonstration necessarily involves an iterative exercise in 'fitting' the model to data, by correcting parameter estimates and time series forcing information so as to show what values (or ranges of values, or alternative hypotheses about key processes) could explain the observed historical patterns. For any such fitting exercise, it is critical to have as long a reference period, with as many different disturbance patterns, as is possible to assemble. Note though, that only where a time series is used to 'drive' the model, (i.e. fishing mortalities and effort series) is it necessary to have information for all years in the time series.

Estimates of relative abundance, catches, etc. are not required for all years. Short reference data series carry little information about responses to some disturbances, and hence ability of a model to fit such short series

is no test at all of its ability to make useful predictions about disturbances not represented in the reference data. In more vivid terms, many model errors (structure and parameter values) will only reveal themselves (make themselves evident through strong departures of predicted from observed patterns) when the model is challenged to reproduce very long time series of responses.

Here we recommend an iterative, stepwise procedure for model fitting. It is generally not possible, or even wise, to try fitting a large ecosystem model using one big nonlinear estimation scheme that simultaneously varies all uncertain model parameters and inputs. There are simply too many inputs, some of the parameters are constrained in complex ways by mass balance considerations, and many model errors involve qualitative omissions of interaction terms (or processes, or disturbing inputs) entirely. Such possible omissions are most productively viewed as 'alternative hypotheses' about what processes and inputs have been important in shaping historical ecosystem behaviour.

The basic idea in this procedure is as follows. Set up an Ecosim model and reference time series (of forcing inputs like fishing rates, and indices of temporal system response like relative

biomasses and estimated total mortality rates). Examine the simulated and observed time patterns of response indices, look for groups that show large discrepancies in time pattern (trend), with particular emphasis on groups that have high biomass and are important prey or predator for other groups. As an example, sardines and anchovy in a Benguela model (Shannon et al., 2004) showed upward trend in data but not in initial simulation results. Focus in turn on each such group, and examine alternative hypotheses for the discrepancy (by varying appropriate parameters to see if the model fit is improved). The following are common hypotheses that should be examined in roughly the order listed:

Bad trend data – it is possible that the model predictions are sound, but that the trend data are misleading for some reason, (e.g., increasing catchability in CPUE indices).

Incomplete or incorrect forcing data, especially for fishing mortality rates—Ecosim-simulated patterns for exploited species will obviously not track observed patterns if those patterns have been caused by fishing, but no good time pattern of fishing mortalities (or at least fishing efforts) have been provided.

Inappropriate vulnerability parameters for the group's prey – low vulnerability multiplier settings (e.g., the 2.0 default) for a group's column in the vulnerability matrix (of its prey to it) can cause two errors: (i) failure of the group to increase following reductions in mortality (due to preventing the group from increasing its total food intake); (ii) and/or failure of the group to decrease following increases in mortality, due to overestimates of compensatory Q/B responses to decreased intraspecific competition. Check this by clicking the 'sensitivity of SS to vulnerabilities' button in the Fit to time series form to determine whether vulnerability changes would cause changes in goodness of fit, and consider using the fitting interface to search for improved vulnerability estimates. See Effect of P/B (Z) and vulnerability for time series fitting for more information.

Incorrect P/B (Z) setting in Ecopath for the group—it is common to see P/B, i.e. Z values set far too large in the Ecopath inputs, resulting in low EE and hence low sensitivity of a group to changes in mortality agents. Check the simulated time plot of total, fishing, and predation mortality rate components on the Ecosim Run Ecosim form to see if the total mortality rate and its partitioning among factors are reasonable. See Effect of P/B (Z) and vulnerability for time series fitting for more information.

Changes in system productivity—in some systems we have seen correlated declines or increases across a variety of species, despite differences among species in harvesting impacts, which might be explained by changes in basic productivity due to factors like upwelling. The Ecosim Fit to time series form can be used to 'reconstruct' an apparent temporal pattern in primary productivity, by fitting the model to time series for all groups while varying a time series of productivity 'anomalies'.

Trophic mediation effects—evaluate the possibility that changes in consumption and mortality have been caused by ‘indirect’ or ‘mediation’ effects, such as groups providing hiding places for other groups or driving behaviour of groups so as to make those groups more or less vulnerable to other predators. In systems that have benthic and pelagic primary producers, note that shading effects by phytoplankton on benthic plants are not represented explicitly in Ecosim, and must be modelled as mediation effects (by setting up a mediation function that causes negative effects on benthic plant production as phytoplankton biomass increases). This is also the case with turbidity and decreased foraging efficiency of visual predators that can be caused by phytoplankton.

If none of these hypotheses produces predicted patterns similar to the data, look closely at the Ecosim predicted patterns of change in consumption, growth, and mortality rates, and try to evaluate how these rates would have to change in order to produce observed trend patterns. Examine the observed time series for other groups, particularly prey and predators of the group under study, to see if those time series suggest changes in trophic conditions (growth, mortality) that have not yet been captured by the model due to inappropriate parameter settings for the other groups.

Repeat the multiple hypothesis evaluation steps above for each group, with initial emphasis on those groups for which the model predictions depart strongly from the data. Note that ‘correcting’ the parameters and time inputs for any one group can either improve or degrade the model fits for other groups, including groups for which good fits have already been obtained. This means that the fitting/evaluation process is necessarily iterative, requiring several passes or tries to obtain an overall valid model. For example, in the Benguela model example, obtaining good fits to strong time trends in sardine and anchovy biomass (using hypotheses (3) and/or (5) above) resulted in predicted increases in several predator populations, particularly hakes, for which the data do not indicate such increase. An interesting question then arose about why the predators did not show responses to the apparently large prey increases, and this question led to examination of a variety of hypotheses about why the response did not occur (limitation of recruitment due to cannibalism, undetected increases in fishing impact as responses started to occur so as to prevent those responses from being expressed, errors in initial estimates of diet composition and dependency on sardines and anchovy by the predators, etc.).

It is possible for the step-wise, iterative process of hypothesis evaluation and model testing/fitting described above to fail completely, in at least two basic ways. First, it may result in an apparently endless cycle back and forth between groups, with each step in the cycle resulting in improvement in fit to one group at the expense of poor fit to others. Such cycles have not yet been seen in case studies, but would indicate either ‘contradictory data’, where the model structure is valid but one or more trend data sets are misleading and apparently contradict the others, or a fundamental failure of the model structure to represent some important interactions or processes.

Second, the model may fail to capture (due to lack of correct input data or structural error) the dynamics of some particular, important group that has driven the dynamics of several others, and inability to simulate this one group may contaminate a variety of model predictions. For example, in models of the Bering Sea ecosystem, we have had trouble simulating (explaining) declines that apparently occurred in small, inshore pelagic fish species in the late 1970s and early 1980s. These declines were associated with onset of a rapid decline in Stellar Sea Lion, and onset of a strong upward trend in jellyfish (which compete with small pelagic fish for zooplankton). In that model, simply forcing the small pelagics to decline (with an arbitrary fake fishery) results in considerably better fits to the data for the other groups. In several models of relatively small oceanic regions (North Sea, West Coast of Vancouver Island), we have had to deal with apparently unpredictable biomass dynamics of species (especially mackerels) that have apparently invaded the regions in conjunction with changing ocean climate regimes. In fact, it is probably a general principle that for any region that might be arbitrarily defined for analysis, there are at least some species that have potentially important impact (on predator-prey relationships) within the region but display changes that can only be explained by examining their dynamics (production, fishing impacts) over some much larger spatial domain. With respect to any small study region, it is appropriate to treat the abundances of such species as forcing functions provided policy choices made within the region are unlikely to affect the larger scale dynamics of those species.

In most early Ecosim fitting exercises, the goal has been to find even one reasonably good fit to the data, i.e. to simply demonstrate whether the model is capable (flexible) of describing historical patterns. During such exercises, interesting alternative hypotheses and parameter changes that might have provided equally good explanations have not been thoroughly documented and pursued, nor have users typically even recorded the often simple research studies and auxiliary measurements that would be needed to test among alternatives (e.g., diet composition studies to detect rare prey in cases where an abundant predator may have big impacts on such prey despite such prey not being important to support of the predator). This failure to document the 'brainstorming' process involved in model fitting/testing can be costly for people who then try to use the model for policy analysis for several reasons:

- Clear articulation of alternative hypotheses that could equally well explain historical changes is a critical part of adaptive policy design involving planned experimental comparisons of policy options;

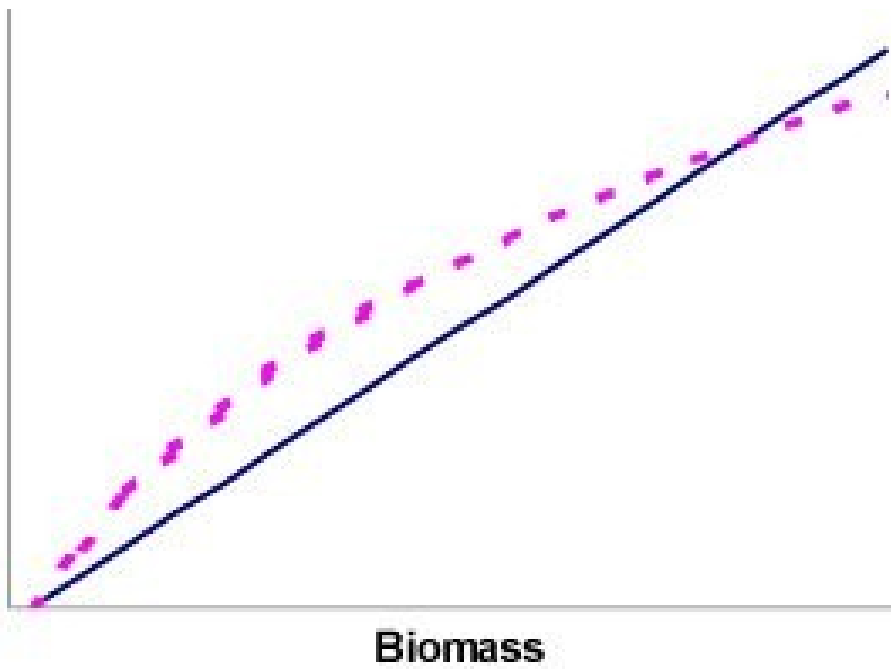
- Analyses based on the model are left open to attack by stakeholders who have vested interest in presuming some particular hypothesis to be true (e.g. people who want to blame stock declines on environmental factors so as to avoid restrictions in fishing); and

- Potential value of the modelling to help guide and prioritize research projects is lost, and this is a very big issue indeed in situations where very limited scientific resources are expected to provide useful information for complex ecosystem management planning.

Documentation of alternative hypotheses and parameter-changes during the sequential fitting process would appear at first glance to be an exceedingly complex process, involving geometric increase in number of hypothesis combinations as more time series and groups are examined (e.g. if there are two ways to explain changes in group 1, and two ways to explain changes in group 2, there are 4 possible ways to explain the joint dynamics). This ‘explosion’ in hypotheses is not that serious a problem in practice, for at least two reasons: (1) uncertainty about why a group has responded or not may be independent of uncertainty about why other groups have responded, e.g. we can examine hypotheses (and policy implications) about failure of hake to increase following sardine-anchovy increases in the Benguela system, without regard to what drove those increases in the first place; and (2) typically the alternative hypotheses involve ‘environmental forcing’ versus fishing effects, and the environmental forcing hypotheses are not independent for each group (i.e. hypotheses about increases or decreases in productivity due to factors like upwelling are expected to apply to a variety of groups). The main implication of point (2) is that we can generally identify just a few overall hypotheses for why an ecosystem has behaved as it has, each with very different policy implications. For example, in the Georgia Strait, B.C. models, two main hypotheses have emerged (can be made to fit the data using Ecosim) about why a whole suite of fish species has declined: either the system as a whole has experienced major decreases in primary production, or the observed dramatic growth in marine mammal populations (harbour seal) has had devastating impacts not reflected in the relatively crude diet information available from historical studies (in conjunction with modest declines in primary production).

## **Impact of P/B (Z) and Vulnerability Multipliers on Time Series Fitting**

For the balancing it is useful to think of how growth and mortality is modelled in Ecosim. Mortality is considered a linear function of biomass (solid line in Figure 1), while the population increase will be a non-linear function of the biomass (dotted line in Figure 3.9). This non-linear function corresponds to the consumption times the gross food conversion efficiency (from Ecopath, where it is estimated as base production over base consumption). For a given biomass, the population will increase or decrease depending on the area between the lines. The growth/decline of a given population can hence be modified by changing either the mortality rate, or food consumption. Food consumption, in turn, is a function of complex predator-prey relationships modelled using a variable ‘vulnerability’ setting for top-down vs. bottom-up control.



**Figure 1** – The solid line shows the predicted mortality calculated as  $Z \cdot B$ , and the dotted line the population growth estimated as a function of the consumption. The area between the lines can be considered 'surplus production'.

# Multi-sim

## General Description

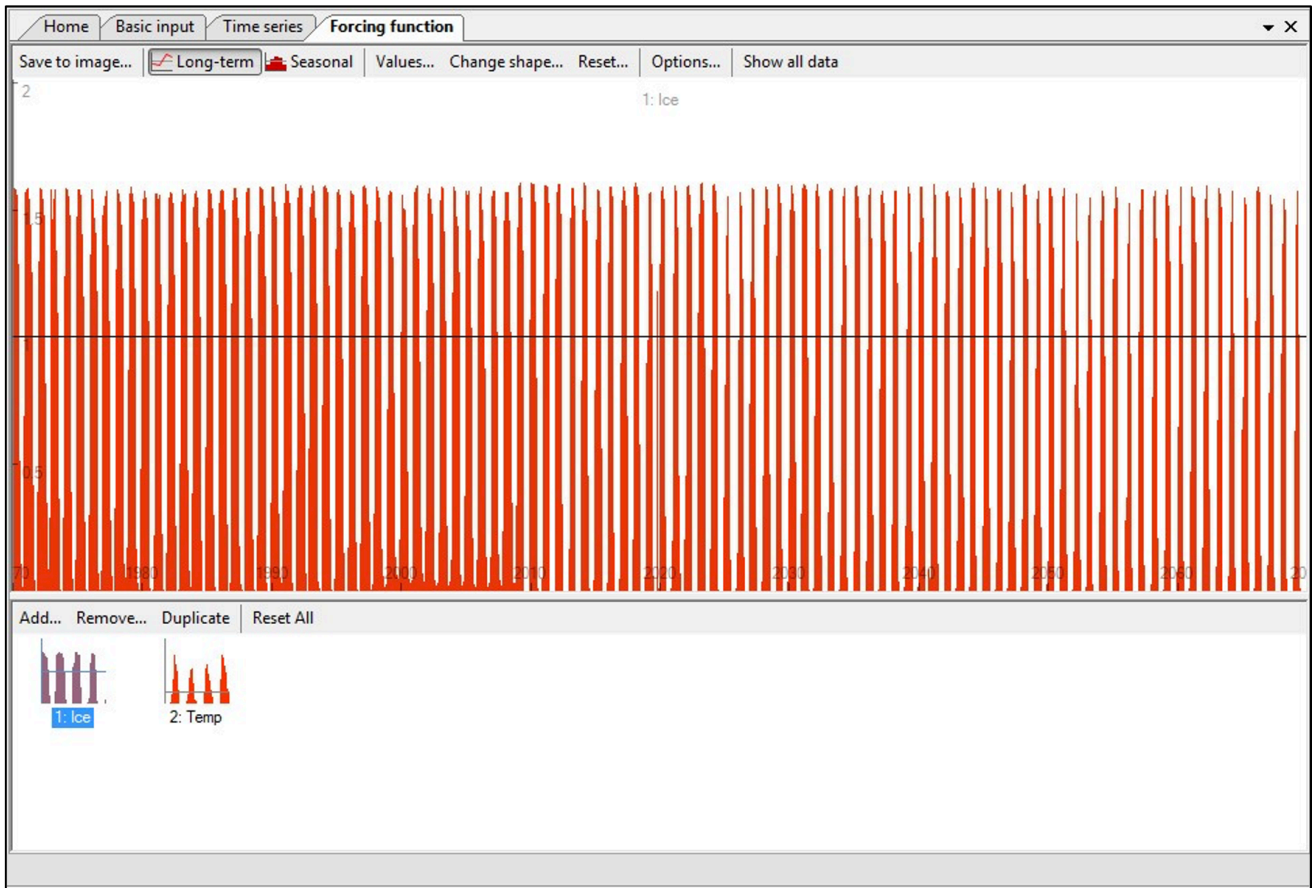
This plug-in was created with Dr. Alida Bundy, Fisheries and Oceans Canada to allow multiple simulations changing one or multiple forcing functions without having to upload files individually. This allows for selection of multiple files (.csv) to be read in collectively, as the plug-in will run one simulation per file used as a forcing function. The file(s) can be used to alter one or more forcing functions within the model, using corresponding names to existing forcing functions. Input and output can be selected as monthly or annual time steps, and allowing one to choose which output files each simulation will generate.

## Setting Up CSV Files Before your Simulations

This plug-in was designed to alter a subset of forcing functions existing within the model to test the effects on the functional groups within the model. In order to correctly read in one or more forcing functions, there are a few criteria you must include in your csv file. It should be noted that the names of your csv files are not important to the program or plug-in, only to the user.

1. The name of the forcing function you are altering must match EXACTLY to the forcing function already existing within the model, so it will be applied correctly. Be sure your names are indicated as text, In order to be sure, you can add quotations to your names in excel so that a name such as Ice will look like "Ice". The best way to check your names are indicated as text is to open them in notepad to be sure there are quotations around the names. Sometimes excel will read things as text, but not indicate this, so best to check in notepad.
2. Your forcing function must be structured as either monthly or annual, with all csv files being read in at a time (as in step #2) being consistent.
3. No labels are needed for time steps. Meaning if you are reading in 1 forcing function, only one column of data should exist in the csv, do not include a month or year column as names/numbers
4. The values for the first year should average 1 (as with any forcing function)

Example: For a model with 2 existing forcing functions, "Temp" and "Ice"



**Figure 1** – Forcing functions to be altered by Multi-sim

If we were going to change only the “Ice” forcing function, the corresponding csv file would look like Figure 2A (for the first 24 time steps). Note: these are monthly time steps with the first 12 months averaging 1. If we wanted to alter both “Temp” and “Ice”, the csv file would look like Figure 2B.

	A	B
1	Ice	
2	1.583574	
3	1.588331	
4	1.582781	
5	1.557211	
6	1.476139	
7	1.287633	
8	0.513785	
9	0.107534	
10	0.020317	
11	0.022498	
12	0.689209	
13	1.570987	
14	1.583574	
15	1.588331	
16	1.582781	
17	1.544822	
18	1.440262	
19	1.254927	
20	0.41636	
21	0.112291	
22	0.044302	
23	0	
24	0.392573	

	A	B
1	Ice	Temp
2	1.583574	0
3	1.588331	0
4	1.582781	0
5	1.557211	0.007336
6	1.476139	0.185863
7	1.287633	0.598097
8	0.513785	1.691662
9	0.107534	2.691848
10	0.020317	3.678034
11	0.022498	2.4313
12	0.689209	0.715859
13	1.570987	0
14	1.583574	0
15	1.588331	0
16	1.582781	0
17	1.544822	0.018077
18	1.440262	0.224808
19	1.254927	0.5828
20	0.41636	1.845588
21	0.112291	2.721301
22	0.044302	3.626257
23	0	2.92977
24	0.392573	1.239273

**Figure 2** – Changing one (A) or both (B) forcing functions

How to Use:

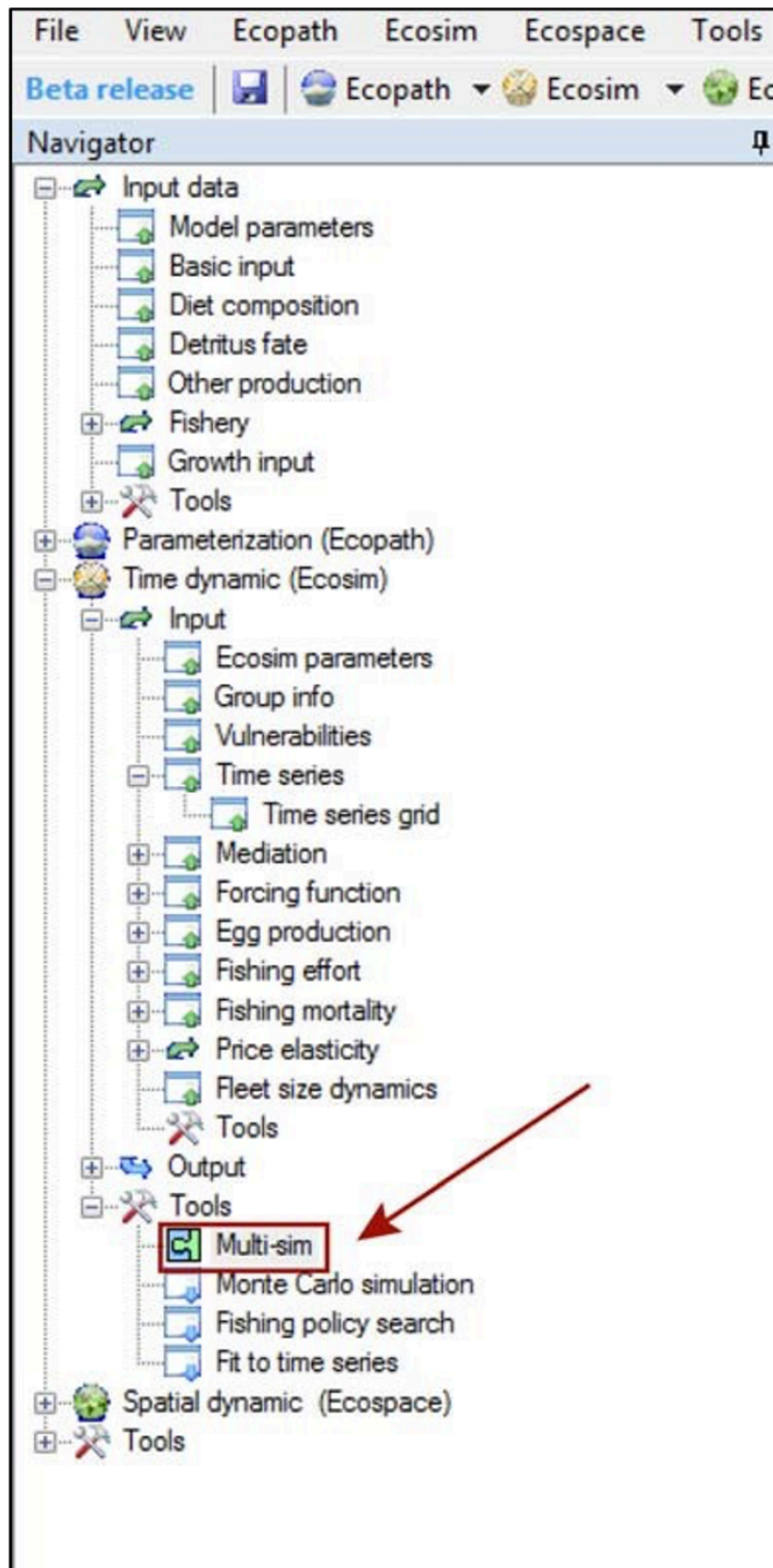
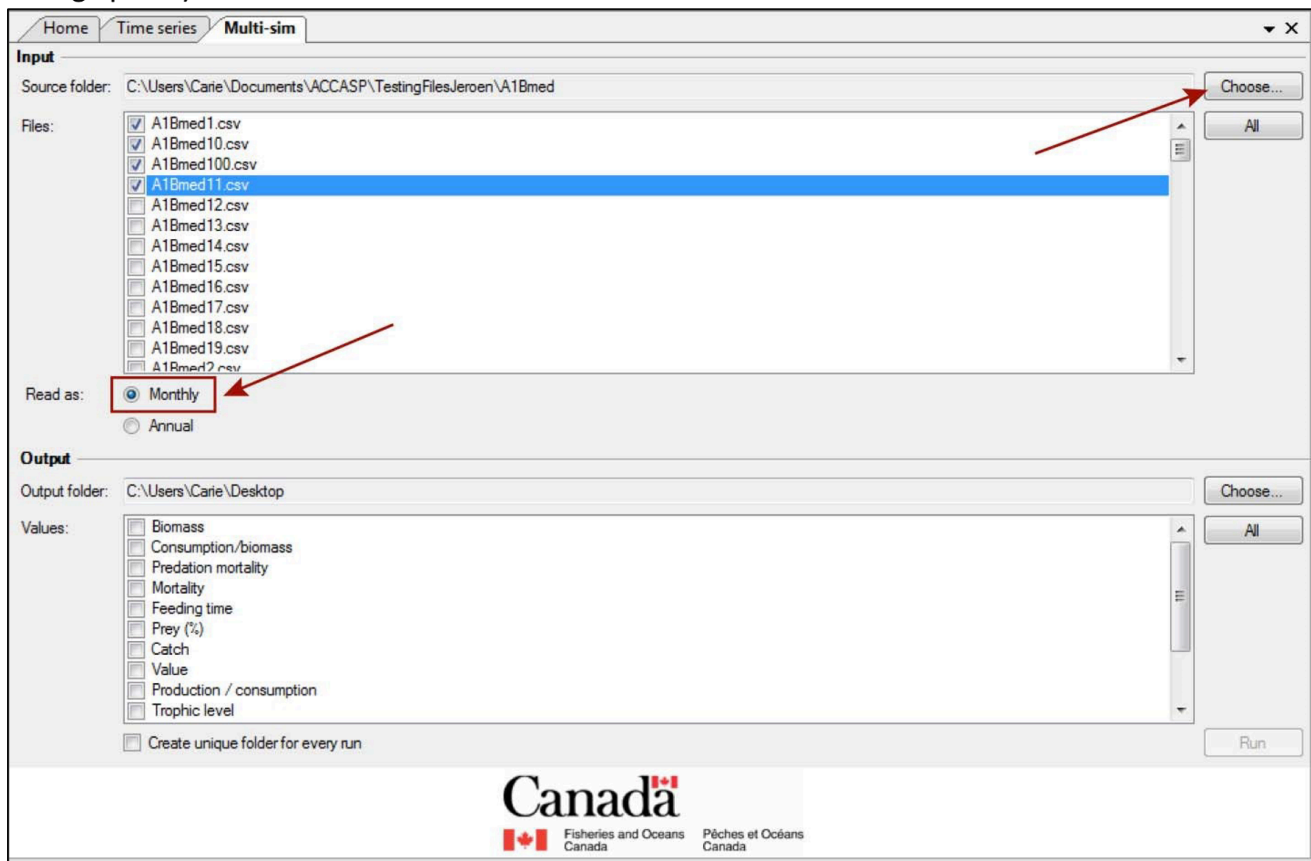


Figure 3 – Finding Multi-sim in the EwE Navigator.

1. Open an Ecosim scenario within your existing model. Be sure to load your time-series and double check all mediation functions, forcing functions, and fishing effort are already applied to the correct groups. Then select Ecosim > Tools > Multi-sim (Figure 3).

2. Selecting Input Files (Figure 4): Click on the choose button at the end of the source file line to select the source files containing the forcing functions to be changes during the simulations. Once you have pointed to the correct folder you may choose to select all files within the folder by selecting the all button, or you can select individual files by checking the boxes located to the left of the file name. Once you have selected all of the files you want to run, be sure to indicate whether the forcing functions should be read in as monthly or annual values. (see section on setting up files).



**Figure 4** – Selecting Multi-sim input files

3. Selecting Output Files: Select the folder where the results of each simulation will be stored by clicking the choose button at the end of the output pathway and point to the correct folder. If you would like each simulation to generate its own folder (rather than all output files ending

up in one folder), check the create unique folder for every run box at the bottom of the page. Once the output path has been chosen, you may select which results you would like saved for each simulation. You may choose to select all options by clicking the all button in the lower right corner, or check the boxes next to individual files.

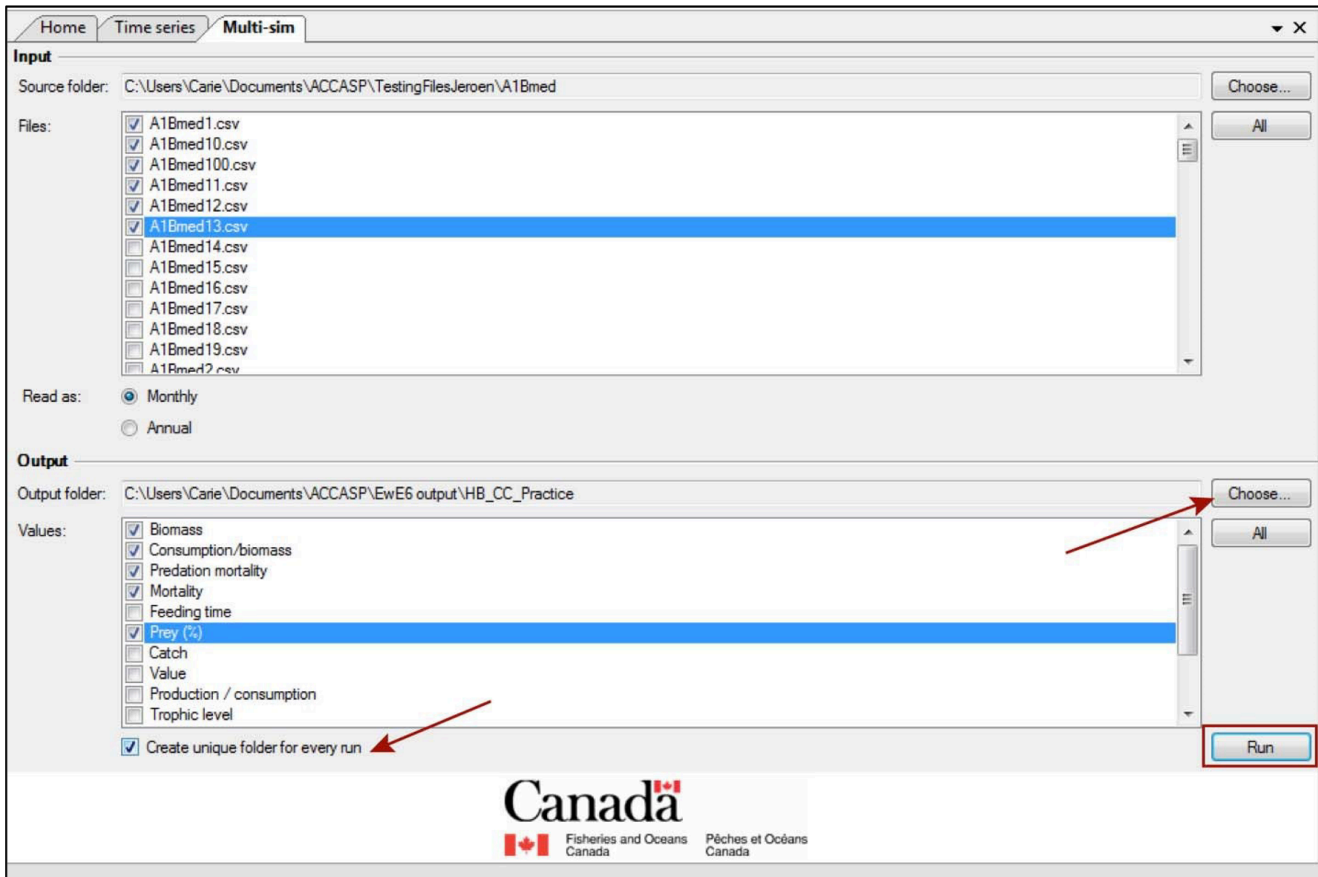


Figure 5 – Select Multi-sim output files

4. Interrupting simulations: Once steps 1-3 are complete you may select the run button to start your simulations. Once simulations have started, there is the option to interrupt and cancel the application by using the stop button. This will halt the current simulation and prevent the plug-in from completing further simulations. You will notice a little red circle at the bottom left of your screen once simulations have started indicating which simulation is running which corresponds to the source file name.

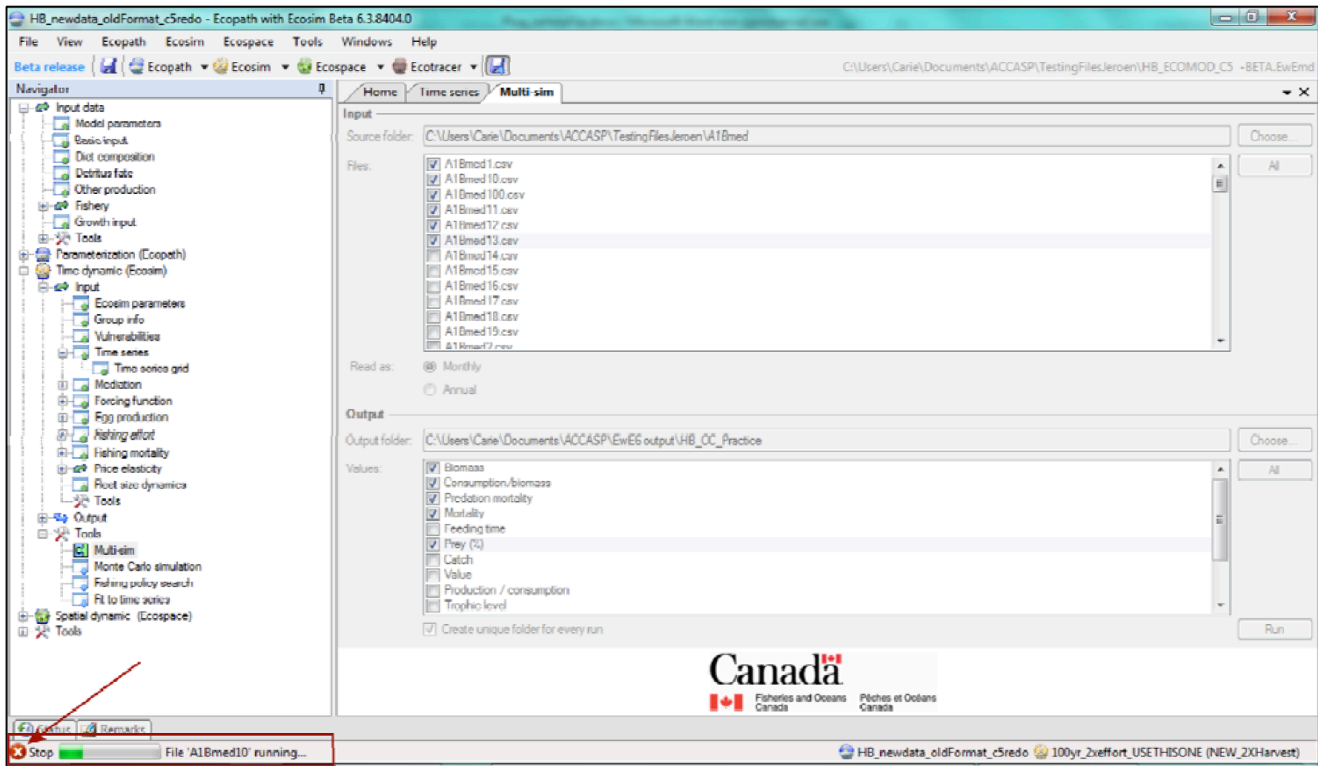
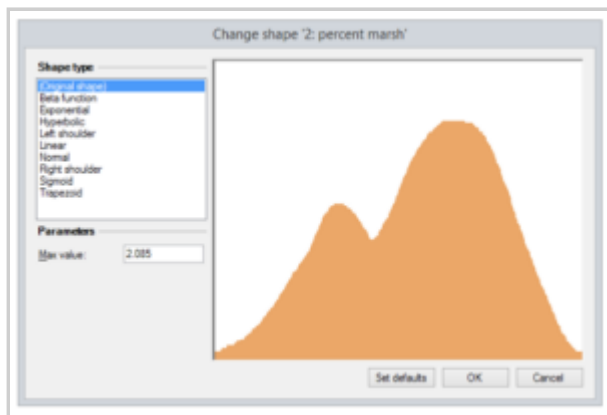


Figure 6 – Interrupting Multi-sim

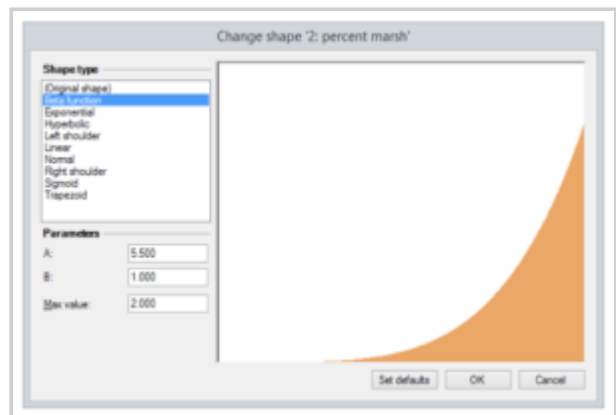
# Function shapes

The Ecosim and Ecospace modules contain forcing functions and mediation functions through which temporal dynamics of the model can be influenced. These functions can be arbitrarily sketched, obtained from external data where known, or derived from a series of predefined mathematical distributions.

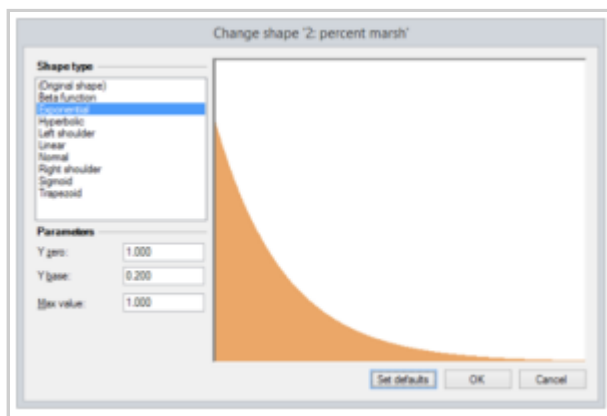
The EwE software offers the predefined distributions illustrated in Figures 1 to 10. In addition, efforts are under way to allow users to programmatically add their own distributions via plug-ins.



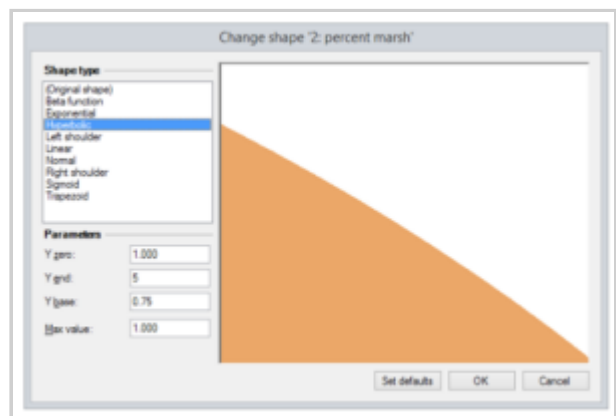
**Figure 1** – Original Contours



**Figure 2** – BetaPDF distribution



**Figure 3** – Exponential Distribution



**Figure 4** – Hyperbolic Distribution

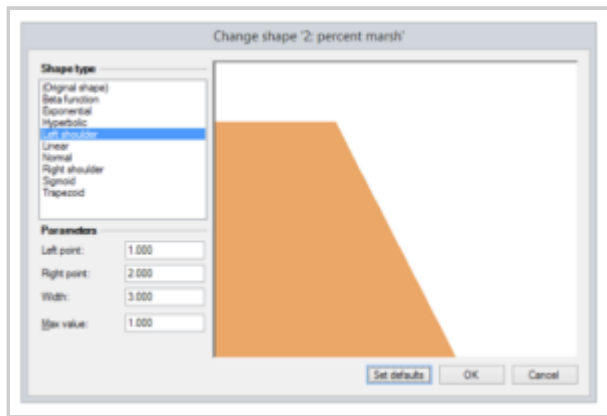


Figure 5 – Left Shoulder Distribution

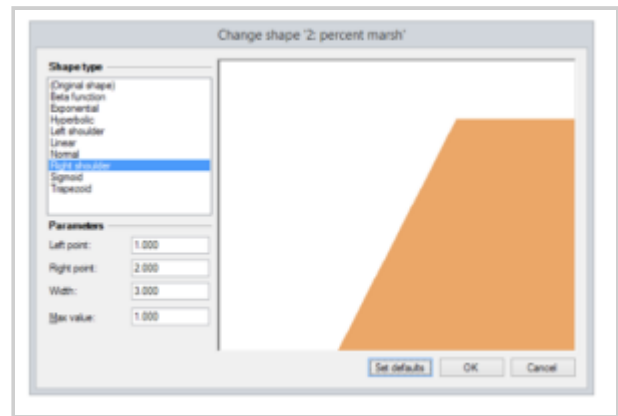


Figure 6 – Right Shoulder Distribution

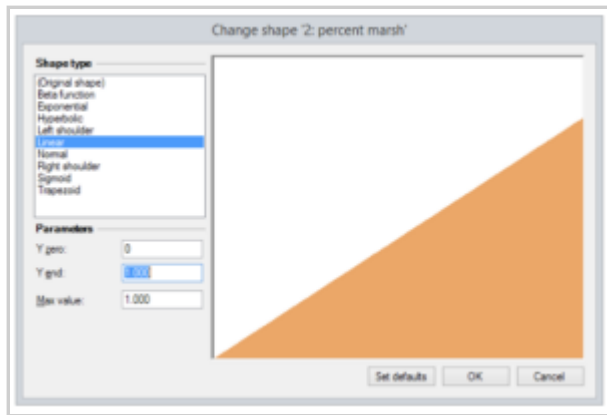


Figure 7 – Linear Distribution

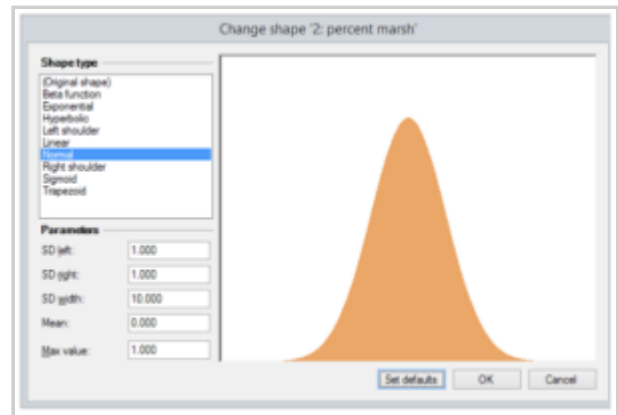


Figure 8 – Normal Distribution

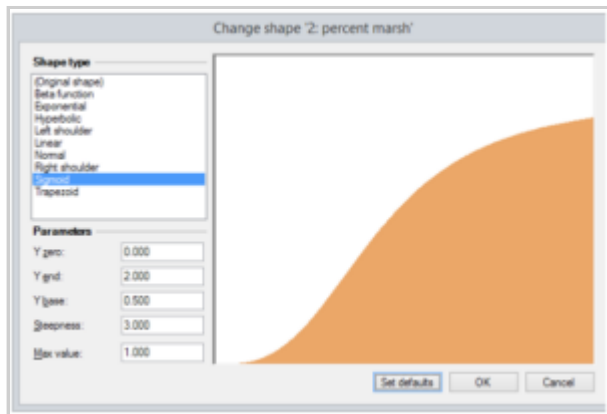


Figure 9 – Sigmoid Distribution

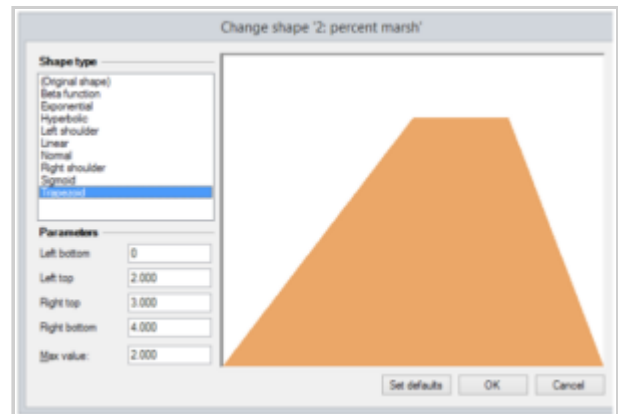
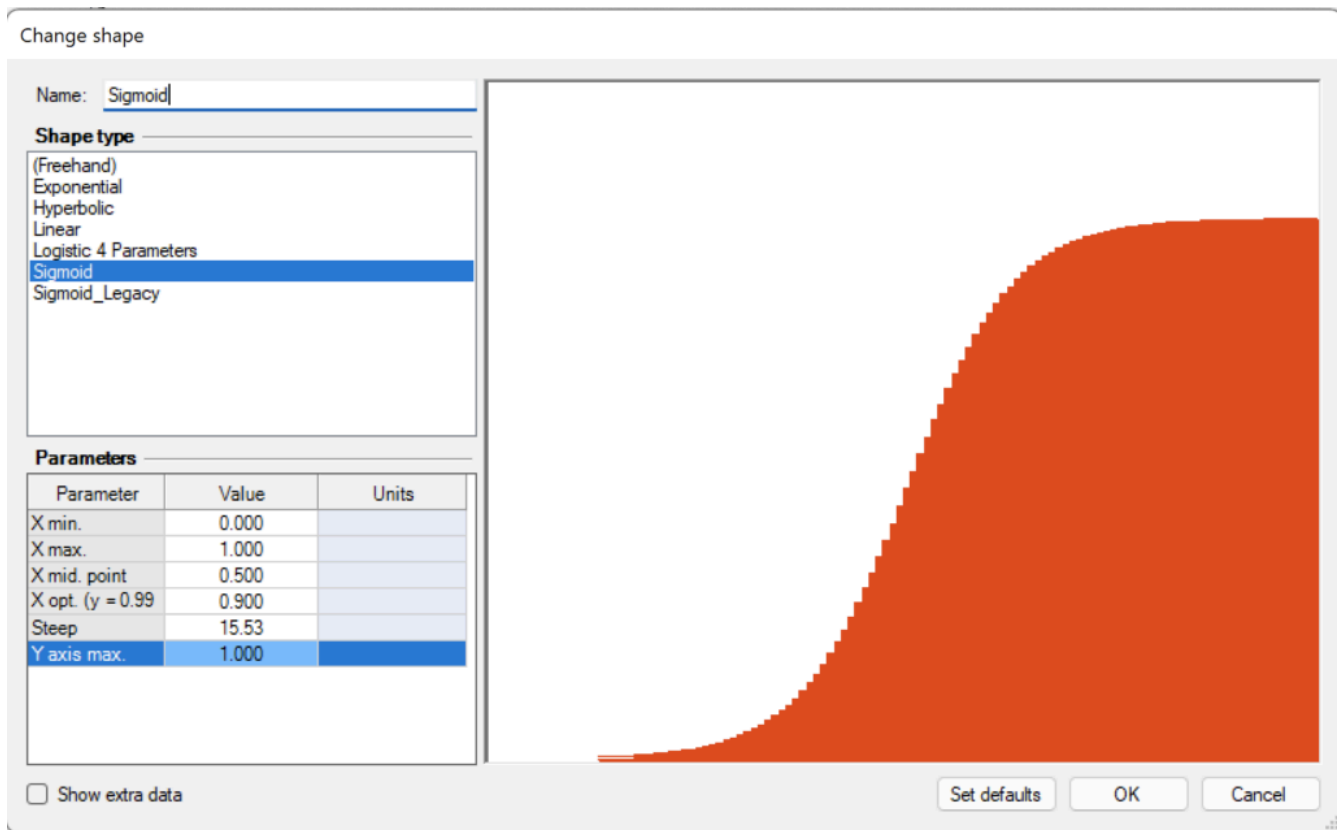


Figure 10 – Trapezoid Distribution

We illustrate the variables and use of forcing functions shape with an example, see Figure 11.



**Figure 11** – Sigmoid response function in the Ecosim > Input > Forcing function > Change shape form.

- **X min** – Minimum value of the X axis data
- **X max** – Maximum value of the X axis data
- **X mid** – Middle of the curve, where the sigmoid function returns 0.5. This does not have to be the mean value of the X axis data.
- **X opt** – Point on the X axis where the sigmoid function returns 0.998, just short of 1.0 so the function doesn't have to be completely flatten at this point. Entering this value cause the Steep parameter to be calculated, even if it has been entered. If X opt. is greater than X mid. then the shoulder is increasing to the right. If X opt. is less than X mid. then the shoulder will decrease to the right.
- **Steep** – Steepness of the curve, high values will make the curve steeper
- **Y max** – Maximum value on the Y axis. By default this is one. Included as a parameter so the sigmoid function shapes can be used as a forcing function, this allows for sigmoidal growth or decay in a forcing function.

From a user's perspective it would be good to set the X axis data range (X min. and X max.) in the **Functional response to environmental forcing**. In this dialogue the response function and the forcing data are both displayed in the **Driver histogram & response function** plot, there is also UI

elements for **X min.** and **X max.** and a button to set the **Default X axis.** Unfortunately, because of the way the **Functional response to environmental forcing...** dialog has been programmed, it is awkward to use these values to set the default X min. and X max. values.

If X opt. has been entered then Steep parameter will always be calculated, even if it has been entered. To use the Steep parameter instead of X opt., clear the X opt. value and enter only Steep.

Sigmoid functions from older version of EwE are still be included for backwards compatibility. They will appear as Sigmoid\_Legacy in the Shape type list

# Other Mortality Response Functions

DAVID CHAGARIS; JOE BUSZOWSKI; AND JEROEN STEENBEEK

## Scope and Purpose

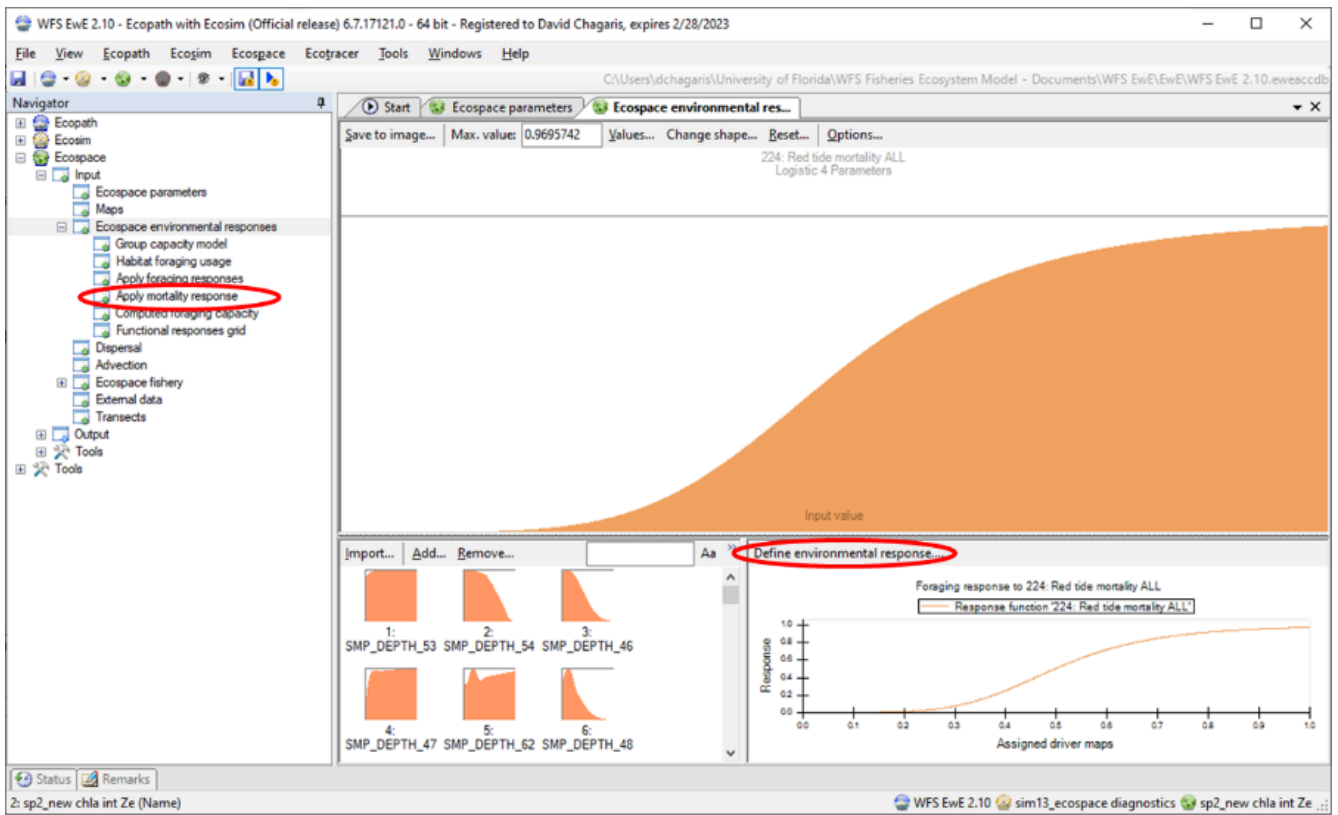
This document provides usage instructions for the other mortality response function in the Ecopath with Ecosim food web modelling approach.

## Summary

Aquatic ecosystems are often exposed to mass mortality events that can be caused by a variety of factors such as low dissolved oxygen, harmful algal blooms, extreme heat/cold events, contaminants, or noise pollution. The EwE software includes the ability link environmental drivers to the 'other mortality' (M0) component (non fishing or predation) to simulate direct lethal effects of environmental stressors. The M0 response function can be used in combination with the habitat capacity model to capture both lethal and sublethal (feeding and movement) effects in the model. An example application to red tide on the West Florida Shelf is provided in publication by Vilas<sup>1</sup> and Vilas et al.<sup>2,3</sup>.

## Computations

The amount of other mortality that is to be added to the baseline M0 is determined by a user defined environment response function and input environment forcing time series (if in Ecosim) or driver maps (in Ecospace). The forcing data must be continuous in nature, representing the concentration or intensity of the mortality agent. The M0 response function can take any shape, but must be constrained between 0 and 1 across all values of the mortality driver. An example of the useful logistic response function is given in Figure 1.



**Figure 1** – An example M0 response function assigned in the Ecospace environmental response form. Here a logistic function is used to model the increasing mortality with higher concentrations of red tide as a mortality agent.

The proportion of the total biomass that will experience mortality in a given time step and grid cell is given as  $P_{mort} = f(x)$ , where  $x$  is the value of the mortality forcing function at the time step and grid cell and  $P_{mort}$  is calculated from the response curve at the value of  $x$ . The proportion killed is converted to an annual instantaneous rate,  $\hat{P}_{mort}$ , to match Ecospace M0 units (1). The rate is then converted to a multiplier ( $M0_{mult}$ ) on the baseline M0 rate ( $M0_{base}$ ).

$$\hat{P}_{mort} = -\ln(1 - P_{mort} \cdot 12) \quad (1)$$

$$M0_{mult} = (\hat{P}_{mort} + M0_{base}) / M0_{base} \quad (2)$$

In Ecosim and Ecospace, the M0 multiplier is included in the loss equation (3) at each time step and grid cell as,

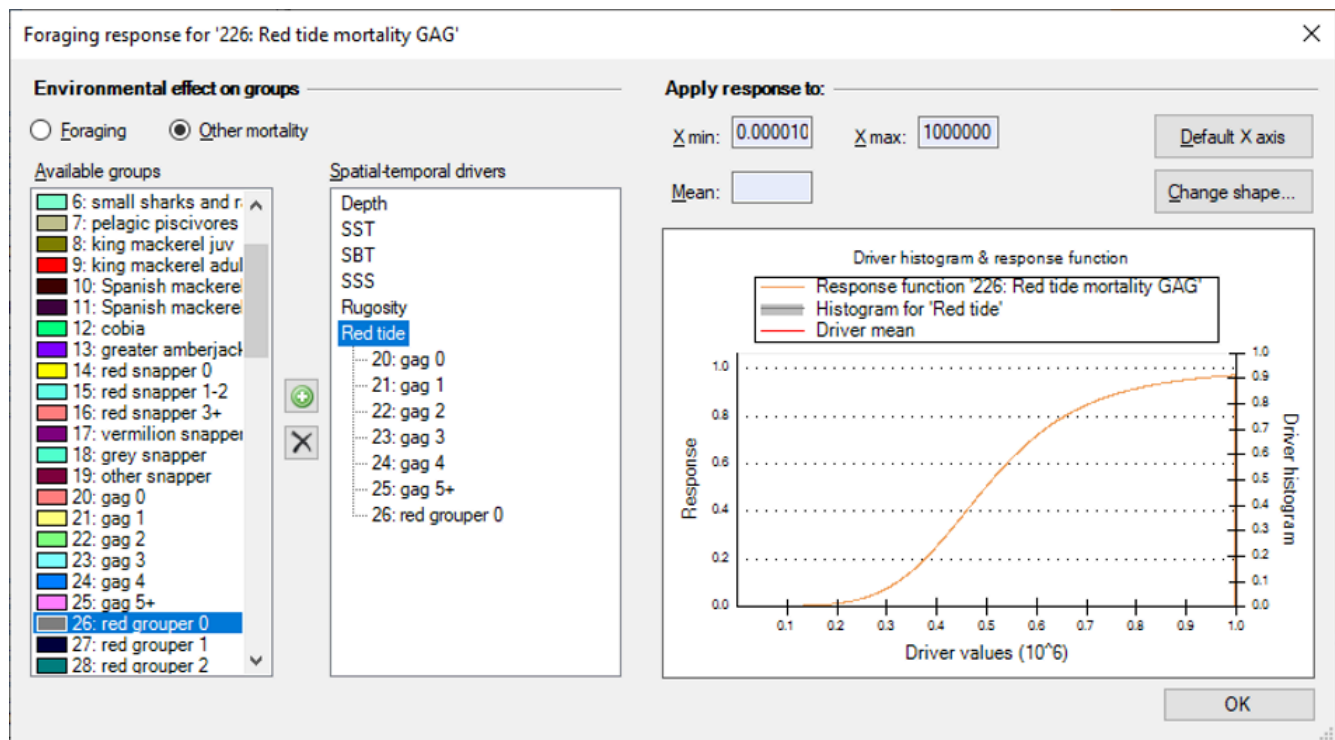
$$loss_i = Q_i + (M0_{base_i} \cdot M0_{mult_i} \cdot (1 - M0_{pred_i} \cdot F_{time_i}) + E_i + F_i) \cdot B_i \quad (3)$$

Where  $Q$  is the total consumption of group  $i$  by all predators,  $F_{time}$  is the fraction of other mortality

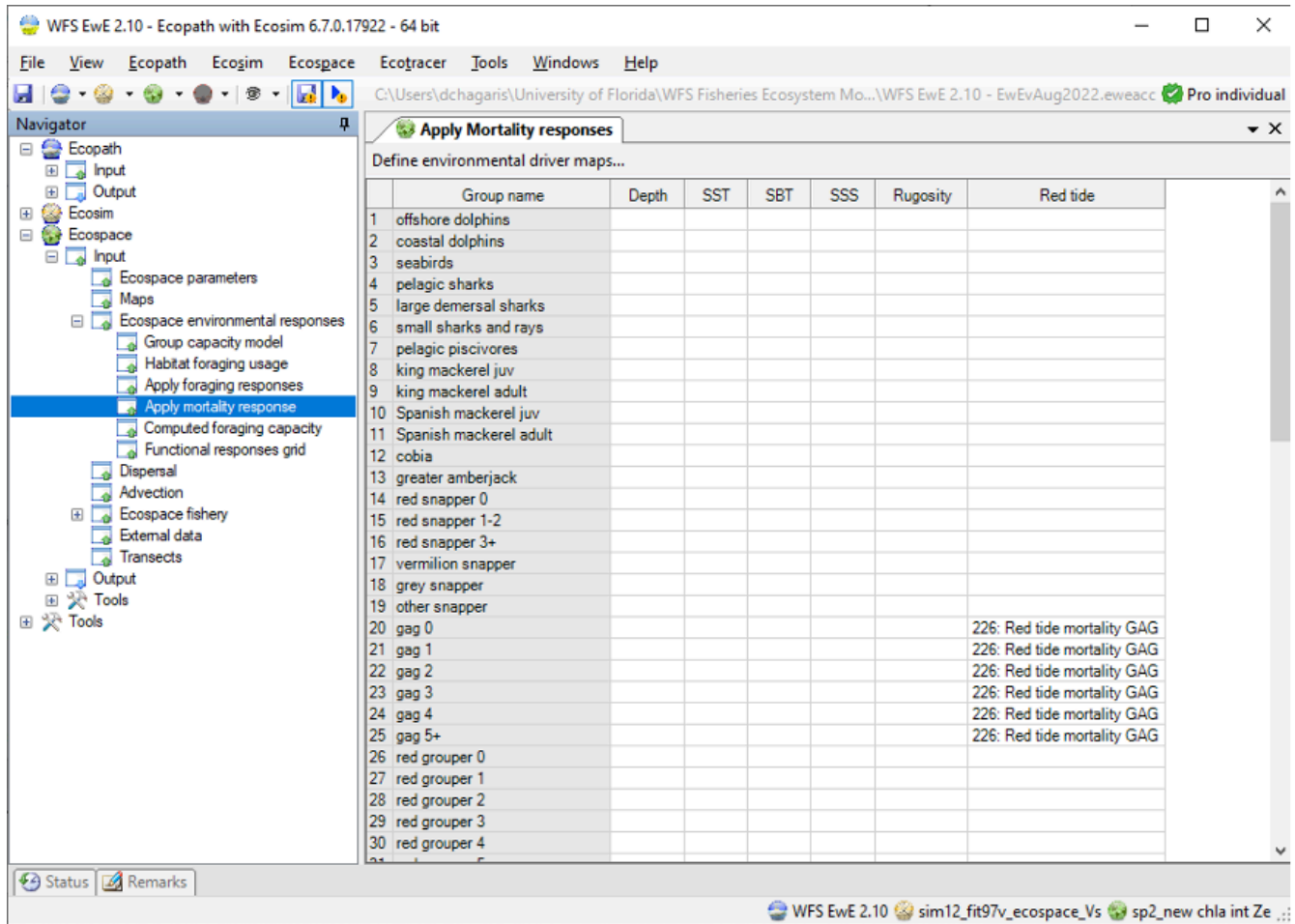
sensitive to changes in feeding time,  $MO_{pred}$  is the effect of predators on feeding time,  $E$  is the emigration rate,  $F$  is the fishing mortality rate, and  $B$  is biomass.

## Configuring Mo Environmental Response Functions

First, the mortality agent must be loaded as a forcing function time series (in Ecosim) or as an environmental driver in Ecospace linked to external data. Next, create a new response function using the *Ecospace > Input > Environmental Responses* interface (Figure 1). From there, select the *Define environmental response...* button to open a new window, select the *Other mortality* radial button, then click on the mortality agent under the list of Spatial-temporal drivers, select a species or functional group, and click the plus button to apply the mortality response (Figure 2). Alternatively, one may go to the *Apply mortality response* under the Environmental Responses menus (Figures 1 and 3) to associate a functional groups with a mortality curve. The total calculate loss due to other mortality forcing is saved as time series, summed over all grid cells by Ecospace region, or as ascii maps for biomass loss in each grid cell. These output options must be selected in the Ecospace parameters save settings.



**Figure 2** -Linking a species to a mortality response curve can be accomplished in the *Define environmental response...* form, accessed from the *Ecospace > Input > Ecospace environmental responses* window (see Figure 1). Here all six age stanzas of gag are assigned a mortality response to red tide, as well as red group age-0.



**Figure 3** – Linking a species to a mortality response curve can be accomplished in the Apply mortality response form under Ecospace > Input > Ecospace Environmental responses. Here all six age stanzas of gag are assigned a mortality response to red tide.

## Acknowledgements

Other mortality forcing was implemented by Joe Buszowski and Jeroen Steenbeek after an idea by David Chagaris, with input from Carl Walters and Villy Christensen. The work is a result of research funded by the National Oceanic and Atmospheric Administration’s RESTORE Science Program under award NA17NOS4510098 to the University of Florida.

## Notes

1. Vilas Gonzalez, Daniel. 2022. Spatiotemporal Ecosystem Dynamics on the West Florida Shelf: Prediction, Validation, and Application to Red Tides and Stock Assessment. PhD Dissertation, University of Florida, 2022. Available online: <https://ufdc.ufl.edu/ufe0058578/00001>
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3. Vilas, D., Buszowski, J., Sagarese, S., Steenbeek, J., Siders, Z., Chagaris, D., 2023. Evaluating red tide effects on the West Florida Shelf using a spatiotemporal ecosystem modeling framework. Scientific Reports 13, 2541. <https://doi.org/10.1038/s41598-023-29327-z>

# Monte Carlo

Ecosim includes a Monte Carlo approach to search for Ecopath parameter-combinations that improve the fit of the model to time series data (i.e., reduce the weighted sum of squared deviations, SS; see Time series fitting in Ecosim). The Monte Carlo approach can also be used to test for sensitivity of Ecosim's outputs to Ecopath input parameters.

To use the Monte Carlo interface, open the *Monte Carlo run* form (*Ecosim > Output > Tools > Monte Carlo runs*).

## Monte Carlo inputs

### Number of simulation trials

Set the number of trials. Each trial represents an Ecosim run with a randomly-selected set of Ecopath parameters (B, P/B, EE, BA) for each group. Parameters are drawn from a uniform distribution centred on the base Ecopath value with coefficient of variation (c.v.), which may be derived from pedigree.

### Show biomass trajectories on Ecosim plot

Displays Ecosim results on the *Biomass plot* tab in the lower panel of the form.

### Apply time series

Opens a dialogue box where you can apply time series that have been loaded into Ecosim (i.e., you do not have to return to the Time series form to apply time series). You can also remove time series from the analysis using this dialogue box. See Time series for more information about loading time series in Ecosim.

*B, P/B, EE, BA*

The Ecopath parameters tabs in the lower panel show the mean, lower limit and upper limit of the distribution used to draw random values for B, P/B, EE and BA for each group in the model. The mean of the distribution is set as the base Ecopath value of the parameter. Users can set the coefficient of variation (c.v.) which is then used to calculate the upper and lower limits of the distribution (upper limit = mean + 2 \* c.v. \* mean; lower limit = mean - 2 \* c.v. \* mean). For parameters you do not wish to change, set the c.v. to zero.

Note that the parameter combinations resulting from the random draw must result in a balanced Ecopath model (i.e., before running each trial, Ecosim keeps drawing new sets of parameters until a balanced Ecopath model is achieved). This means that the range of the parameter values actually used may be smaller than that set by the user. Users should check the range of the input parameters that were actually used in the trials in the output .csv file (see below).

## Monte Carlo outputs

### Trial

Tracks the current trial number.

### Ecopath runs

Tracks the number of parameter-combinations tried until a balanced Ecopath model is achieved. Note that the maximum number of tries is 2000. If a trial reaches 2000 Ecopath runs then a balanced model could not be achieved with any parameter combinations and the simulation trial is run with an unbalanced model.

This may indicate that the cv's have been set too large, reducing the likelihood of finding parameter values that combine to produce a balanced model.

### SS measures

At the top right-hand side of the form, the original (i.e., before the simulation) weighted sum of squared deviations (SS) is shown. Current SS shows the value of SS achieved for the current trial. Best SS shows the lowest SS achieved for any of the runs.

## Data from best fitting trial

After all trials have been completed, the parameter-values that resulted in the lowest SS are shown on the second-last tab in the lower panel of the form. When the trials are complete, the software automatically displays this tab.

## Biomass plot

If the *Show biomass trajectories* on Ecosim plot box is checked, biomass trajectories are displayed for each trial on the *Biomass plot* tab. This tab is automatically displayed when you click *Run trials*.

You can choose to overlay trajectories for each trial, switch from monthly to annual output and scale the results using check boxes. *Show/hide groups*, highlighting of trajectories for a single group and viewing of layers is also enabled, with the same functionality as for the Run Ecosim form.

The *Apply best fits* button applies the parameter-values that resulted in the lowest SS (shown on the *Data from best fitting trial* tab) to your Ecopath model (i.e., overwrites the original values).

Warning: it is a good idea to save a backup of your model using *Save as* on the File menu before you overwrite your original parameters using *Apply best fits*!

### Attribution

This chapter is in part adapted from the unpublished EwE User Guide: Christensen V, C Walters, D Pauly, R Forrest. Ecopath with Ecosim. User Guide. November 2008.

# Fishing policy exploration

## Parameters

**Discount rate:** What is it worth for you today to get a million Euro next year, compared to getting it today? Economists discount the present value of future income by using a discount rate. The optimization routine uses a default a discount rate of 4%, which means that the current value of getting a Euro in one year is €0.96 ( $= (1+\text{Discount rate})^{-1}$ ). (Use *default if you don't have a prescribed discount rate to use*)

**Number of runs:** If you set the **Initialize using** option to “Random F”, the optimization routine will use a random starting point. As the routine may get stuck on local minima, it makes sense to try several times. (*perhaps 10*). In nonlinear optimization practice, this is called “multiple shooting”.

**Initialize using:** There are three options,

1. Ecopath base F: Starts with the Ecopath base fishing effort, (which typically will be 1)
2. Current F: when used with a base year that's different from year 1, selecting this option will make the policy search start with the effort of the base year
3. Random F: selects random effort for each fleet. This option is important to evaluate if there are local minima. The policy search can get stuck on local minima, and the best way to evaluate the risk of that is to run a number of trials, starting each with random effort. Note that if the **Number of runs** is set to more than 1, the **Initialize using** will change to using Random F.

**Max. no of evals:** The optimization routine does a large number of Ecosim runs during an optimization, often several hundred. The parameter sets a limit for how many. (*Use default setting unless your model won't converge with this*).

**Base year:** By default this is year 1, and if so, your economic parameters should be for the Ecopath base year (= year 1). Assuming your model is fitted to time series data, e.g., for years 1 to  $n$ , it may make sense to do the optimization looking forward to the post-fitting period (year  $n+1$  on). In that case, add, e.g., 20-30 year to the run time (*Ecosim > Input > Ecosim parameters > Duration of simulation (years)*), and change the Base year accordingly. If you increase the base year, the interface will block out (in black) the years prior to the base year, i.e. Ecosim will run with stored effort for those years, not try to estimate any.

To minimize the risk that the optimization will result in overexploitation towards the end of the

simulation, the simulation routine will run for an additional 20 years beyond the last year, and the results for that last block of years will be included in the output.

**Max effort change:** Provides a limit for how much effort is allowed to change from one year to the next. The parameter should be entered as a factor  $\diamond \geq 1$ . With a value of, e.g.,  $\diamond = 1.1$ , the routine will at most accept a change in effort for the following year in the range [0.909, 1.1]. With the default value of 0, there is no limit for how much effort can change.

The changes are only for between-blocks years, for instance where there are several blocks for a given fleet, perhaps to have some additional years for rebuilding a stock followed by a different management patterns for later years. In that case, the max. effort change will be evaluated only when changing from one block of years to the next.

**Search using:** Decides which search algorithm to use for the minimization, either DFPmin or Fletch,

1. *DFPmin*: The Davidson-Fletcher-Powell<sup>1</sup> optimization procedure is a nonlinear optimization procedure to iteratively improve an objective function by changing relative fishing rates, where each colour-coded “year/fleet block” defines one parameter to be varied by the procedure, (e.g., setting four colour code blocks means a 4-parameter nonlinear search). DFP runs the Ecosim model repeatedly while varying these parameters; in the search output display, each simulation trial is labelled an “eval” or function evaluation. So if you are running a large model for many years, where each simulation takes several seconds to do, the search may take quite a long time to do enough function evaluations to find a maximum for the objective function.

The parameter variation scheme used by DFP is known as a ‘conjugate-gradient’ method, which involves testing alternative parameter values so as to locally approximate the objective function as a quadratic function of the parameter values, and using this approximation to make parameter update steps. It is one of the more efficient algorithms for complex and highly nonlinear optimization problems like the one of finding a best fishing pattern over time for a nonlinear dynamic model.

2. *Fletch*: An efficient non-linear search routine, older and less-well known than DFP, but faster and more efficient for many problems. Used by default.

**Use plug-in economic data:** When defining a fleet in the Ecopath base model, there are input values for costs as a fraction of income (*Ecopath* > *Input* > *Fishery* > *Fleets*) based on which the baseline costs are obtained (*default is that cost is 80% of revenue*). The revenue is obtained from the Ecopath baseline landings times off-vessel price. In Ecosim, revenue for each time step will be calculated the same way, while cost will change proportionally to effort.

The checkbox will be enabled if a value chain has been defined for the model, and the “Run with

searches” option has been checked (at Ecopath > Output > Tools > Value chain > Parameters). If the **Use plug-in economic data** is checked, the fishing policy search routine will run the value chain for each run and obtain revenue and costs by fleet and time from there.

**Limit cost > earnings:** When maximizing for jobs (landed value) the search routine can create rather extreme policies, often driving the system towards mono-culture system configuration or fishing at a loss (implied subsidy to increase jobs). For Anchovy Bay, as an example, this may result in higher landed value, comprised almost exclusively of shrimp and anchovies. This corresponds to a “sole owner” or societal approach (see [textbox](#) in Fishing policy exploration chapter), and it is implemented if you do not check the **Limit cost > earnings** option (*default option*).

Checking the **Limit cost > earnings** option, leads to an optimization where the policy search will seek to make each fleet profitable, corresponding to a “multiple fishing rights” approach, (see [textbox](#) in Fishing policy exploration chapter).

The **Limit cost > earnings** will only have impact if the **Net economic value** is included in the objective function.

**Maximize portfolio utility:** As described in the [Fishing policy exploration](#) chapter, there are two alternative objective functions in the policy search. Checking the **Maximize portfolio utility** option invokes the alternative objective function that invokes risk-averse utility measures that favour a balanced ‘investment portfolio’ of fishing activities. See the [Risk-averse portfolio utility](#) chapter for details.

## Blocks

This section of the interface is designed to set up how many fishing effort fleet-time blocks that the fishing policy search should try to optimize. A block is represented by a colour, and by default the routine searches for one fishing effort per fleet (one time block). The base year (by default year 1) and any preceding year are by default coloured black, that means that the routine will not search for those years but instead retain whatever the fishing effort variable has in memory.

If you as an example colour the whole spreadsheet with one colour, the policy search will find the one (relative) fishing effort across all fleets that optimizes the objective function

A colour in the block spreadsheet means: “find me a fishing effort for this fleet/year combination”. All blocks with a given colour will get the same relative fishing effort.

**No of blocks:** Use this to get more colours = blocks

**Selected:** With many colours (blocks) it can be difficult to see which one is selected. It can be easier to change the number of **Selected** to selectively set blocks. The horizontal slider under the colours indicate which one is selected.

If the optimizations starts at a point where the system is degraded/overfished, it can make sense to have an initial rebuilding period followed by sustainable use. This can be set with by setting two colours blocks per fleet, one for the rebuilding period and one for the sustainable use period.

## Set block year and sequence

This, somewhat complex part of the interface, can be used to set blocks of years. The default is that there is one block per fleet spanning from year 2 to the end, the optimization thus starting in Year 2 and ending in the last year of simulation.

**Year:** Gives number of years per block. The default is number of years in simulation. Changing this, for instance to 10 years, will signal that there should be one block for each 10 years simulated for each fleet

**Set:** Clicking will set the number of blocks by fleet based on the **Year** setting.

**Start:** Increasing the start year will result in the years prior be blocked (indicated in black) and not included in simulations

**End:** Decreasing the end year will cause the following years to be blocked and not included in simulations.

## Objectives, iteration results and plot results

The lower panel has three tabs, each explained next.

## Objectives

This tab will be displayed while setting up the policy scenario. The objectives are described above, this section deals with how they are implemented. The objectives are described in the [Fishing policy exploration](#) chapter of the EwE textbook.

**Search objective, relative weight:** List the five objectives (or three if the **Maximize portfolio utility** option has been checked) with relative weights. Be aware that putting the same weight on two or more objectives does not translate into these objectives actually being balanced (see the [Policy exploration procedure](#) tutorial in the EwE textbook. This is because changing for instance how much *Ecosystem structure* may change will be much harder than changing *Net economic value*. To get an overview of the range for each objective it may be advisable to conduct a series of optimizations placing weight on one objective at the time.

If the **Maximize portfolio utility** option is checked, there will be three objectives listed: *Net economic value*, *Prediction variance* and *Existence value*. The details of these are explained in the [Risk-averse portfolio utility](#) chapter in the EwE textbook.

**Jobs/catch value:** This parameter implements the *Social value (employment)* objective, and can be obtained from economic analysis, e.g., through value chain analysis. If such data are not available, consider the assumption that the number of jobs is proportional to the value of the catch. The default parameter (1) is based on this assumption.

A tweak: If instead of entering landed value in your Ecopath model, you enter the trophic level of each group in the *Ecopath > Input > Fishery > Off-vessel price* form, the optimization can be for *Trophic level of the catch* instead of for *Social value*.

**Mandated relative biomass:** The default parameter for this parameter is 0 for all groups, which means that by default, the *Mandated rebuilding* will not be considered in the optimization even if there's a weight entered in the *Search objective* spreadsheet. If you want to invoke the objective, change the *Mandated relative biomass* for groups where you want to invoke the *Mandated rebuilding* objective to a minimum acceptable biomass (often called  $B_{lim}$ ) and give considerable weight to the *Mandated rebuilding* objective to make sure that this objective is considered fully.

**Structure relative weight:** This objective is used to implement the *Ecosystem structure* objective, and is by default parameterized with the inverse production/biomass (unit: *year*) for group with a  $P/B$  ( $year^{-1}$ ) lower than  $\sim 5 year^{-1}$ . The objective thus implements one of the ecosystem maturity parameters.

The default values can be replaced, e.g., by other network analysis indicators. An example could

be the trophic level of the group, or it could be indicators such as the number of species in a functional group to bring in more biodiversity aspects.

**Maximum fishing mortality:** This parameter is not linked to any of the objectives, but if a *Max F* is entered on this spreadsheet, the search routine will penalize runs where the *Max F* is exceeded. This parameter can thus be used to reduce the risk of collapse of fished groups.

The default value is set so high ( $1000 \text{ year}^{-1}$ ) that it does not have any impact.

#### Acknowledgement



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## Notes

1. Fletcher, R. 1987. Practical methods of optimization. Wiley-Interscience, New York. 436 p.

# CEFAS Management Strategy Evaluation (CEFAS-MSE)

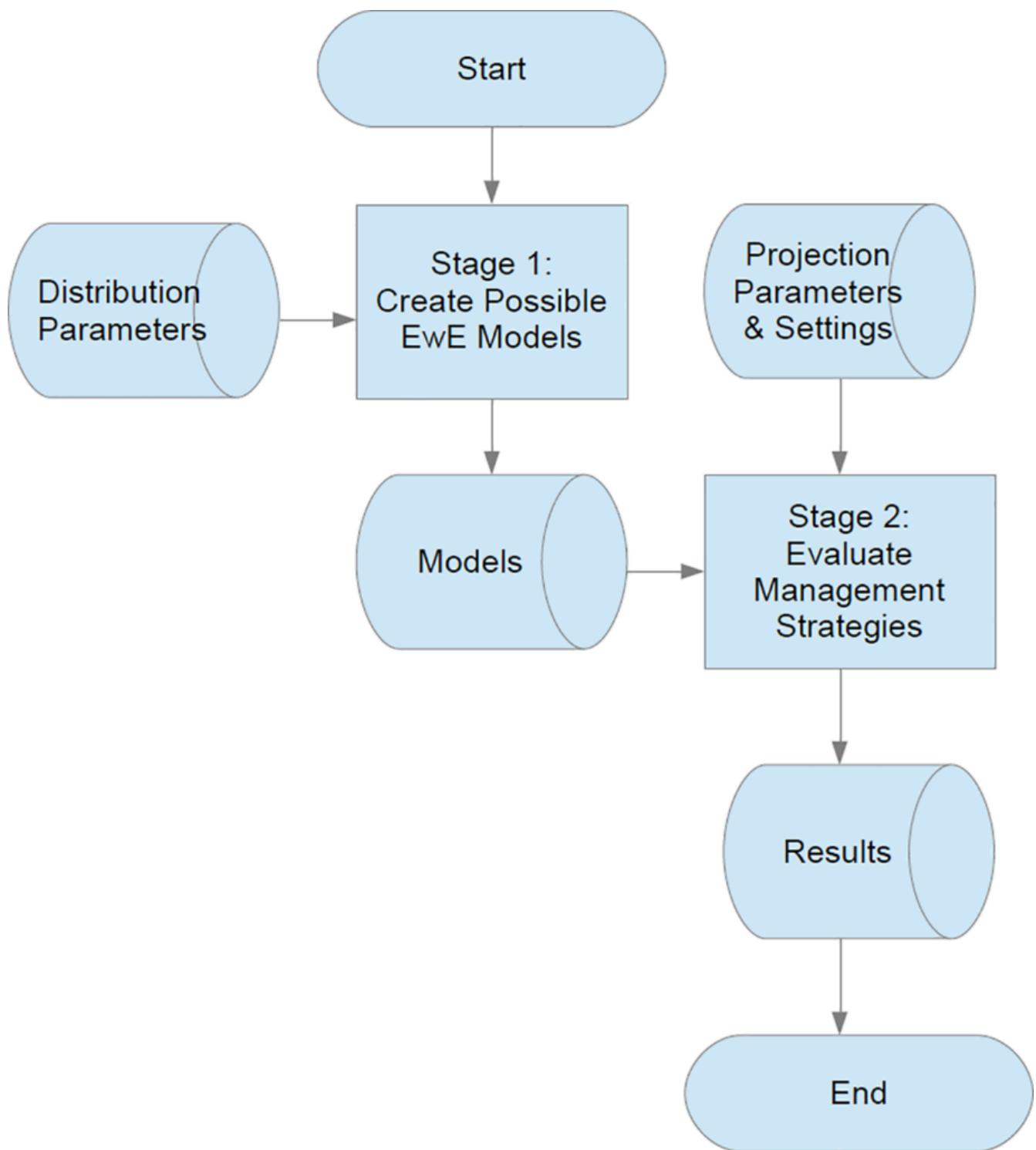
STEVEN MACKINSON; MARK PLATTS; CLEMENT GARCIA; AND CHRISTOPHER LYNAM

## Overview

Management strategy evaluation (MSE) has become a major tool for evaluating and comparing management options, mainly for single-species management. The basic concept in MSE is to set up a basic “operating model” or set of models, then simulate the year-to-year management of model species by first representing estimation of abundances (stock assessments) each year, then application of harvest control rules (HCRs) to set fishing policies within that year. HCRs are basically feedback rules for varying target fishing mortality rates or allowable catches with changes in target species abundance, typically by specifying population sizes below which harvesting should not be allowed and above which harvesting should be at rates that come close to maximizing average long term yield. Alternative HCRs are typically compared over simulations using a variety of performance measures representing fishery values and risk of having dangerously low population sizes due to effects of environmental variation and overestimation of abundance by stock assessments.

EwE has two modules for doing MSE simulations, one developed by Mackinson et al. at CEFAS<sup>1</sup>, and another programmed earlier for EwE6. The CEFAS version aims to represent “output control” of harvesting via quotas or total allowable catches/bycatches, while the older EwE model uses an optimization method called linear programming to find optimum fishing efforts within each simulation year.

This chapter provides a general overview of the MSE structure and components (Figure 1), and details shared by both of the MSE modules. The following chapter provides a bit more detail about the linear programming procedure used to optimize fishing efforts within each year.



**Figure 1. Flow chart showing an overview of the two main stages of management strategy evaluation setup.**

The Ecopath with Ecosim (EwE) CEFAS plug-in has two main stages of execution (Figure 1).

- Stage 1: Create possible EwE Models – uses user-specified probability distributions to sample the input parameters of which an EwE model is comprised, and saves them to disk.
- Stage 2: Evaluate Management Strategies (Figure 2) gets input from the user about Harvest Control Rules, Discards Policies, Quota shares for each fleet, Number of Years to Project, Observation and Implementation Errors, Maximum fractional increase in effort and Biomass limits. Applying these settings, Ecosim is then run for all selected combinations of strategies and models created in stage 1, and providing the results are plausible, they are saved to disk.

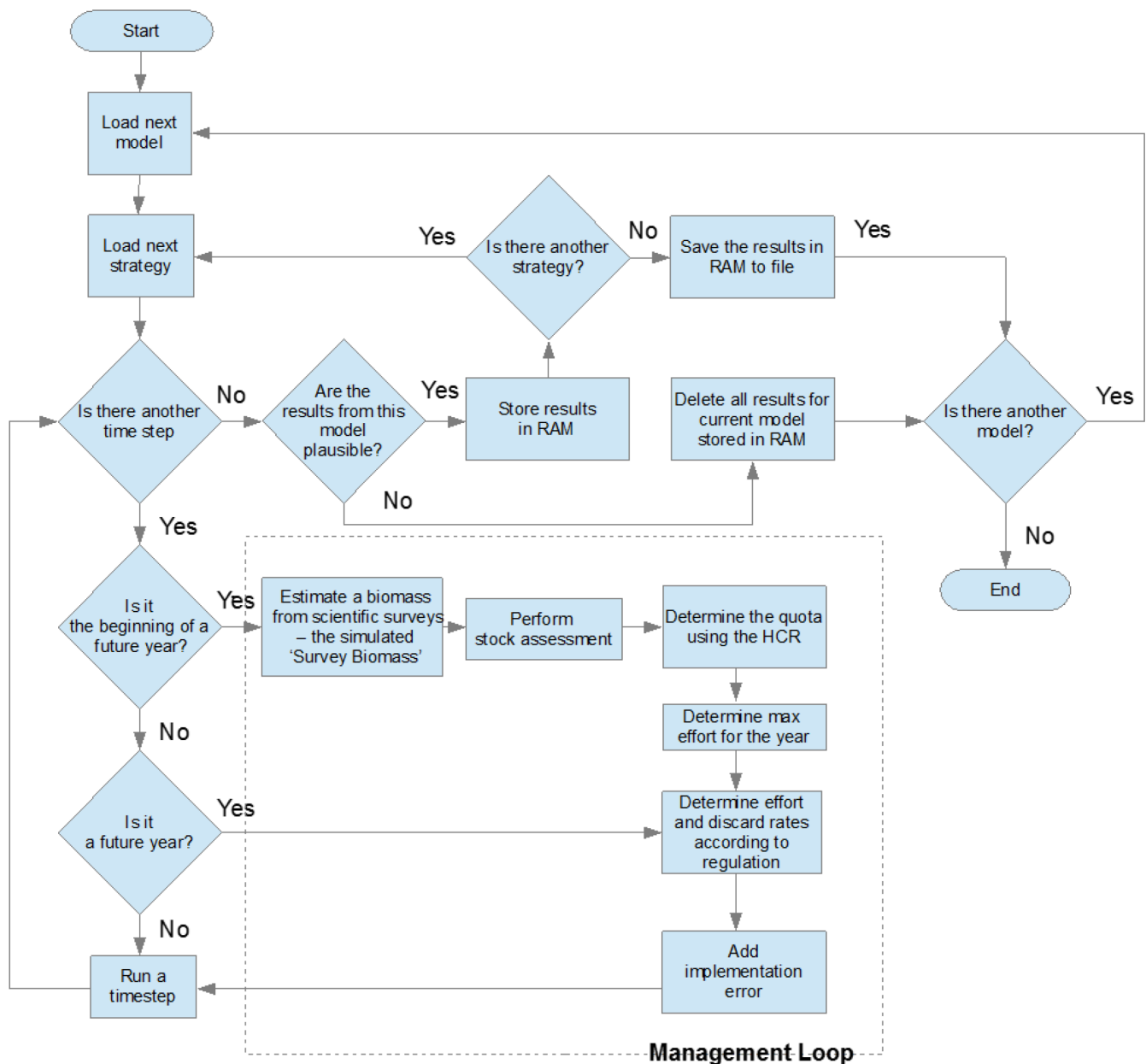


Figure 2. Flowchart for the evaluation of management strategies.

## Creating alternative ecosystem models

The process of creating alternative Ecopath models involves sampling the basic input parameters for biomass, biomass accumulation, ecotrophic efficiency (*EE*), production/biomass (*P/B*) and consumption/ biomass (*Q/B*) parameters using a truncated normal distribution. In addition, the diet proportions for each predator are sampled using a Dirichlet distribution. Together the sampled Ecopath and diet proportions are checked to see that they meet the criteria for  $EE < 1$ , positive respiration and  $P/Q < 0.5$ . The sampling process is repeated until a valid model is determined.

For each of the Ecopath models created, a set of Ecosim parameters comprising of density dependent catchability, feeding time adjustment rate, max relative feeding time, fraction of other mortality sensitive to changes in feeding time, predator effect on feeding time,  $QB_{Max}/QB_o$  and switching power are generated by sampling either a uniform or triangular distribution. Discard survival proportions, or more explicitly, the proportions of discards that survive are sampled for each fleet species combination using a beta distribution. The vulnerability parameters are sampled for all possible interactions, using the formula (Gaichas et al. 2012):

$$v_{rk} = 1 + e^{9(U-0.5)} \quad (1)$$

Where  $v_{rk}$  is the vulnerability,  $r$  is the predator,  $k$  is the prey, and  $U$  is a value sampled from a standard uniform distribution.

A single set of all the Ecopath and associated Ecosim parameters are combined to form a single EwE model. Multiple sets combined form an approximate representation of the probability distribution for all possible EwE parameterisations. By running strategies (see next section) across all these models, strategies are tested for robustness to parameter uncertainty.

## Evaluating the management strategies

Strategies are evaluated by running each one across the entire range of possible ecosystem models to produce a single outcome for each strategy-model pair. If a model produces a biomass trajectory beyond a plausible range for any strategy the model is excluded from the analysis.

The management loop, core to the evaluation, becomes active as soon as the model projects into the future, the methodological steps of which are described below.

## Estimate a biomass from scientific surveys – the simulated ‘Survey Biomass’

At the beginning of the year the average biomass predicted by the model over the previous 12 months is calculated. Observation error sampled from a log-normal distribution parametrised using a user specified coefficient of variation is then added to it, giving an estimate of biomass at the beginning of the year. This is the simulated ‘Survey Biomass’ which is used by the stock assessment (see next section).

## Performing stock assessment

The results of complex assessments (which are not practical to simulate for multiple functional groups in the Ecosim MSE framework) are simulated by approximating the results of stock assessments as a weighted average of the predicted biomass and biomass estimated from surveys (Walters 2004, equations 1-6):

$$B_{t|t} = B_{t|t-1} + K_t^* (B_t^* - B_{t|t-1}) \quad (2)$$

Where  $B_{t|t}$  is the best (minimum variance) estimate of  $B_t$  given all of the data up to time  $t$ ,  $B_{t|t-1}$  is the best prediction of the biomass at time  $t$  given only the data up to time  $t-1$ ,  $K_t^*$  is the Kalman gain and  $B_t^*$  is the simulated “Survey” biomass at time  $t$ . The prediction ( $B_{t|t-1}$ ) comes from Schnute’s generalization of the original Deriso model (Schnute, J. 1985), with a simplified representation of biomass dynamics:

$$B_{t|t-1} = gB_{t-1}e^{-\text{FishMort}-\text{NatMort}} + wR_t \quad (3)$$

$$g = \max\left[0, e^{\frac{\text{Ecopath}_{BA}}{\text{Ecopath}_B} - \text{RecruitOverPop}}\right] \quad (4)$$

Where  $g$  is the growth rate,  $\text{Ecopath}_{BA}$  is Ecopath biomass accumulation,  $\text{Ecopath}_B$  is the Ecopath Biomass,  $\text{RecruitOverPop}$  is the percentage of total population that will recruit, and  $wR_t$  is the biomass recruited estimated using the Beverton-Holt Stock Recruit model:

$$wR_t = \frac{\alpha \cdot S_{t-1}}{\beta + S_{t-1}} \quad (5)$$

$$\alpha = \text{RecruitOverPop} \cdot \text{Start Biomass} \cdot \text{RatioBt} \quad (6)$$

$$\beta = \text{RatioBt} \cdot \text{Start Biomass} \quad (7)$$

$$S_{t-1} = B_{t-1}e^{-Z_{t-1}} \quad (8)$$

Where  $RatioB_t$  is the Ratio of biomass at time to Ecopath base biomass for 50% of recruitment, and  $RecruitCV$  is the coefficient of variation of the actual recruits around the predicted recruits from the stock recruit model.

The Kalman gain is the proportion that the predicted biomass variance ( $Var(B_{t|t-1})$ ) is of the total predicted and observed biomass variances:

$$Var(B_{t|t-1}) = \frac{(RecruitOverPop \cdot RecruitCV)^2}{1 - g^2} \quad (9)$$

$$K_t^* = \frac{Var(B_{t|t-1})}{Var(B_{t|t-1}) + Var(B_t^*)} \quad (10)$$

## Determine the Quota using the HCR

A quota is determined for each functional group that has a HCR using:

$$F_i = \begin{cases} 0, & \text{if } B_{i,t} < B_i^{\min} \\ \frac{B_{i,t} - B_i^{\min}}{B_i^{\max} - B_i^{\min}} \cdot F_i^{\max}, & \text{if } B_i^{\min} < B_{i,t} < B_i^{\max} \\ F_i^{\max}, & \text{if } B_{i,t} > B_i^{\max} \end{cases} \tag{11}$$

Where  $F_i$  is the instantaneous landings mortality rate,  $B_{i,t}$  is the stock assessment estimate of the biomass for species  $i$ ,  $B_i^{\min}$  is the biomass at which the  $F$  from the HCR declines to zero and  $B_i^{\max}$  is the biomass at which the HCR  $F$  arrives at  $F_i^{\max}$ , the maximum  $F$ , which is in many cases is MSY  $F$ .

This  $F_i$  is then converted into quotas for each fleet-species combination using:

$$Q_{i,j}^* = F_i B_{i,t} q_{i,j} \quad (12)$$

Where  $q_{i,j}$  is the share of the quota of species  $i$  assigned to fleet  $j$ .

HCRs can be specified as either Target HCRs or Conservation HCRs:

- Target HCRs – normal HCRs, used as above to determine an  $F$  given the biomass of a functional group.
- Conservation HCRs – calculates an upper limit for the Target HCR  $F$ , so that if it is above Conservation HCR  $F$  the Conservation HCR  $F$  will be used instead.

Both Target and Conservation HCRs can be specified as a traditional HCR (Figure 3) or as a Multi-level HCRs (Figure 4) which allow a greater degree of flexibility in the HCR shape by enabling the

specification of a minimum fishing mortality as well as a biomass level known in the plugin as the “Biomass step” at which the F steps down to the minimum fishing mortality.

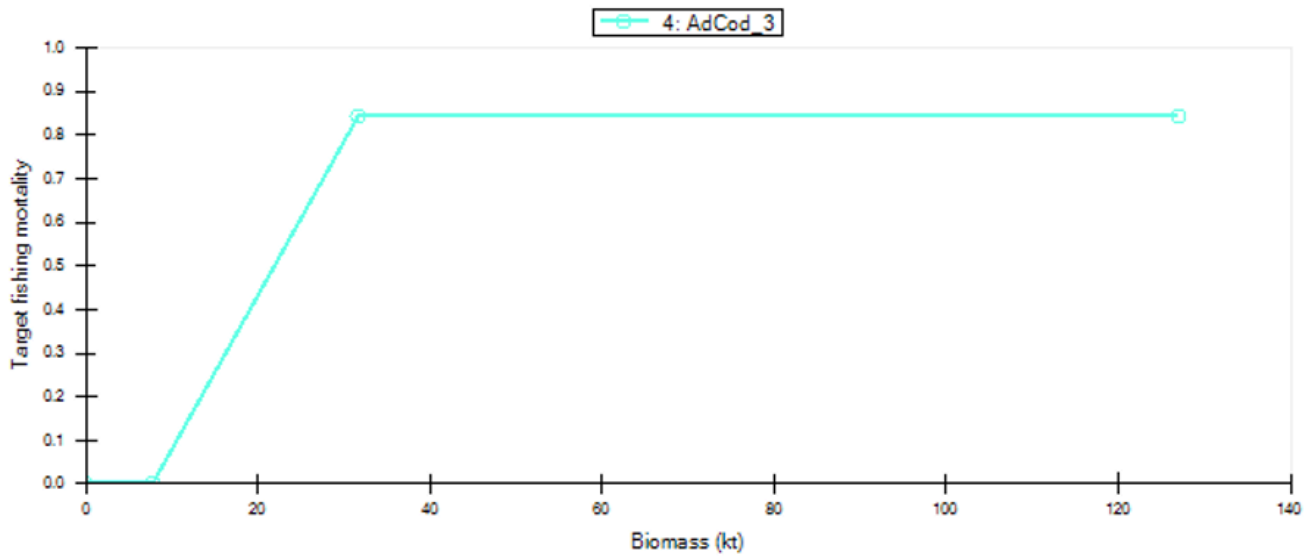


Figure 3. Screenshot of a traditional HCR plotted by the MSE Plugin

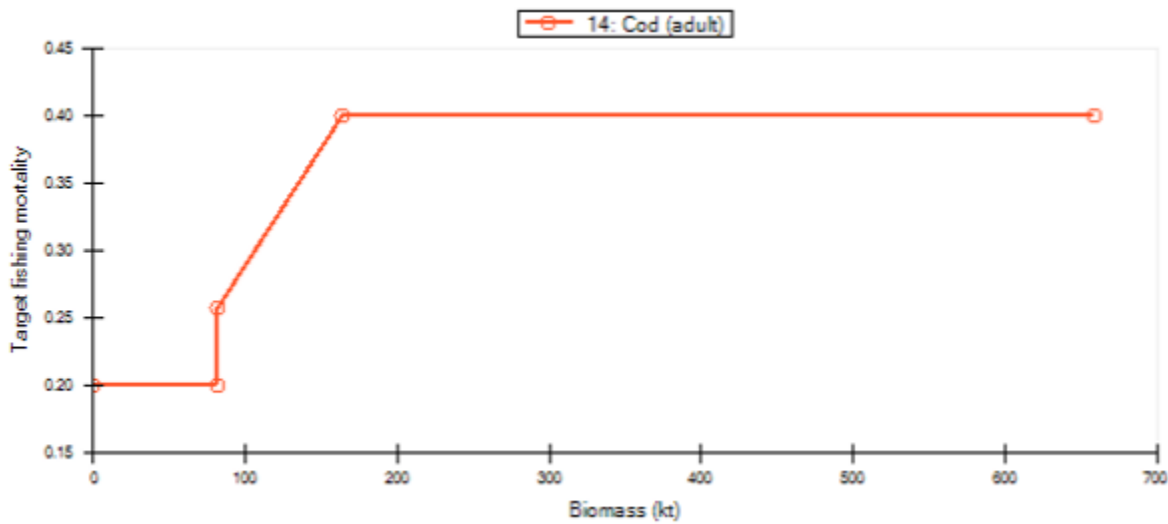


Figure 4. Screenshot of a Multi-level HCR plotted by the MSE Plugin.

## Determine maximum effort for the year

The increase in effort is limited between years to represent realistic limits in the rate of growth of fishing capacity. As a consequence the maximum effort for a given year is calculated as follows:

$$l_j^{max} = l_j^{prev} + l_j^{prev} \cdot \kappa_j \quad (13)$$

Where  $l_j^{max}$  is the maximum effort for fleet  $j$ ,  $l_j^{prev}$  is the effort at last time step of the previous year, and  $\kappa_j$  is the maximum percentage increase in the effort between years.

## Determine relative effort and discard rates according to regulations

Regulations are settings that can be applied uniquely to each fleet and specify whether the fleet is subject to a discard ban or not. They are also a way of specifying how the fleet might behave in response to a discard ban, that is, whether or not they are able to avoid species to prevent them becoming choke species.

Accurately modelling fleet behaviour is extremely difficult. To overcome this problem two regulation methods were specified, the 'Weakest stock' and 'Selective Fishing', both of which represent different degrees of implementation of (or fleet response to) a no discard policy. The 'Weakest stock' represents the possibility that fleets are incapable of being selective of its catch composition while 'Selective Fishing' represents the possibility that fleets are 100% capable of selecting their catch composition. While both scenarios are unlikely to be true, it is a fair assumption that the reality is somewhere between these two possibilities. Consequently the results from these two regulations should be considered together as a range of what is possible given a no discard policy.

### *'Weakest stock' (=Strict no discarding)*

The weakest stock regulation represents a no-discards policy. The effort required to catch 1/12<sup>th</sup> of the quota of each species is calculated each month (each time step) and then set equal to the minimum effort value calculated (the effort required to catch the 'weakest stock'), to ensure that none of the quotas will be exceeded throughout a year. The weakest stock is calculated each month and in some cases may change over the course of a year. This is due to fluctuations in the biomass of each species, causing the effort required to catch its quota to vary; as the biomass of a species increases or decreases, catching it becomes easier or harder respectively and therefore the effort required decreases or increases respectively.

The fleet has no ability to alter its catch composition (i.e. unselective), meaning that the species that requires the least effort to fulfil its quota becomes the bottleneck or ‘choke species’ and determines the amount of effort deployed. Note that species that are defined as non-target species without a quota are exempt from being a ‘choke species’ and can be discarded. Presently, discards are allowed for fish below minimum size if they have been specified in the basic Ecopath model.

### Step-by-step explanation

For each fleet that has a quota for at least one functional group, at each time step:

1. Cycle through each functional group for which the fleet has a quota and calculate the effort required to catch the 1/12th of the functional group’s yearly quota using:

$$E_j^T = (q_{i,j} q_i^T) / (M_i F_{i,j} B_i) \quad (14)$$

Where  $E_j^T$  is target effort,  $q_{i,j}$  is the quota share,  $q_i^T$  is 1/12<sup>th</sup> of the yearly target quota,  $M_i$  is the density dependent catchability multiplier at current timestep,  $F_{i,j}$  is the fishing mortality,  $B_i$  is the biomass.

2. Repeat step 1 with any conservation HCR Fs using:

$$E_j^C = (q_{i,j} q_i^C) / (M_i F_{i,j} B_i) \quad (15)$$

Where  $E_j^C$  is the conservation effort,  $q_i^C$  is the conservation quota.

3. If the target effort is less than the conservation effort use the target effort, otherwise use the conservation effort.
4. From all the efforts calculated for a fleet, apply the lowest to the current time-step. By applying the lowest we ensure that the main objective of this regulation is achieved, to never catch beyond the quota of any functional group.  
If the effort is outside the upper effort limit reset the effort to the upper limit (see section Determine relative effort limits for the year)
5. Set the proportions landed and discarded to the proportion in the EwE model
6. Set the proportion surviving being discarded to the survivability value sampled for the current model

### *‘Highest value’ (=Continued discarding)*

The highest value regulation is a discard permitting policy that assumes that the fleet will catch the entirety of the highest valued quota. The highest value quota in the fleets’ portfolio is calculated at the beginning of each year based on quota and price. The effort required to catch 1/12 of the highest values quota is calculated each month. Any fish caught beyond quota for other stocks are discarded.

## Step-by-step explanation

For each fleet that has a quota for at least one functional group:

1. At the beginning of each year determine which functional group has the highest value quota (where value = price x quota)
2. For each timestep
  1. Calculate the effort that would land the quota

$$E_{i,j}^T = (q_{i,j}q_i^T)/(m_{i,j}^l M_i F_{i,j} B_i) \quad (16)$$

Where  $E_{i,j}^T$  is the effort to catch the target quota,  $m_{i,j}^l$  is the proportion of the catch that is landed, and  $i$  is the index of the highest value group.

2. Calculate the effort required to catch the conservation quota for this highest value group if a conservation quota exists:

$$E_{i,j}^C = (q_{i,j}q_i^C)/(m_{i,j}^l M_i F_{i,j} B_i) \quad (17)$$

3. Let  $E_j = \min[E_{i,j}^T, E_{i,j}^C]$

1. If the effort is outside the upper and lower limits reset the effort to the breached limit
2. For each functional group for which the fleet has a quota:

1. Estimate the catch if the fleet was to fish at the current level for 12 months

$$C_{i,j} = E_j M_i F_{i,j} B_i \quad (18)$$

2. if the catch is greater than the smallest quota from either the conservation and target HCR/prop landed as set in EwE then
  1. Set the proportion landed to quota/catch
  2. Set the proportion surviving being discarded to the value sampled for the current model
3. If the catch is not greater than the smallest quota
  1. Set the proportion landed to the proportion in the EwE model

Note that there are some inaccuracies in the proportions of the catch discarded. These inaccuracies are rooted in the problem of combining discard proportions specified in the EwE model and the discard proportions calculated by the plug-in. The EwE discard rate represents discards for a variety of reasons including catches beyond quota. The MSE Plugin discard rate is calculated dynamically and represents only catches beyond quota. Summing the two would result in a double accounting of discards due to catches beyond quota. Because there is no way of knowing what proportion of the EwE discard rate relates to catches beyond quota, we have no way of knowing what to subtract from the summation of both rates to prevent this.

Because of this a pragmatic decision was made to use only the EwE discard rate for any years where the total catch is below quota, and use the MSE dynamic discard rate for any years where

the total catch is above quota. This has the slight effect of overestimating discards when catches are below quota and underestimating discards when catches are above quota. In further work, we hope to address this issue.

### *‘Selective Fishing’ (=Avoiding discarding)*

The selective fishing is a discard prohibiting policy, which mimics the fleet being able to avoid catching species beyond their allocated quota, by whatever means. Fleets target the highest value quota (as above) and can continue fishing until this species’ quota is exhausted. The ability to be selective only applies to species that have an HCR. Therefore if avoiding the catch of a species that does not typically get assigned a quota is desired, then a HCR with a zero F must be applied to that species.

### **Step-by-step explanation**

For each fleet that has a quota for at least one functional group:

1. Determine which functional group has the highest value quota
2. Calculate the effort that would land the highest value quota

$$E_{i,j}^T = (q_{i,j}q_i^T)/(m_{i,j}^l M_i F_{i,j} B_i) \quad (19)$$

3. Calculate the effort required to catch the conservation quota for this highest value group if a conservation quota exists:

$$E_{(i,j)}^C = (q_{(i,j)}q_i^C)/(m_{(i,j)}^l M_i F_{(i,j)} B_i) \quad (20)$$

4. If conservation quota exists:

$$E_j = \min[E_{i,j}^T, E_{i,j}^C], \text{ else } E_j = E_{i,j}^T \quad (21)$$

5. If the effort is outside the upper and lower limits reset the effort to the breached limit
6. For each functional group for which the fleet has a quota:

1. Estimate the catch if the fleet was to fish at the current level for 12 months

$$C_{i,j} = E_j M_i F_{i,j} B_i \quad (22)$$

2. If the catch is greater than the smallest quota from either the conservation or target HCR/prop landed as set in EwE then

1. Set the proportion landed to quota/catch
2. Set the proportion of the catch that is discarded and dies to:

$$m_{i,j}(d) = (1 - m_{i,j}^l) \cdot (C_{i,j}^L)/(C_{i,j}^S) \cdot (1 - s_{i,j}) \quad (23)$$

Where  $m_{i,j}(d)$  is the proportion of the catch that dies,  $C_{i,j}^L$  is the catch required to land the quota,  $C_{i,j}^S$  is the catch that would have been caught if the fleet had not altered its mortality rate by being selective.

Note: The equation for the *ProportionCatchDying* has the effect of making the

difference between the actual catch and *CatchifNotSelective* to all be discarded and survive, essentially as if it had never been caught. This is not an intuitive approach, but accurately represents the fleet avoiding catching a species once it has landed its entire quota.

3. If the catch is not greater than the smallest quota from either the conservation and target HCR/prop landed as set in EwE then
  1. Set the proportion landed to the proportion in the EwE model
  2. Set the proportion surviving being discarded to the survival proportion sampled for the given model.

Note that in all these cases the quota is the quota as calculated at the beginning of each year; it is not the remaining quota after catches and therefore does not decrease throughout the year. Consequently the relative effort calculated using this quota is the effort that will, based on the biomass and density dependent catchability at the current time-step, catch a proportion of 1/12 (since each time step represents a month) of the quota. Applying these calculated efforts at each time-step throughout the year will catch the entire quota except for when the effort is unable to adequately change due to the maximum change in the effort.

### *'NONE'*

Fleets regulated by 'None' have their effort maintained at a constant level equal to that at the end of the hindcast. Proportions surviving discarding are as sampled (see section [Creating alternative ecosystem models](#)).

### *'No Fishing'*

Fleets with this regulation setting do not fish throughout the entire projection period. This is achieved by setting the efforts for these fleets to zero.

## Add implementation error

Typically the historic difference between catch and quota is used to set implementation error as a proxy. Since fleet behaviour, the regulation settings, conservation quota's and limits to changes in effort already represent many of the mechanisms that create implementation error, a value of zero was used.

Each regulation method produces implementation error for different reasons because fleets respond differently to them. In the case of the “highest value regulation” catches can be less than quota because applying effort to catch the highest value species does not fully utilise another species quota. In other cases though, it can lead to catches exceeding quota because catching the highest value quota results in catching more than the quota of another species. The “weakest stock regulation” tends to lead to underfishing in most cases, because fleets are only able to catch the entire quota of a single species. Similarly, the “selective regulation” also tends to lead to underfishing, because fleets are restricted from landing beyond quota. However, when regulated by either the “weakest stock regulation” or the “selective regulation” for some species there can be slight overfishing. This happens because a small amount of discarding is allowed to occur, meaning fleets need to catch slightly beyond quota to land up to quota (Platts & Mackinson section 5.3).

Note that there are some slight inconsistencies in the way that proportions of the catch discarded are calculated for each regulation method. These inconsistencies are rooted in the discard proportions specified in the EwE model, the discard proportions calculated by the plug-in and the problem of combining them. There are various reasons that a fleet discards: no remaining quota, undersized catch and high-grading being the most significant causes. The values in the EwE model specify as a fixed value the proportion discarded for all these reasons. The plug-in builds on this by calculating the discards dynamically, however this calculation is only of the discards due to no remaining quota. The inconsistencies arise because of the difficulty of combining these two discard proportions in an attempt to account for all elements of discarding while trying to avoid double accounting (Platts & Mackinson section 5.3).

## Handling applied forcing F time series

When forcing F time series are applied in the hindcast of an ecosim model it ends abruptly at the beginning of the forecast, which creates a technical problem for matching a smoothly transition in F. The problem is that the forcing F values cannot be created by multiplying the baseline catchabilities by any combination of fleet efforts. The reason for this is that the forcing Fs commonly reflect changes in the catchabilities and therefore the baseline catchabilities multiplied with the efforts no longer align with them. To solve this problem up-to-date catchabilities must be estimated, but to do this we must make an assumption about how the forced F is partitioned into fleet Fs. The assumption made is that:

$$F_{i,j}^* = \frac{F_{i,j}}{\sum_j F_{i,j}} F_i^T \tag{24}$$

Where  $F_{i,j}^*$  is the partial F which is used to determine an up-to-date estimate of catchability,  $F_{i,j}$  is what the F would have been on group i by fleet j if the effort at the last time step of the hindcast

was applied with the baseline catchability and  $F_i^T$  is the  $F$  at the forcing  $F$  at the last time step of the hindcast.

Since landings and discards can now be calculated on a per fleet basis, updated catchabilities can be calculated using:

$$q_{i,j} = \frac{L_{i,j} + D_{i,j}}{B_i E_j} \quad (25)$$

Where  $q_{i,j}$  is the catchability,  $L_{i,j}$  and  $D_{i,j}$  are the landings and discards respectively of the last time step of the hindcast,  $B_i$  is the biomass at the last time step of the hindcast and  $E_j$  is the effort at the last time step of the hindcast.

## Screening the Results

Before the results of a model are saved to file, a test is performed to check whether the results are plausible. To do this, the biomass trajectories are checked to be within upper and lower biomass bounds. Any model that contains a functional group with a biomass outside these bounds for any strategy has its results discarded.

**Attribution** This chapter is based on the supplementary materials for Mackinson S, Platts M, Garcia C, Lynam C. (2018). Evaluating the fishery and ecological consequences of the proposed North Sea multi-annual plan. PLoS ONE13(1): e0190015. <https://doi.org/10.1371/journal.pone.0190015>. Rather than citing this chapter, please cite the source.

## Notes

1. Mackinson S,Platts M,Garcia C,Lynam C(2018) Evaluating thefishery andecological consequencesoftheproposed North Seamultiannual plan. PLoS ONE13(1): e0190015. <https://doi.org/10.1371/journal.pone.0190015>

# MSE LP Constrained Optimization of Fishing Effort

CARL J. WALTERS

Optimization methods like Ecosim's policy optimization search procedure have been used to find by-fleet fishing efforts that maximize various multi criteria benefit functions for ecosystem management, with criteria ranging from total profits to total employment and maintenance of ecosystem structure. These optimization methods work by running an ecosystem model that includes fishing mortality rates for multiple biomass groups by the multiple fleets, for long enough simulation periods for production and trophic interaction effects to play out. Fishing efforts by fleet are varied across simulation runs so as to seek the effort combination that maximizes the long term benefit function. The result is a vector  $EOPT_j$ ,  $j=1,\dots,nf$ , of optimum long term efforts for the  $nf$  fleets included in the model.

Unfortunately, these optimum long term efforts typically cannot be used directly in management strategy evaluations, since they ignore constraints associated with fishery development (how fast efforts can grow or be reduced) and more importantly typically involve fishing efforts that would cause ecosystem simplification (overfishing of weaker stocks, even use of fleets to cull some species so as to increase productivity of others). In at least some jurisdictions like the United States, there is a strict legal mandate not to allow overharvesting (fishing rate exceeding  $F_{msy}$ ) for any species. Further, in modeling management decision making over time, it is often necessary to represent the use of 'control rules' that prescribe reduced fishing mortality rates for particular stocks when those stocks are below desired reference biomass levels.

A relatively simple linear programming method could theoretically be used to find long-term efforts that are constrained to be at or below the long term optima  $EOPT_j$ , while respecting the relative fishery values represented in the long term optimization and also constraints associated with fishing mortality rate targets or upper limits by species. But more importantly, the same optimization procedure can also be used to set annual effort limits in MSE simulations, as an option to use effort input controls rather than the output (quota) controls assumed in the CEFAS MSE module. This chapter explains the basic linear programming formulation.

Suppose that the fleets harvest  $i=1,\dots,ns$  species (or biomass groups), with each unit of effort for fleet  $j$  causing a fishing mortality rate  $q_{ij}$  on species  $i$  ( $q_{ij}$  is the catchability coefficient for species  $i$  by fleet  $j$ , and is also the Ecopath base fishing mortality rate for  $i,j$ ). Suppose that for each species  $i$ , there is a target or maximum allowable fishing mortality rate  $FTARGET_i$ , summed over all fleets that cause fishing mortality (landings and/or discards) on  $i$ . Suppose that we assign

an ‘importance weight’  $v_j$  to effort by fleet  $j$ , where  $v_j$  reflects the relative value of increasing (or maintaining) effort for fleet  $j$  because of its contribution to overall long term ecosystem value and/or its legal entitlement to fish. Then the linear programming optimization can be formulated simply, as, maximize,

$$\sum_{j=1}^{nf} v_j E_j \tag{1}$$

by varying the  $E_j$  subject to the constraints,

$$EMIN_j \leq E_j \leq EOPT_j \quad \text{for } j=1, \dots, nf \tag{2}$$

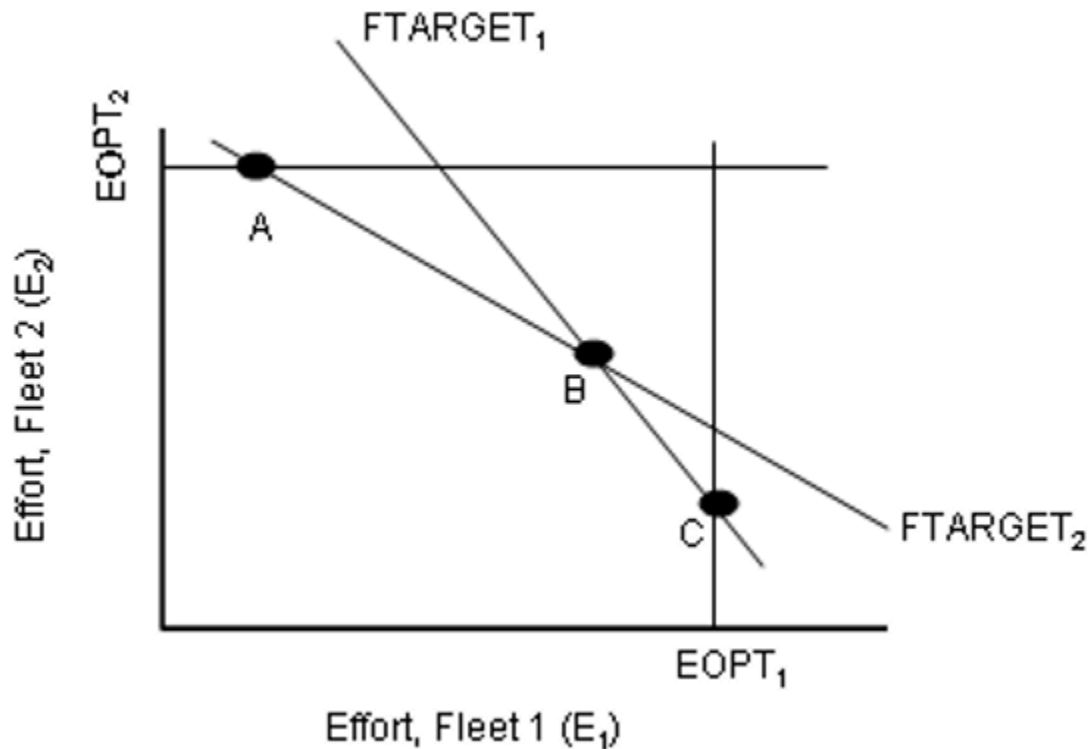
$$\sum_{j=1}^{nf} q_{ij} E_j \leq FTARGET_i \quad \text{for } i=1, \dots, nf \tag{3}$$

That is, try to make the efforts  $E_j$  as large as possible without exceeding  $EOPT_j$ , while allowing efforts of at least  $EMIN_j$  and not allowing the sums of  $q_{ij}E_j$  to exceed target fishing rate for any species  $i$ . An alternative formulation for recognizing fishery development rate constraints would be to replace the first set of  $nf$  constraints (2) with,

$$EMIN_j < E_j < EMAX_j \tag{4}$$

Where the  $EMIN$  and  $EMAX$  are allowed to vary from year to year by limited increments from the previous year’s values, and are not allowed to exceed  $EOPT$ .

Figure 1 illustrates the kind of complicated solutions that can arise from this optimization, even for a very simple case where two fishing fleets pursue just two species, with one fleet having higher catchability for one of the species and the other fleet having higher catchability for the other species.



**Figure 1** – Graphical representation of the linear programming problem. Each line represents a constraint (vertical and horizontal lines are the EOPT constraints, sloped lines are the FTARGET constraints).

The lines in Figure 1 represent effort levels that exactly meet the constraints; efforts must be to the left and below each line in order to be feasible. Thus the feasible effort combinations are only those in the polygon from the graph origin out to the first constraint lines met. Since efforts are to be as large as possible, the solution has to lie along one of those first lines met, and in fact has to be on one of the three vertices marked A, B, C.

- Effort combination A represents Fleet 1 being severely restricted, but Fleet 2 operating at its EOPT.
- Effort combination C represents Fleet 2 being severely restricted but Fleet 1 operating at its EOPT, and
- Effort combination B represents a ‘balanced’ policy choice where both fleets are restricted to below EOPT in order to ‘share the burden’ of avoiding exceeding either of the two FTARGET species constraints.

Which of these three combinations will be chosen (solve the linear programming maximization) depends on the value weights  $v_j$  in (1). If  $v_1$  is much higher than  $v_2$ , combination C will be chosen,

combination A will be chosen if  $v_2$  is larger, and setting the two  $v$ 's equal will more likely lead to the balanced combination B. Note also in Figure 1 that as the  $FTARGET$  constraints are 'relaxed' (increased so the sloped lines move upward and to the right), it becomes more likely that the optimum effort combination will lie near  $EOPT$  for both fleets; likewise, as these constraints are 'tightened' (reduced so the sloped lines move down and to the left), it becomes more likely that the  $EOPT$ s will not be in the feasible region so that the optimum solution will lie either with a mixed effort combination or with one or another of the fleets shut down entirely.

Using the linear programming formulation, it is simple to evaluate the cost, in terms of lost total value, of introducing more restrictive constraints on species harvest rates. In the overall management strategy evaluation setup for Ecosim, the only other way to evaluate this cost is to do policy runs with and without 'weakest stock' constraints on fleet quotas, where all fleets are assumed to share equally in reductions needed to meet such constraints. The linear programming solution may well demonstrate that such equal sharing of the conservation burden is in fact far from optimum.

The linear programming formulation can also be used to demonstrate potential increases in fishery value from selective fishing practices that change the species-specific catchabilities  $q_{ij}$ . For example, if  $q_{12}$  and  $q_{21}$  (catchability of species 1 by fleet 2 and of species 2 by fleet 1) could be greatly reduced in the Figure 1 example, the slopes of the two  $FTARGET$  constraint lines would decrease/increase so as to move the solution toward higher total efforts (move point B up and to the right, closer to the  $EOPT1$ - $EOPT2$  intersection) and thus higher total value.

The key to getting useful results from the linear programming exercise is to make wise choice of the fleet value weights  $v_j$ . One objective option for doing this each year (assuming a management strategy where biomass and perhaps catchability  $q_{ij}$  estimates are being updated regularly) is to set each weight to be

$$v_j = \sum_{i=1}^{nf} P_{ij} q_{ij} B_i \quad (5)$$

where  $P_{ij}$  is the landed price for species  $i$  by fleet  $j$  and  $B_i$  is the current estimated biomass of species  $i$ . Using this formula,  $v_j$  is just the sum over species of predicted catches per effort times prices, so that  $v_j B_j$  represents the (short term) predicted total value of landings by fleet  $j$  and the overall linear programming objective function just becomes the predicted total landed value of all catches.

An option in the management strategy evaluation interface allows users to replace the complicated CEFAS rules for setting quotas for each simulation year to limit mortality rates to acceptable levels, to instead use annual LP optimization each year during each MSE simulation run so as to limit fishing efforts rather than quotas. The basic idea is to replace the single  $EOPT_j$

values in the equations above with time-varying values calculated for each year and group, and to use an annual value for the  $FTARGET_i$  target fishing rate for each group  $i$  for that year, calculated from the estimated biomass of the group and the group's harvest control rule that specifies how target fishing rate for the group should vary with stock size. This option can lead to complex policy changes over time when the  $FTARGET_i$  decrease with decreases in biomasses  $B_i$ .

# Other mortality forcing

A forcing multiplier has been added to the other mortality term of the Ecosim biomass loss equation. This allows the Ecopath baseline other mortality rate to vary over time. This new functionality allows you to simulate a die-off event by changing the baseline other mortality rate.

The biomass loss is now calculated for group  $i$  at time stop  $t$  as,

$$loss_i = Eatnof_i + (M0_i \cdot M0Mult_{it} \cdot (1 - M0Pred_i + M0Pred_i \cdot Ftime_{it}) + Emig_i + FishTime_{it}) \cdot Biomass_{it} \quad (1)$$

Further,  $M0mult_i$  = The new other mortality forcing multiplier for this group at this time step;

$Eatenof_i$  = total biomass lost to predation on this group. This is the result of foraging arena biomass flows, all summed up into one number. This is the actual biomass not a rate;

$M0_i = (1-EE) * PB_i$  (Other mortality rate in the Ecopath Mortalities rates grid);

$M0Pred_i$  = Fraction of other mortality sensitive to changes in feeding time Ecosim > Group info;

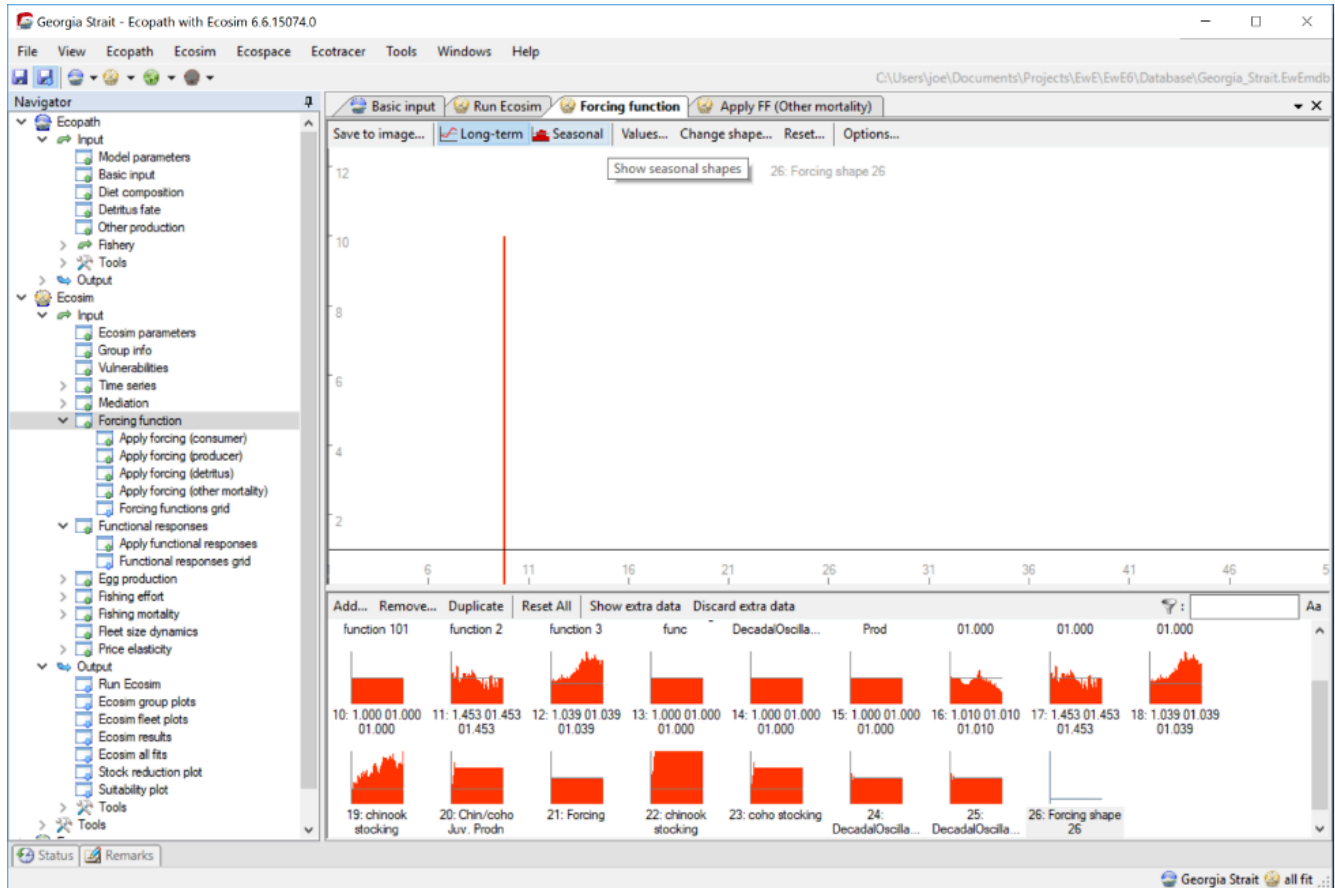
$Ftime_{it}$  = Feeding time predation risk modifier. Usually around 1.0 but gets set at each timestep based on the Ecosim parameters *Minimum foraging time*, Group info *Feeding time adjustment rate* and Group info *Predator effect on feeding time*. If these are all left at their default values then this will be basically 1.0;

$Emig_i$  = Emigration rate from Ecopath > Other Production > Emig. Rate (year<sup>-1</sup>);

$FishTime_i = F$ , fishing mortality rate (year<sup>-1</sup>), again all summed into one rate for this group;

$Biomass_{it}$  = biomass of this group at this time step.

# Discussion



**Figure 1** – Forcing function user interface with an Other Mortality forcing spike defined.

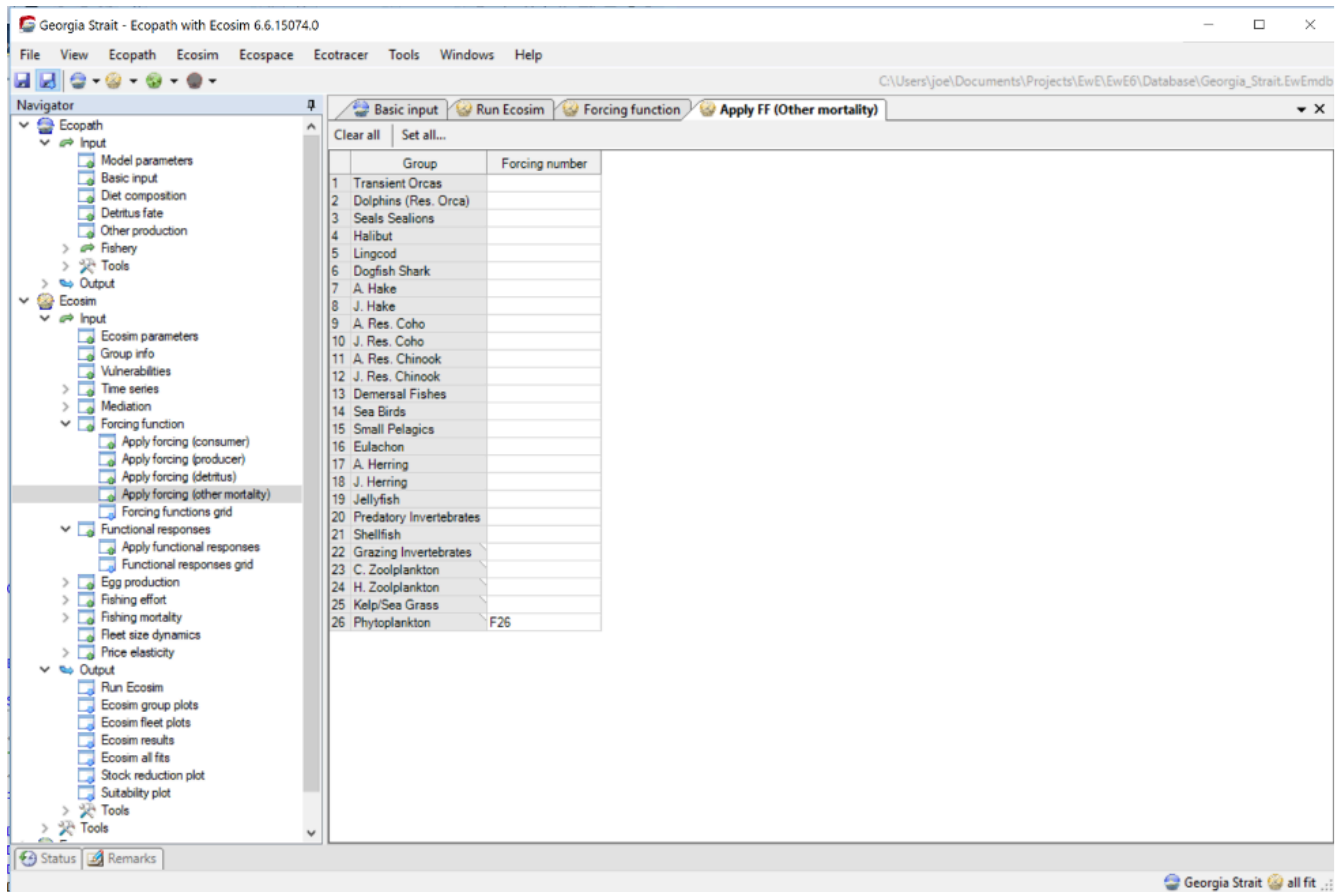
Other Mortality forcing has been implemented as a straight multiplier on  $M_0$  by group in Ecosim, rather than an Environmental Response Function that is applied to  $MO_i$  instead of the feeding rates. This means they fall under the *Forcing function* user interface in Ecosim rather than the *Functional response* form. The creation of an other mortality forcing function, from a time series of environmental data, will have to be done outside of EwE. To do this step, one will need to figure out how large of an other mortality multiplier it will take to achieve the desired mortality in response to the environmental driver. This will vary a lot depending on the base other mortality rate, which is displayed in the user interface under *Ecopath > Output > Mortality rates > Mortalities > + Other mortality rate (year<sup>-1</sup>)* and the growth rate of the group. If either the growth rate is high, or the other mortality is low, the multiplier will need to be large to simulate a large die-off event.

Currently there's no functionality in Ecosim to help you choose a suitable other mortality multiplier for a specific event. To do this you will need to calculate the appropriate size multiplier

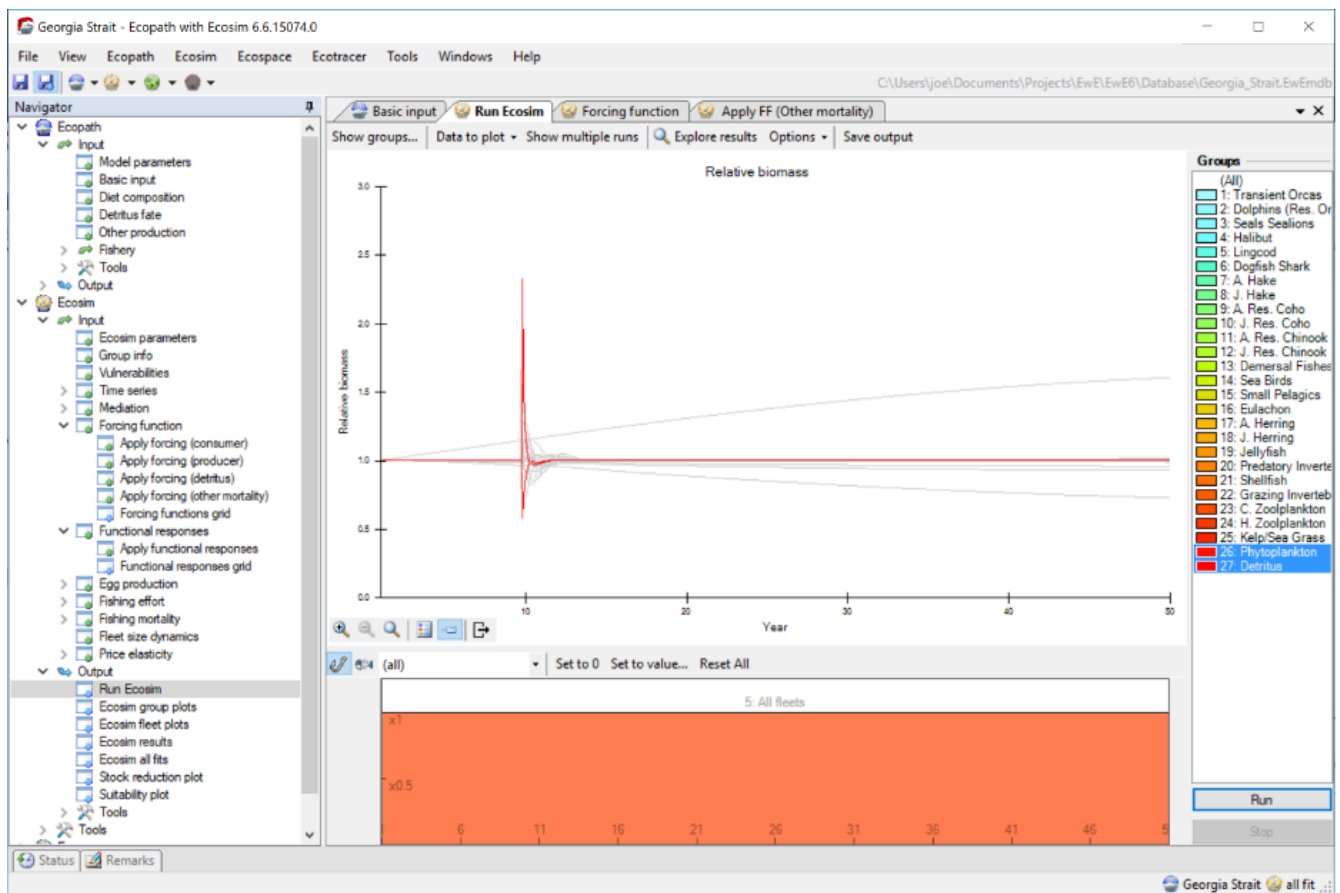
from the Ecopath baseline growth and mortality rates.

For an Other Mortality forcing value to be considered as valid it will need to be non-zero. Zero values will be skipped, and no multiplier will be applied. Values are applied as a straight multiplier, this means values less than one will decrease the Other Mortality rate. This allows you to include a short term spike in Other Mortality without affecting the majority of the run.

The application of Other mortality forcing functions has its own Apply FF (other mortality) user interface grid.



**Figure 2** – Application of an Other mortality forcing function.



**Figure 3** – Ecosim run with a one-month spike Other mortality forcing

The Figure 3 legend points out that one can see the drop in one group and the increase in another – one can, but it is really difficult to see who’s who. You can get around that by using random colours for groups instead of the default colour scale. This is done where you define the groups at Ecopath > Input > Basic Input > Define groups.

# Environmental Productivity

## Primary Production

For primary producers the production is estimated as a function of the producers' biomass,  $B_i$ , from a simple saturating relationship

$$f(B_i) = \frac{r_i B_i}{1 + B_i h_i} \quad (1)$$

where,  $r_i$  is the maximum production/biomass ratio that can be realized (for low  $B_i$ 's), and  $r_i/h_i$  is the maximum net primary production when the biomass is not limiting to production (high  $B_i$ 's). For parameterization it is only necessary to provide an estimate of  $r_i/(P/B)_i$ , i.e., a factor expressing how much primary production can be increased compared to the base model state. If a forcing function is applied to primary production, it multiplies the  $r$  parameter in (1).

## Nutrient Cycling and Nutrient Limitation in Ecosim

Ecosim uses a very simple strategy to represent nutrient cycling and potential nutrient limitation of primary production rates. It is assumed that at any instant in time the system has a total nutrient concentration  $N_T$ , which is partitioned between nutrient 'bound' in biomass versus free in the environment (accessible to plants for nutrient uptake). That is,  $T$  is represented as the sum

$$N_T = \sum_i \eta_i B_i + N_f \quad (2)$$

,where  $\eta_i$  is (fixed) nutrient content per unit of group  $i$  biomass, and  $N_f$  is free nutrient concentration. Then assuming that  $N_T$  varies as  $dN_T/dt = I - vN_T$ , where  $I$  is total inflow rate to the system from all nutrient loading sources and  $v$  is total loss rate from the system due to all loss agents (volume exchange, sedimentation, export in harvests, etc.), and that  $v$  is relatively large,  $N_T$  is approximated in Ecosim by the (possibly moving) equilibrium value  $N_T = I/v$ .

Changes in nutrient loading can be simulated by assigning a time forcing function number to  $N_T$  on the Ecosim > Input > Ecosim parameters form, in which case  $N_T$  is calculated as  $N_T = f_t N_{T0}$  where  $N_{T0}$  is the Ecopath base estimate of  $N_T$  (at the start of each simulation) and  $f_t$  is a time multiplier ( $f_t = 1$  implies Ecopath base value of  $>N_T$ ) supplied by the user the same as any other time forcing

function. Note that under the moving equilibrium assumption, changes in  $f_t$  can be viewed as caused by either changes in input rate  $I$  or nutrient loss rate  $v$ .

The Ecopath base estimate  $N_{T0}$  of total nutrient is entered by specifying the base free nutrient proportion  $P_f = N_f / N_{T0}$  on entry to Ecosim (at Ecosim >Input > Ecosim parameters), from which the Ecosim initialization can calculate  $N_{T0}$  as simply,

$$N_{T0} = \sum_i \eta_i B_i / (1 - p_f) \quad (3)$$

Note here that the units of nutrient concentration are contained in the per-biomass relative nutrient concentrations  $\eta_i$ , and these need not be specified in any particular absolute units. During each simulation,  $N_f$  is varied dynamically by setting it equal at any time to

$$N_T - \sum_i I \eta_i B_i \quad (4)$$

so that accumulation of nutrient in any biomass pool(s) can reduce free nutrient available to promote primary production.

Primary production rates for producer pools  $j$  are linked to free nutrient concentration during each simulation through assumed Michaelis-Menten uptake relationships of the form

$$P/B_j = P/B_{max,j} N_f / (k_j + N_f) \quad (5)$$

where the parameters  $P/B_{max,j}$  and  $K_j$  are calculated as part of the Ecosim initialization using input estimates by the user of the ratios  $P/B_{max,j} / P/B_{Ecopath,j}$  (Ecosim > Input > Group info form). The Michaelis constant  $K_j$  is set so that  $P/B_j = P/B_{Ecopath,j}$  when  $N_f$  is at the initial concentration determined by

$$N_T - \sum_i I \eta_i B_i \quad (6)$$

when all  $B_i$  are at Ecopath base values. One can increase sensitivity to changes in nutrient concentration (make  $P/B_j$  more variable with changes in  $N_T$  and  $N_f$ ) by increasing the input  $(P/B)_{max,j} / (P/B)_{Ecopath,j}$  ratio.

The default free nutrient proportion  $p_f$  is set at unity, which causes  $N_f$  to be virtually constant over time (and hence  $P/B_j$ 's to be virtually independent of nutrient concentration changes). Thus to “turn on” nutrient limitation effects, you must set a lower value for  $p_f$ , (e.g., 0.3) on the Ecosim parameters form.

Be aware that this simple approach to accounting for nutrient limitation can interact with the numerical method used to simulate very fast phytoplankton dynamics over time, to cause numerical instability or “chattering” in the values of phytoplankton biomass. This happens mainly

in cases where  $\rho_f$  is low, so that  $N_f$  is initially small. Then any biomass decline in the system (e.g., due to decline in zooplankton biomass) results in a relatively large increase in  $N_f$ , which can cause an over-response in the calculated phytoplankton biomass(es)  $B_j$ , which then drives  $N_f$  to near zero, which in turn causes too large a decrease in calculated  $B_j$  for the next monthly Ecosim time step.

Chattering can be reduced by using the Runge-Kutta integration option and/or higher  $\rho_f$  settings. Improved numerical integration procedures should allow us to avoid the problem entirely in future Ecosim versions, but at present the computational cost of avoiding the problem by 'brute force' (shorter simulation time steps) would be prohibitively expensive of computer time.

Note further that the single free nutrient concentration  $N_f$  is linked to all primary producer groups in the model (through the uptake kinetics-P/B relationships), implying competition among all plant types in the model for free nutrients. This can cause major shifts in primary production structure over time, e.g., between benthic and pelagic primary production and between grazeable and non-grazeable algal types.

# Results Extractor

## Introduction

The *Results Extractor* was developed in response to the need users have, to easily retrieve data and parameter values from within EwE6. This chapter will explain how to use the *Results Extractor* to do this.

In most cases the language used for titles of options is explained in this EwE User Guide. Only where the language and functionality is new will an explanation be given here.

## Starting the Results Extractor

The Results Extractor can only be started after Ecosim has been run. After Ecosim has been run, it can be started by selecting *Menu > Tools > Results Extractor*. After the *Results Extractor* has been started, you will be presented with a window of checkboxes.

Functional groups only	Predators with attached prey
<input type="checkbox"/> Biomass <input type="checkbox"/> Catch <input type="checkbox"/> Biomass integrated <input type="checkbox"/> Predation mortality <input type="checkbox"/> Fishing mortality <input type="button" value="Change Selection"/>	<input type="checkbox"/> Consumption <input type="checkbox"/> Diet Proportions <input type="button" value="Change Selection"/>
Prey with attached predators	Fleets only
<input type="checkbox"/> Predation mortality per predator <input type="button" value="Change Selection"/>	<input type="checkbox"/> Effort <input type="checkbox"/> Value per fleet <input type="button" value="Change Selection"/>
Fleets with attached prey	Fitting statistics
<input type="checkbox"/> Fishing mortality (Fleet to Prey) <input type="checkbox"/> Catch per fleet <input type="button" value="Change Selection"/>	<input type="checkbox"/> Residuals <input type="checkbox"/> Sum of squares
Indicators	
<input type="checkbox"/> Basic estimates <input type="checkbox"/> Initial fishing mortality <input type="checkbox"/> Key indices <input type="checkbox"/> Initial consumption <input type="checkbox"/> Mortality coefficients <input type="checkbox"/> Respiration <input type="checkbox"/> Initial predation mortality	<input type="checkbox"/> Prey overlap <input type="checkbox"/> Fishing quantities <input type="checkbox"/> Pedator overlap <input type="checkbox"/> Fishing values <input type="checkbox"/> Electivity <input type="checkbox"/> Search rates



Excel     .CSV     Yearly

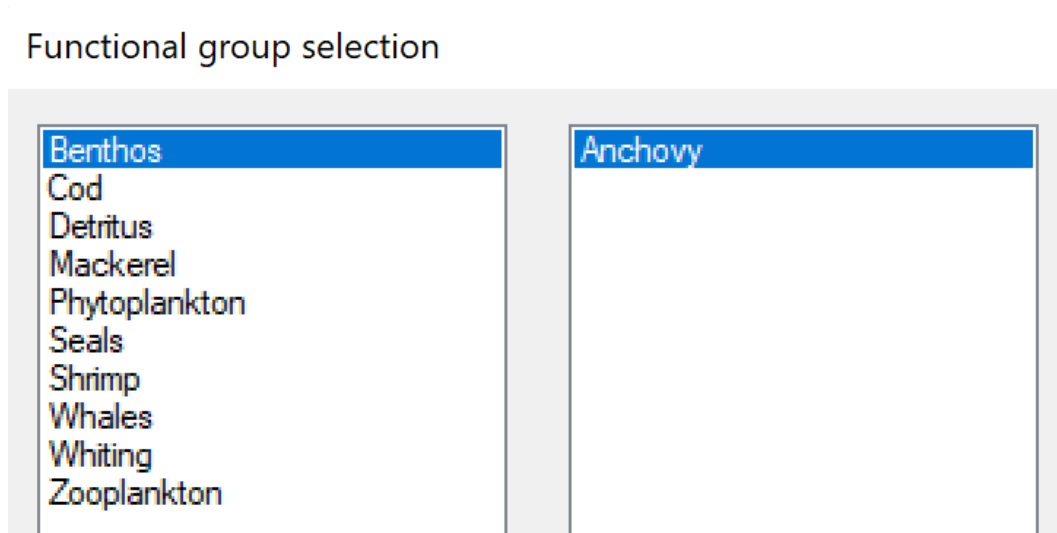
**Figure 1** – Results Extractor start-up interface for settings.

Simply check all boxes for the data and parameter values that you would like to retrieve from within EwE.

## Selection Windows

For some checkboxes a selection window will be opened. Figure 2 shows the selection window that opens when you click on *Biomass*.

These selection windows are how you select which functional groups and fleets you want the data and parameter values for. Simply double click on a group or use the arrows at the bottom to move the groups you want output for.



**Figure 2** – Selection window, here anchovy has been selected.

Some selection windows have three columns like this window that opens when you click on *Consumption* as you need to select both predators and prey. So, when you are getting output for *Consumption*, you first select which predators you are interested, and then for each predator you have selected, you select which prey you want consumption values for.

## Option Groupings

The checkboxes have been visually grouped together in a box. An example is the *Functional groups only* top left section in Figure 1. When the checkboxes that are grouped together in a box that has a *Change Selection* button, it means that whatever selection is made in the selection window, will apply to all other checked options within that group. Selections can also be modified for that group by clicking on the *Change Selection* button to re-open the selection window.

## Biomass Integrated Checkbox

*Biomass integrated* has been introduced as a quantity that can be used to compare two different

management strategies. It works by subtracting the initial biomass from the biomass at each time step to give the change from initial biomass. The area under the time series for change from initial biomass is then calculated.

This is helpful because it indicates not just what the difference is between the initial and final biomass but also incorporates what the biomass has been throughout the time series. The benefit of this can best be seen by imagining two different biomass time series, A and B, each being the result of a different management strategy. Each time series starts and finishes at the same point, but time series A spends most of the time above the initial biomass, whilst time series B spends most of the time below the initial biomass. If we just compared the two management strategies by comparing the final biomass values or initial/final biomass the indicator calculated would suggest no preference between the two strategies, whilst the integrated method would suggest that strategy A would be the preferable strategy as it leads to a higher biomass on average over the time period.

## Consumption

The *Consumption* option retrieves the values required to calculate the rate of consumption of a predator on a prey and outputs the calculated result. Consumption is given as an absolute rate of consumption not a relative rate of consumption. The equation used for calculation is,

$$Q_{ji} = B_j (Q/B)_j DC_{ji} \quad (1)$$

Where  $Q_{ji}$  is consumption rate of predator  $j$  on prey  $i$ ,  $B_j$  the biomass of predator  $j$ ,  $(Q/B)_j$  is the consumption/biomass ratio for predator  $j$ , and  $DC_{ji}$  is the percentage of predator  $j$ 's diet that is prey  $i$ .

## Fitting Statistics

The first option is the residual option. As the name suggests this produces output for the time series of residuals for each functional group. This can be helpful in identifying where in a time series the model differs most from the data.

The second option is the SS or sum of squares option. This gives output of the sum of squares for all function groups as well as an overall SS value for the whole model.

## Yearly

When you select this option the *Results Extractor* will calculate and output the values for each year rather than each month for all time series outputs. This is done by calculating the mean over the year.

## All Options

You can click on this option if you want the *Results Extractor* to retrieve everything (i.e. tick all boxes). After you have clicked on it, you will be taken through all the selection windows required to select all options. When this process is complete, all options will be checked.

## References

The Results Extractor was developed by CEFAS

# ECOSPACE

# Do You Need Ecospace?

Ecospace is a versatile simulation and modeling tool that can be applied to a broad range of research and management questions that require inclusion of a spatially-explicit component. Before deciding to construct a relatively complex spatial-dynamic ecosystem model, one must critically assess whether the complexity of Ecospace is justified to answer the research questions at hand. Simpler tools may exist for applications that do not require explicit or implicit consideration of trophic interactions over time and space. For example, there are many species distribution models capable of predicting past and future spatial patterns of species abundance based solely on oceanographic variables, and there are approaches for simulating spatial harvest policies in single- and multi-species fisheries that do not require modeling complex species interaction processes. Marine spatial planning tools that combine spatial information on basic ecological processes, threats, and socio-economics are also available for conservation planning and optimization (e.g. Marxan with Zones). All these approaches are useful when interactions (trophic and non-trophic) among species are far less important than oceanographic or anthropogenic pressures in determining the spatio-temporal dynamics of species under study.

Yet, Ecospace is one of the few modeling frameworks that can combine species distributions, spatial harvest policies, and spatial planning while considering species interactions throughout complete marine food webs over space and time. Therefore, within a single modeling framework, Ecospace allows accounting for trophic dynamics, seasonality, primary production distributions, ecological niches, habitat suitability, environmental impacts, and species movement related to advection and migration, while also providing a suite of options (notably alternative future scenarios) to evaluate spatial-temporal management of fisheries and other anthropogenic pressures under a context of global change. It can therefore provide comprehensive assessments of ecosystem productivity, cumulative environmental and human impacts, and multi-sector tradeoffs that arise through food-web interactions in scenarios of multiple human activities.

However, the host of capabilities come with an added cost of increased complexity, increased needs for input parameters and validation data with associated uncertainty and data requirements, and computational demands that should be considered carefully prior to choosing Ecospace.

## Adaption

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De Mutsert K, Marta Coll, Jeroen Steenbeek, Cameron Ainsworth, Joe Buszowski, David Chagaris, Villy Christensen, Sheila J.J. Heymans, Kristy A. Lewis, Simone Libralato, Greig Oldford, Chiara Piroddi, Giovanni Romagnoni, Natalia Serpetti, Michael Spence, Carl Walters. 2023. [Advances in spatial-temporal coastal and marine ecosystem modeling using Ecopath with Ecosim and Ecospace](#). Treatise on Estuarine and Coastal Science, 2nd Edition. Elsevier.

# What Transfers from Ecosim to Ecospace?

Ecospace inherits settings, parameters, and data from Ecosim (which in turn has inherited some parameter values from Ecopath), and requires expression of additional parameters that explain how the food web and fisheries utilize space. But Ecospace cannot use all Ecosim values, but only parameters that either do not have an explicit spatial component (such as vulnerability settings, mediation effects and environmental response functions) or that Ecospace can spatialize (such as total functional group biomasses and fishing effort intensity). Driver and reference time series in Ecosim do not transfer to Ecospace as these time series lack a spatial component explaining how their impacts are distributed, and Ecospace does not have sufficient basic structure to spatialize these drivers. Instead, Ecospace requires the user to re-express these drivers and reference time series as explicit maps that have both spatial distribution and magnitude patterns.

## Biomass

The total biomass per functional group is used from the base Ecopath model at initialization. During the initialization of a run, Ecospace will distribute the functional group biomasses based on the HFC model settings. While the model runs, dynamic food-web processes and other effects will take place and influence species distributions<sup>1</sup>.

## Biomass Forcing Time Series

Ecosim biomass forcing time series inputs can be used to force the biomass of Ecospace. When this feature is enabled the spatially averaged biomass predicted by Ecospace will be equal to the Ecosim forced biomass from the forcing time series at the current time step. The spatial distribution of biomass will still be predicted by the Ecospace dispersal model.

## How it Works

During the initialization of Ecospace the Capacity Model sets the capacity of each cell based on either the Foraging Response or the Habitat Base Foraging settings. Then the Ecopath biomass is spatially distributed across the map using the cell capacity and or the migration preference of

each cell as a weighting factor. At the end of the initialization the spatially average biomass of Ecospace will equal the baseline Ecopath biomass.

When the Ecosim biomass forcing is enabled the biomass from the time series will be distributed across the map using the current biomass distribution pattern. This maintains the spatial distributions predicted by Ecospace but overrides the biomass in a given cell.

This takes the form,

$$B_{ijk} = Bf_{kt} \frac{B_{ijk}}{\bar{B}_k} \quad (1)$$

where  $B_{ijk}$  is the biomass in row  $i$  column  $j$  for group  $k$ ,  $Bf_{kt}$  is the time series forced biomass for group  $k$  at time step  $t$ ,  $\bar{B}_k$  is the mean Ecospace biomass of group  $k$ .

## How to Use It

Load time series data containing biomass forcing into Ecopath via the Ecosim Time series interface. Only time series data define as Biomass forcing (-1) will be used to force the Ecospace biomass. This makes the forcing data available to Ecospace but by default it will not be enabled. To enable it check the Use Ecosim biomass forcing check box on the Ecospace parameters interface, under the Time Series heading. If no forcing data is loaded this check box will be grayed out. You can turn individual forcing time series on or off via the Ecosim Time series interface.

## Fishing Effort

The magnitude of fishing effort is inherited from Ecosim and is spatially distributed with the dedicated Ecospace gravity model<sup>2</sup>. Effort distributions are thus an Ecospace output, as are fishing mortality estimates (see 1.4.6). Note that Ecospace does NOT use Ecosim fishing mortalities, as it cannot predict where these mortalities might occur.

## Vulnerabilities

Ecospace will use the vulnerability settings of Ecosim. Low vulnerabilities for a given predator imply that it is close to its carrying capacity, hence limiting how much the predator's consumption

can increase if it should become more abundant. Note that vulnerabilities fitted in Ecosim assume spatial homogeneity, which becomes a less appropriate assumption for Ecospace maps that strongly partition predator and prey. In Ecospace, a species can be confined in small core areas depending on their habitat preferences (e.g., defined depth ranges) and area occupancy can change dynamically in response to predator and prey dynamics in which, when there is a match of distributions of either their predators or the fisheries, the species can have a higher encounter rate and mortality. There is currently no option in the software to perform the vulnerability parameter fitting, as in Ecosim, using Ecospace dynamics.

## Mediation Effects

In Ecosim, inter-species mediation effects are applied to the modelled domain as a whole<sup>3 4</sup>. In Ecospace, these effects play out in each individual Ecospace cell.

## Environmental Responses

Both Ecosim and Ecospace offer the ability to express functional group sensitivities to environmental conditions. The sensitivities are defined via environmental response functions<sup>5</sup>, definitions that are shared between Ecosim and Ecospace.

In Ecosim, environmental conditions are expressed as time varying forcing functions that represent environmental variables for the modeled area as a whole. In Ecospace, environmental conditions are expressed as maps that indicate both magnitude and distribution of an environmental variable, and these maps can be made time varying via the spatial temporal data framework<sup>6</sup>.

There is no satisfactory way to internally convert non-spatial environmental driver forcing functions in Ecosim to their spatially explicit counterpart in Ecospace. There is also no satisfactory way to ensure that the same environmental conditions are adequately represented in both Ecosim and Ecospace. Therefore, the EwE software is not able to transfer applied environmental drivers from Ecosim to Ecospace. Users therefore must configure environmental driver data in Ecosim and Ecospace separately.

# Adaption

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# Ecospace Workflow

There are numerous ways to develop an Ecospace model, all of which have in common that the first step should always be to ensure that a spatially-explicit ecosystem model is actually required to evaluate the research questions at hand. With that being the case, the same three-step process to get started is

1. develop and balance an Ecopath model;
2. calibrate the balanced model in Ecosim; and
3. define the spatial model domain in Ecospace.

The core of the Ecospace workflow begins with a balanced Ecopath model. Thus, once the research questions have been clearly defined, the first step is to develop (or adopt) an Ecopath model. See Heymans et al. <sup>1</sup> for the best practices in developing a balanced Ecopath model and Ainsworth and Walters <sup>2</sup> for the most common mistakes to avoid when using EwE. After the Ecopath model is balanced, the best practice is to use the Ecosim temporal simulations and its calibration capabilities as the ‘go-to’ calibration method prior to building an Ecospace model. This approach allows one to assess the capabilities of the model to represent past dynamics under past forcing conditions (hind-cast calibration) and assess the impact of the strength of the prey-predator interactions (or vulnerability parameters) prior to expanding to the more complex Ecospace module. This also helps provide an understanding for the main temporal drivers of the system and their impacts. The current and primary benefit of using Ecosim to calibrate the model is that calibration has yet to be included in Ecospace. There are more informal ways to ‘visually’ calibrate the spatial model (see [Spatial Model Skill Assessment](#)), but there has yet to be a tool developed within the software to systematically calibrate an Ecospace model <sup>3</sup>.

Many recent examples show the implementation of the Ecosim module of EwE for calibration of time-dynamic models (e.g., <sup>4 5 6 7 8 9 10 11 12 13 14</sup>).

The general method for calibration using the Fit to Time Series module in Ecosim and detailed methods using this tool have been well-documented <sup>15 16</sup>. However, when a traditional fit cannot be achieved due to lack of time series data, exploratory analyses to determine the uncertainty associated with changes in vulnerabilities is recommended (e.g., Rehren et al. <sup>17</sup>).

The primary goal of fitting the Ecosim model to time series data is to evaluate if the model can reproduce historical patterns while refining key parameters, such as the vulnerabilities <sup>18</sup>. Ecosim simulations are especially sensitive to the ‘vulnerability’ settings, which incorporates density-dependence by representing behavioral ecology responses by prey that can limit predation

impacts and access to prey food resources, and expresses how far a group is from carrying capacity<sup>19</sup>.

Fitting a model to data is a process that usually involves an iterative approach, using long-term fisheries, biological, and environmental data together with vulnerability settings to evaluate which combination of data and vulnerabilities minimizes residuals relative to observations calculated during the fitting procedure. This calibration process also allow for evaluation of model sensitivity to forcing functions and vulnerability setting, and can provide a priori information on how the user should conduct a model sensitivity analysis (usually using the built-in Monte Carlo routine plugin).

The data to incorporate into the calibration process cannot be predefined, and ultimately depends on data availability for the modelled ecosystem. A general rule of thumb is to have as long a reference period as possible to capture historical disturbance patterns and productivity shifts that may have occurred through both natural and anthropogenic fluctuations. Moreover, we can reflect data quality and error in the model fitting process. We can weigh the contributions made by different species to the goodness of fit term differently to reflect data quality. After defining what observational data to use for calibration, the sum of squared model deviations (SS) and Akaike Information Criterion (AIC) values should be used to find the most parsimonious model configuration that captures the most variation of the historical period in consideration<sup>20 21</sup>. Calibration in Ecosim is not required for running Ecospace, but if done, the model is more reliable and interpretable, and more likely to lead to temporal dynamics in Ecospace for most species and functional groups, which are similar to the underlying Ecosim model.

## Adaption

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# Movement

In Ecospace, the movement of organisms across space can be realized through dispersal, migration and advection<sup>1 2 3</sup>

## Dispersal

Dispersal is the pseudo random movement of wandering. While dispersing, species in Ecospace by default have simple random movement. But an option is to have biased movement, with a higher chance of moving to a neighboring cell if feeding is better, and the risk of predation is lower. This is called Cell fitness, or the ratio between the ability to feed versus the risk of predation in a cell<sup>4</sup>. The main parameter to regulate dispersal is the Dispersal rate of a functional group. This is the absolute value of average individual annual movement distances as a result of random movements. The default value is 300 km year<sup>-1</sup> for all groups apart from detritus groups (with a default of 10 km/year). General values can be assumed to be of different relative magnitudes (e.g. 3, 30 and 300 km year<sup>-1</sup>) representing essentially non-dispersing, and demersal and pelagic groups, respectively. It is recommended to use these general assumptions unless there are good reasons to believe otherwise. As is sometimes incorrectly quoted, Martell et al.<sup>5</sup> do not provide a way to calculate dispersal rates from swimming speeds. Instead, see Bradbury et al.<sup>6</sup>.

An individual based model (IBM) to estimate Ecospace dispersal rates from movement parameters has been implemented as a Shiny app. See the dispersal app at <https://ecopath.app/> and the User Guide [chapter](#).

Other parameters that influence movement are Relative vulnerability to predation (or grazing) outside their preferred habitat, which allows for increasing the strength of the prey-predation interaction outside the preferred habitat of a species grouping (Martell et al., 2005). In addition, the Relative movement to cell fitness or local fitness (per capita gain from net food intake minus predation mortality) is an experimental feature in EwE 6.6. Species move faster when a cell is less fit, trying to find food, avoiding predation, and improving chances of running into areas where conditions are better.

This Relative movement to cell fitness field partially replaces the Relative feeding rate in bad habitat, where dispersal rates were assumed to differ between preferred and non-preferred

habitats, with higher values within non-preferred habitats than in preferred habitats. Organisms outside their preferred habitat may be conceived as less likely to consume as much appropriate food as within preferred habitat, due to the unavailability of such food or the danger associated with foraging. Organisms in non-preferred habitats will strive to leave these, and attempt to return as rapidly as possible to their preferred habitats. Ecospace users can reduce the feeding rate of ecosystem components down to 0.01 times the Ecopath baseline (i.e., the Q/B value). This mechanism can be turned off by setting the feeding rate multiplier equal to unity (1). Note that this mechanism has been integrated with the habitat foraging capacity model (EwE 6.4+). The default value for this multiplier is 5.0, the upper limit 10. A value of 1 will make this mechanism inoperative. Currently, this only applies to multi-stanza groups when running the IBM model<sup>7</sup>; (and see below).

## Migration

This type of movement concerns directed forced movement unrelated to habitat or feeding preferences to represent ontogenetic annual migrations (e.g.,<sup>8</sup>). A way to incorporate this movement is through migration target maps (in EwE 6.5+). Weight maps indicate migratory preferred areas for each month. Migration is different to dispersal, but migrating groups disperse during migration and when they reach their migration areas. To represent migrating species that leave the model area, users can designate a cell to be 'outside' and give this cell independent dynamics.

## Advection

Ecospace also includes a rudimentary advection model to capture current drift of organisms like phytoplankton that tend to be transported with surface currents. Currents can be entered (monthly), can be calculated, or can be driven by an expert model. The advection field is calculated from wind/geostrophic forcing patterns for surface currents by solving the linearized pressure field and velocity equations across the Ecospace grid. Users can specify which groups are subject to advection velocities. Advected movement adds to dispersal and migration. Advection data is entered as u and v fields (x and y velocity), in cm/sec, where positive u = east, and positive v = south (not north, as is the common convention in current models).

While the simple built-in advection model is useful for testing purposes, we recommend that users obtain advection fields from 3D hydrodynamic models, and import those via the spatial temporal data framework for advanced applications.

Advection also affects environmental contaminant distributions in the EwE Ecotracer model<sup>9 10 11</sup>. For an illustrative example of the combined use of Ecospace, advection and Ecotracer see Tierney et al.<sup>12</sup>.

## Adaption

The chapter is in part adapted, with permission, from:

De Mutsert K, Marta Coll, Jeroen Steenbeek, Cameron Ainsworth, Joe Buszowski, David Chagaris, Villy Christensen, Sheila J.J. Heymans, Kristy A. Lewis, Simone Libralato, Greig Oldford, Chiara Piroddi, Giovanni Romagnoni, Natalia Serpetti, Michael Spence, Carl Walters. 2023. [Advances in spatial-temporal coastal and marine ecosystem modeling using Ecopath with Ecosim and Ecospace](#). Treatise on Estuarine and Coastal Science, 2nd Edition. Elsevier.

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# Dispersal Rate IBM

CARL J. WALTERS AND VILLY CHRISTENSEN

## An Individual-Based Model and Utility for Estimating Diffusive Mixing Rates of Organisms Between Spatial Model Cells

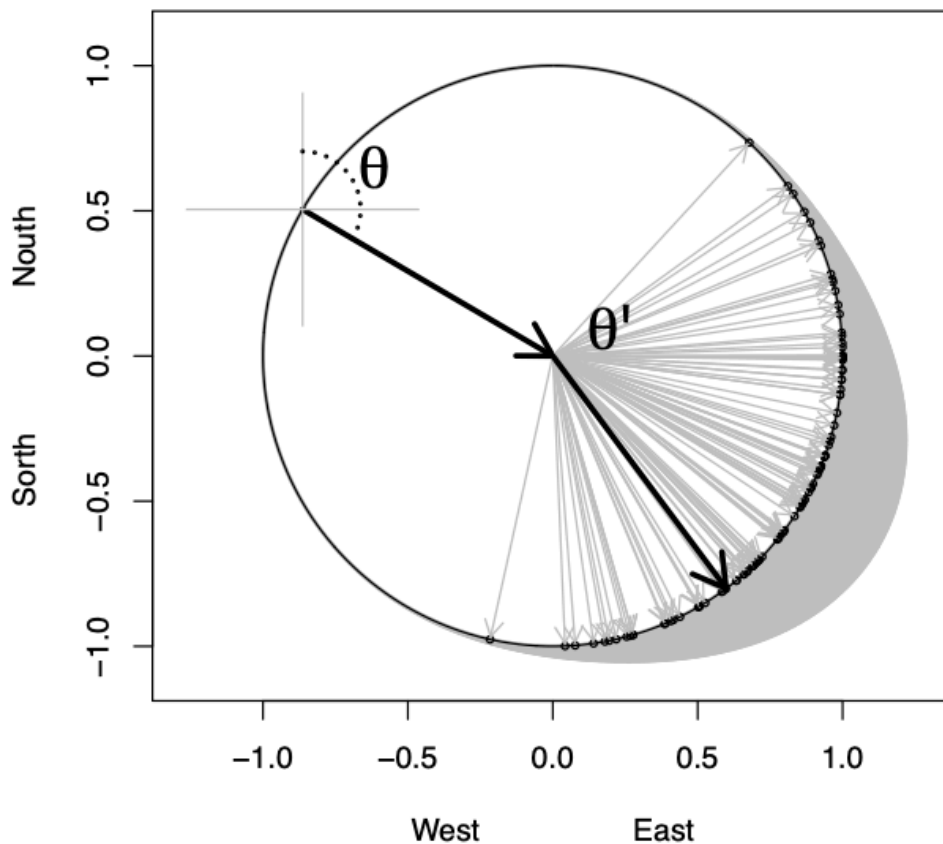
Spatial models typically need to simulate diffusive spread of creatures between spatial model cells or grid points. We usually approximate this spread by estimating instantaneous movement rates between adjacent discrete model grid cells; in terms of mathematical diffusion theory, such rates are approximations for  $D/L^2$ , where  $D$  ( $\text{km}^2/\text{time}$ ) is the theoretical diffusion coefficient for the diffusion process and  $L$  is the discrete cell length in km.

Instantaneous mixing rates for any particular creature depend on three factors: its swimming speed, how frequently it makes turns (changes in direction), and how much change in direction it is likely to make each time it turns. Mixing rates are predicted to increase with increasing swimming speed, but to decrease with increasing number of turns per day and increasing variability in the movement direction after each turn. There is no simple theoretical way to integrate these three effects into an instantaneous mixing rate estimate except under very restrictive assumptions about how the creature changes direction at each turn.

The Ecospace dispersal estimator Shiny app at [Ecopath.app](https://ecopath.app) generates estimates of instantaneous mixing rates by the simple tactic of simulating movement over one day of a large number of individual fish that are initially distributed at random over one spatial model grid cell, while counting how many of these individuals cross the model cell boundary at least once over the day. The approximate instantaneous mixing rate per day is then just the number of fish that exit the cell divided by the number of fish simulated.

Swimming speed is typically predictable from body size (many organisms swim at about one body length per second for some proportion of each day), but the number of turns per day and how much direction changes at each turn may vary a lot depending in particular on how the creature searches for food, (e.g., whether it turns more frequently or tends to turn more sharply when it is in an area of high food concentration). Absent direct sample data on fine-scale movement patterns, you can at least obtain some range of credible estimates for the instantaneous daily mixing rate by varying the number of turns (or distance between turns), and how much variability there is from turn to turn in the change in direction.

For each simulated movement step, each creature is assigned a random movement direction measured by the creature's angle  $\Theta$  in the X-Y plane (see Figure 1), and it moves a distance  $D_{move}$  set by its movement speed and number of turns per day. Using a wrapped normal distribution, the movement angle  $\Theta'$  for its next move is set as  $\Theta' = \Theta + N(0, sd)$  where  $N(0, sd)$  is a normally distributed random deviate with mean 0 and standard deviation  $sd$  (radians). This method of generating random changes in direction results in creatures tending to keep going in the same direction if  $sd$  is small, (e.g.,  $sd = 0.2$  [ $11^\circ$ ]), and to make completely random direction changes at each move when  $sd$  is high, (e.g.,  $sd = 2$  [ $115^\circ$ ]). For each model run, one of the individual movement patterns over the day is plotted, and model users are encouraged to do runs with multiple  $sd$  values so as to see the effect of the  $sd$  parameter on predicted movement trajectories. Note that similar results are obtained if there are many daily moves with low  $sd$  or fewer moves with high  $sd$ .



**Figure 1.** Direction of a moving organism at any time is measured by its angle  $\Theta$  relative to north,  $\Theta = 0.0$  being due north. Change in direction for its next movement to angle  $\Theta'$  is modeled with a normal distribution (relative probability shown in gray around the circle defining possible positions after the next move) with mean zero and standard deviation  $sd$ . Example shows random new movements sampled with standard deviation = 0.5 radian ( $29^\circ$ ), and a single sample realization  $\Theta'$ .

Note that estimates of instantaneous mixing rates from the IBM simulations can be badly biased

downward for creatures that have high daily movement speed  $S$ , when the model cell length  $L$  is small compared to this speed, in particular if  $S/L$  is larger than about 0.5, (e.g., a tuna moving 80 km/day over a model grid of 20 km x 20 km cells has  $S/L=4$ ). In such cases, the exit probability per day can approach 1.0. But the daily exit probability is only a good approximation for the daily instantaneous movement rate when this probability is very low, 0.05 or less.

## Assumptions and Parameters

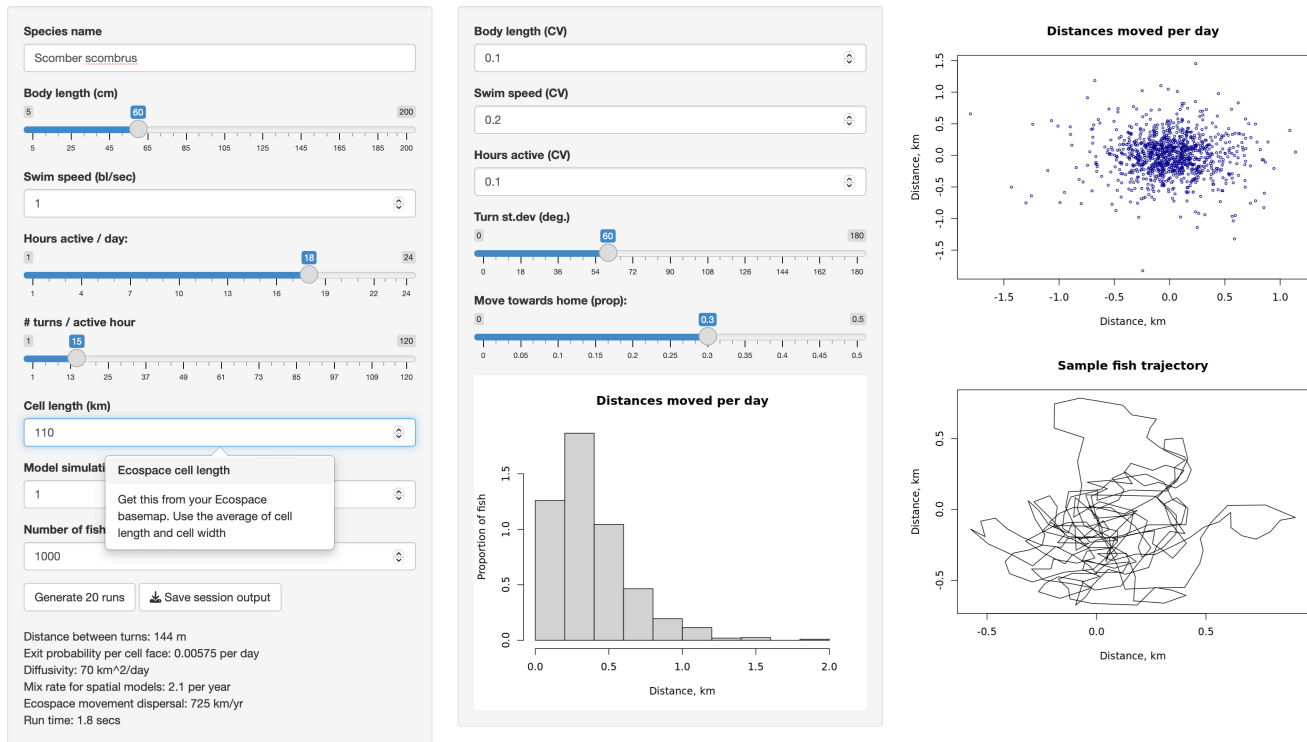
The utility is based on assumptions that,

- A swimming organism tends to move in a given direction with a swimming speed that is a function of its body length. Swim speed is usually a linear function of body length ( $bl$ ). Typical numbers are 1  $bl$ /sec when searching, 2  $bl$ /sec when hunting actively, and 0.5  $bl$ /sec when slowing down to feed. The swim speed is, however, species depending, and will be much lower for, e.g, ambush predators.
  - Parameter: body length (cm).
  - Parameter: CV of body length (Coefficient of Variation = standard deviation / mean)
  - Parameter: swimming speed (body lengths per second).
  - Parameter: CV of swimming speed
- The organism will change direction occasionally, notably after encountering potential prey and after being exposed to predators, so it will, e.g., be fewer turns per hour for a piscivore compared to a planktivore. How often does an organism make a turn? Run time is almost proportional to number of turns/hour.
  - Parameter: number of turns per active hour
  - Parameter: standard deviation of turns (in degrees)
- The organism is active for a number of hours each day. Some species may swim for 24 hours per day, with only ultra-brief micro sleeping episodes, others will build a cocoon and sleep the night away, and many are only active around dawn and dusk. Hence, the number of hours active per day is very species dependent. Run time is almost proportional to number of hours active per day.
  - Parameter: number of hours active per day.
  - Parameter: CV of number of hours active
- Some organisms may have a home base or range, and a propensity to stay near home
  - Parameter: proportion of moves that are towards the home base or range
- Cell length, Ecospace does not keep track of where species are within cells, therefore the relationship between dispersal rate and cell size matters. The cell length parameter is easily

available from the base map knowing the latitude and cell size. Use the average of cell height and cell width.

- Parameter: cell length (km)
- If cell size is small and swim speed is high, it may be necessary to simulate only a proportion of a day. The output is sensitive to this parameter setting.
  - Parameter: Model simulation time (prop. of day)
- An IBM model, models, well individuals. By default the dispersal of 1000 individual organisms is simulated. This typically takes 1-2 seconds on the server (including transmission), so reasonably fast. Simulating more fish will take longer and not necessarily change the results.
  - Parameter: Number of fish
- Simulation time: When exit probability > 0.05/day, we recommend you decrease the model simulation time. Default is one day.
  - Parameter: Model simulation time (proportion of day)

### Ecospace dispersal IBM



**Figure 2** – Interface for the dispersal estimator at [Ecopath.app](http://Ecopath.app).

The dispersal estimator IBM is implemented as a Shiny app at [Ecopath.app](http://Ecopath.app)'s Dispersal IBM tab, and hosted at a site that hopefully will host also other Shiny apps<sup>1</sup> that may be of benefit for the

Ecopath user community. Upon load of the app, it will let 1000 individual organisms (particles) move at random according for one day (24 hours) with the default parameter settings, and show the resulting Ecospace dispersal rates, a.o. Every time parameters are changed in the app it will redo the movements for the (by default) 1000 individual organisms, and it will store the input parameter settings along with the estimated parameters.

## Action Buttons

**Generate 20 runs:** When clicked, will generate 20 random runs (each with however many organisms that is specified in the *Number of fish* setting). The results for the 20 runs are stored in memory, and can be saved with the *Save session output* button.

**Save session output:** By selecting the *Save session output*, the information from the entire session will be saved to a CSV file. If pressed consecutively, it will hold more and more information. The stored data will only be reset when the app is reloaded.

## Output

**Distances moved per day (histogram, day<sup>-1</sup>):** Estimated based on input parameter setting and averaged over the simulated *number of fish* (i.e. organisms) simulated.

**Distances moved per day (scatter plot, day<sup>-1</sup>):** Plot shows the distance moved during a day for each of the *Number of fish* organisms.

**Sample fish trajectory (X-Y plot, day<sup>-1</sup>):** The trajectory for the first organisms simulated, drawn with uncertainty in input parameters as represented based on the parameter uncertainty.

**Distance between turns (m):** Calculated as swim speed (bl/sec) x body length (cm) x 60 (sec/min) x 60 (min/hour) x 0.01 (m/cm).

**Exit probability per cell face (per day):** Calculated from average probability over each of the simulated number of organisms that they exit a cell within the time period simulated. When exit probability > 0.05/day, we recommend you decrease the model simulation time.

**Diffusivity (km<sup>2</sup>/day):** Calculated as exit probability / (cell length)<sup>2</sup> / model steps per day

**Mix rate for spatial models (year<sup>-1</sup>):** Calculated as 365 x probability of exit / model steps per day

**Ecospace movement dispersal ( $\text{km year}^{-1}$ ):** Calculated as the mixing rate  $\times$  cell length  $\times \pi$ . This is the estimated dispersal rate for use in Ecospace.

**Run time (secs):** For information only, will provide some guidance for how long extended runs will take.

The R code for the dispersal simulator is available at [this link](#).

## Notes

1. Let us know if you have an app that may be of interest

# Land or water?

The most important layer in Ecospace is the Depth layer that specifies which cells have ecosystem dynamics, and which do not. As EwE is mostly used in aquatic environments, the Depth layer uses the monikers Land to indicate cells of depths 0 where no ecosystem dynamics take place, and Water cells with positive depth values where ecosystem dynamics take place. The terms Land and Water are only labels, and can be interpreted freely to build terrestrial or mixed terrestrial/aquatic Ecospace models. Depths are implicitly expressed in meters, but any unit can be used as long as environmental response functions to depth relate to the same scales.

EwE version 6.5 and newer feature an Excluded cells layer, which indicates cells that do not have ecosystem dynamics without having to turn these cells to land: this permits to keep the Ecospace map topography intact while running Ecospace in a part of the Water domain (e.g., excluding some shallower areas or enclosed coastal ponds from model dynamics, or areas that fall outside of the model domain of a hydrodynamic model that feeds environmental output into Ecospace through the Spatial Temporal Framework).

Ecospace does not explicitly consider dynamics within the water column; besides indicating cells with ecosystem dynamics, positive depth values are used for generating recognizable maps and can be used for constraining functional groups to specific depth ranges via the HFC model (e.g. benthic, demersal, pelagic groups). Ecospace can implicitly represent the main impacts of depths without the computational overhead of explicitly representing the water column with a 3D model domain by: (a) stratifying food-web components to different depth ranges, (b) making specific groups reliant on specific types of substrate or sensitive to environmental drivers aggregated over specific depth ranges (e.g., demersal fish being driven by bottom layer temperatures), and (c) implicitly parameterizing the Ecopath diet matrix to account for life at specific depths.

## Adaption

The chapter is in part adapted, with permission, from:

De Mutsert K, Marta Coll, Jeroen Steenbeek, Cameron Ainsworth, Joe Buszowski, David Chagaris, Villy Christensen, Sheila J.J. Heymans, Kristy A. Lewis, Simone Libralato, Greig Oldford, Chiara Piroddi, Giovanni Romagnoni, Natalia Serpetti, Michael Spence, Carl Walters. 2023. [Advances in spatial-temporal coastal and marine ecosystem modeling using Ecopath with Ecosim and Ecospace](#). Treatise on Estuarine and Coastal Science, 2nd Edition. Elsevier.

# Excluding Map Cells

JEROEN STEENBEEK

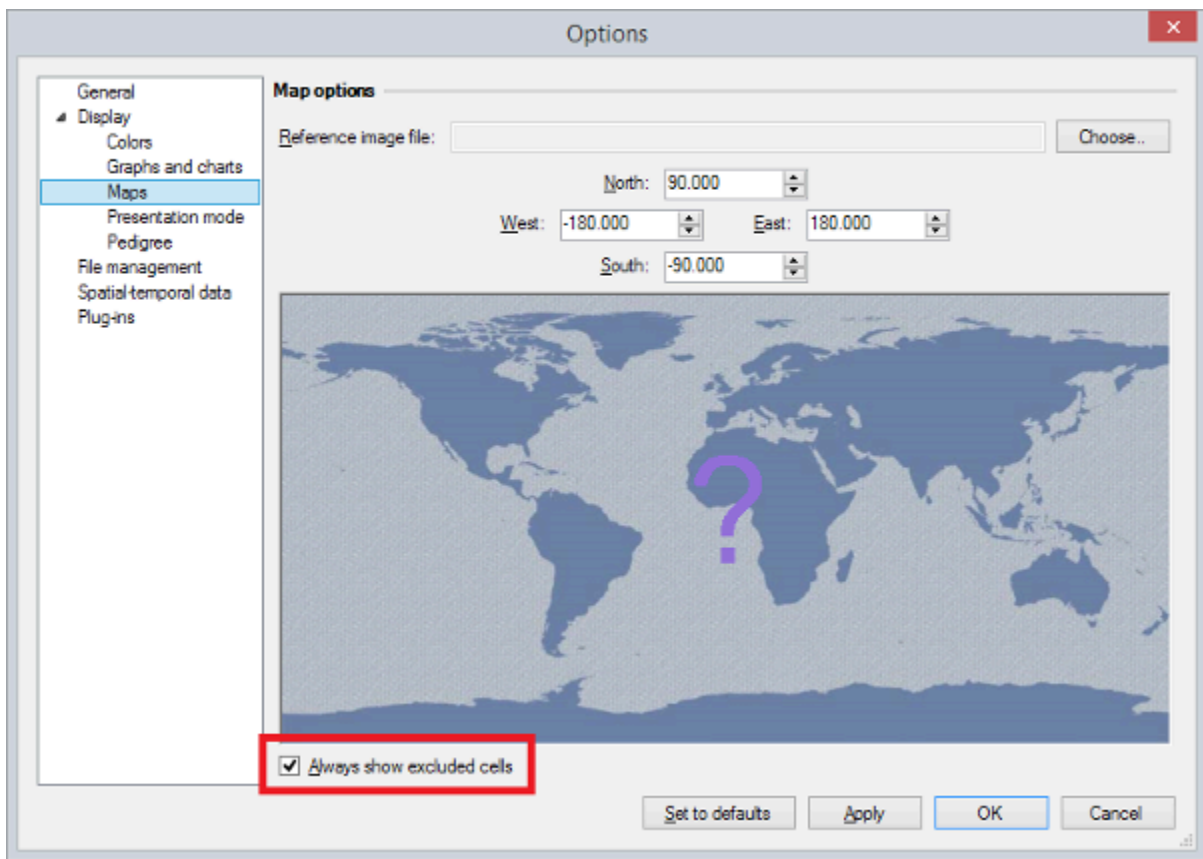
Historically, one could only exclude Ecospace map cells from computations by changing such cells to be 'land'. This would yield confusing maps with unrecognizable land contours. In response, the concept of excluded cells was introduced to the Ecospace model in EwE release 6.4. Excludes cells are defined as cells that do not contain ecosystem dynamics, that are not considered in the Ecospace computations, and that are not rendered in the map displays.

This feature allows accurate display of irregular (e.g., non-square) maps. During a recent project, the feature was used extensively but created confusion during model calibration and testing stages since it was sometimes not explicitly clear whether cells were empty due to misconfiguration of the model or due to excluded cells.

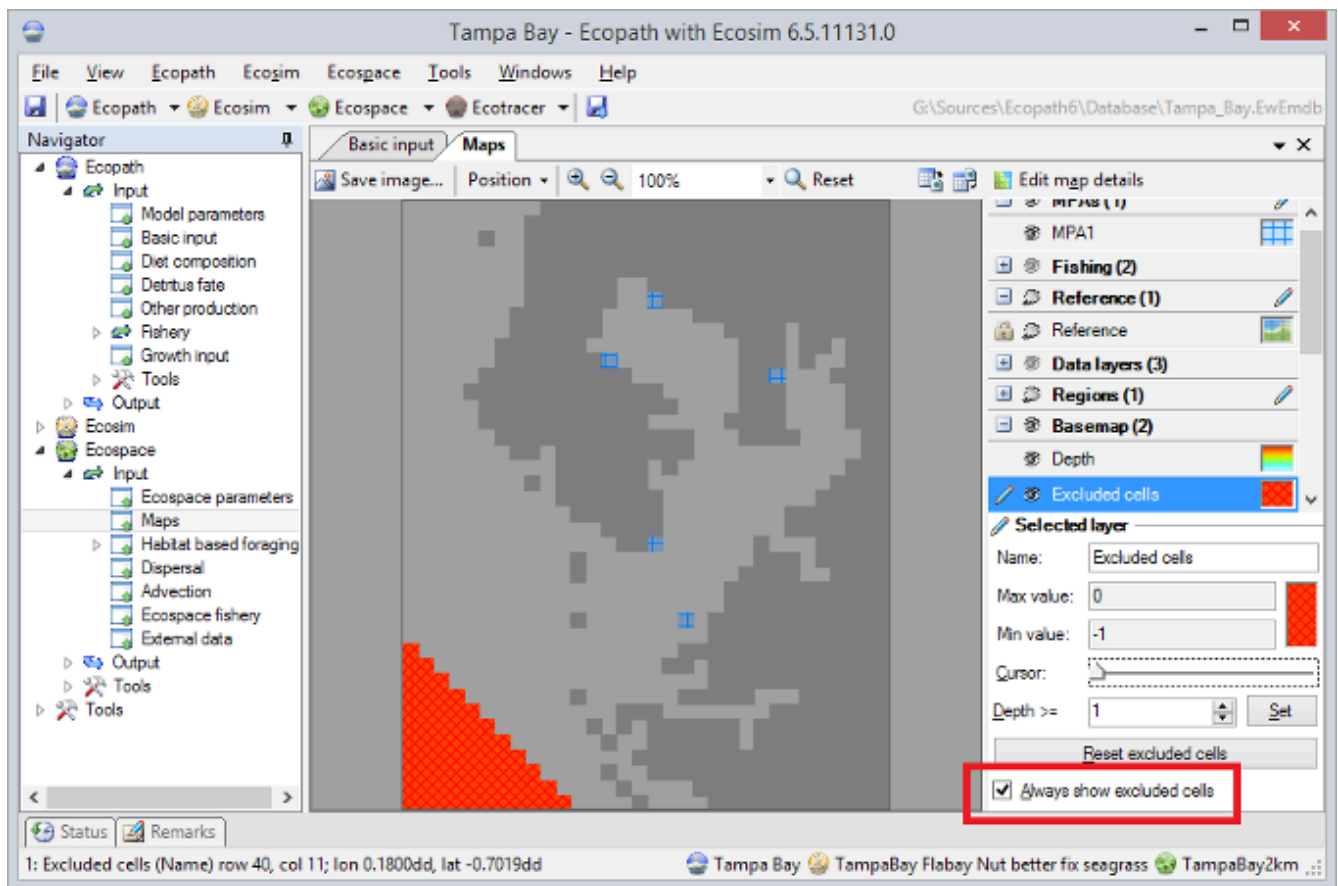
It was decided to add a feature that could be toggled to explicitly display which cells were excluded, and the following changes were made to the EwE software to satisfy this requirement in two aspects of the EwE source code:

1. The EwE user interface has gained the means to toggle display of excluded cells in a few locations.
2. When this option is turned on, the Ecospace input and output maps will always explicitly indicate which map cells are excluded.

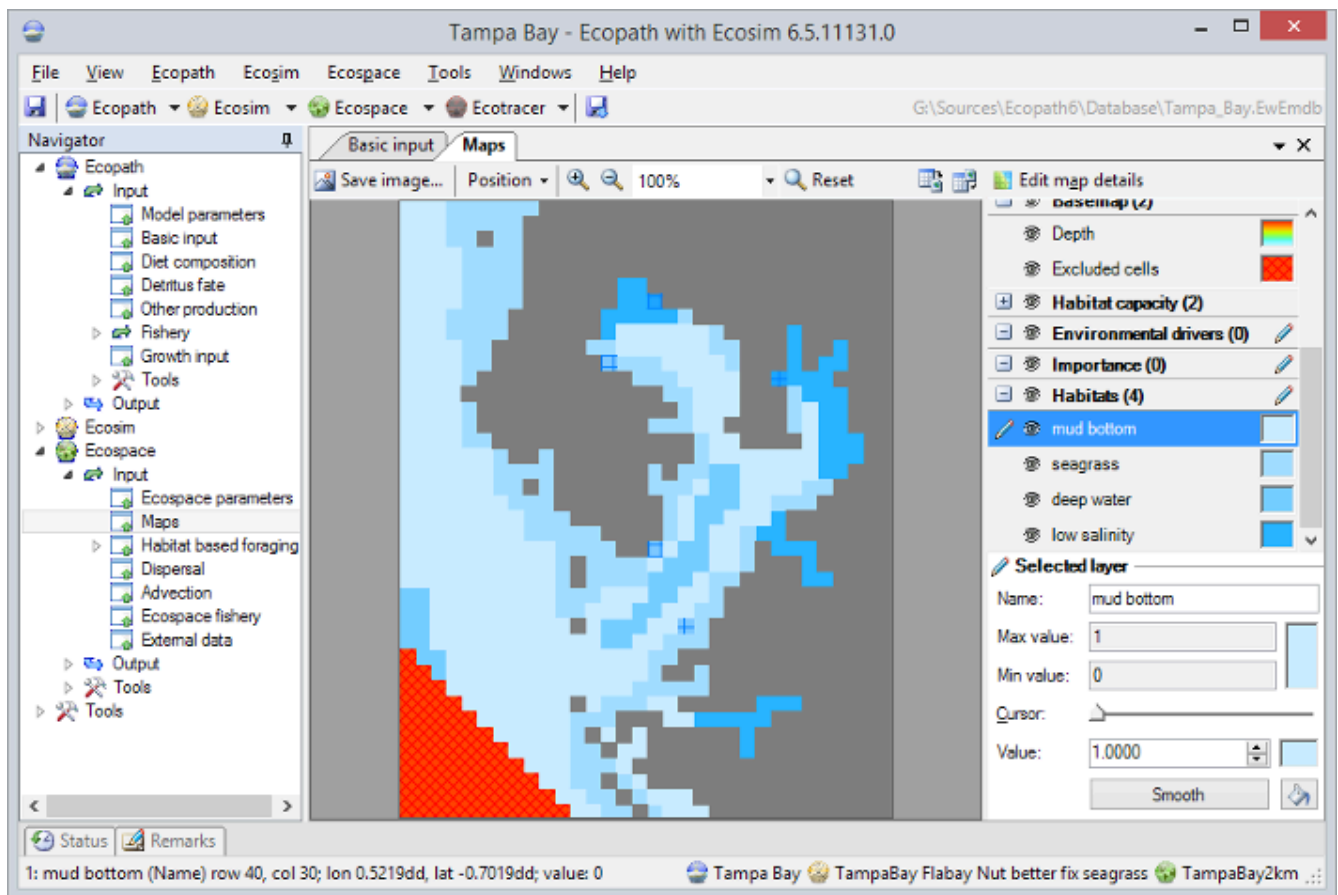
You can toggle the Always show excluded cells flag in the Maps form of the EwE options interface, found in the main menu (Figure 1), as well as in the excluded cell editor in the Ecospace input maps interface (Figure 2). The Ecospace input and output maps provide correct visual feedback (Figure 3 and Figure 4).



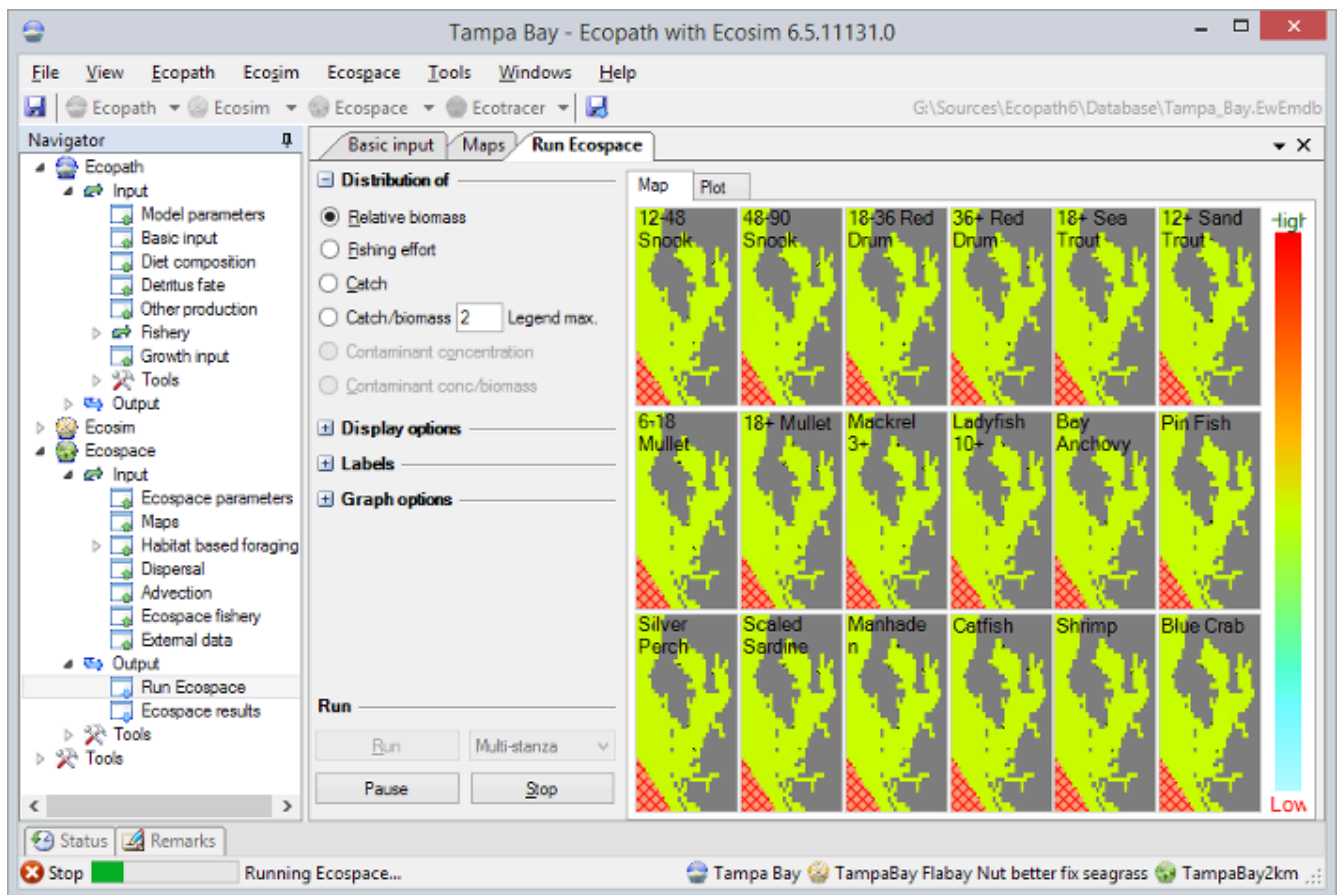
**Figure 1** – Toggling the excluded cells option in the EwE options interface.



**Figure 2** – Toggling the excluded cells option in the EwE maps interface. The toggle is located in the Excluded Cell editor panel (bottom right), while the Ecospace map is showing excluded cells (the bright red area, bottom left, in the map).



**Figure 3** – The Ecospace map input interface responding to the Always show excluded cells setting. Excluded cells are rendered in bright red (bottom left triangle of the map).



**Figure 4** – The Ecospace results maps interface responding to the Always show excluded cells setting (bottom-right area of each map).

# Spatial Data

Any food web is subject to a range of stressors and environmental factors that may or may not change over time and space. Ecospace can include the ecological impacts of a wide range of stressors and environmental factors (for instance climate variables, species niches, layout of and access to Marine Protected Areas, contaminant distributions, etc.), but the magnitude and distribution of stressors and environmental factors are typically defined outside Ecospace by expert models. The spatial-temporal data framework (STDF, [see chapter](#)), available in the professional version of the software, was added to include time-varying distributions of stressors and environmental factors (typically coming from other models) into the running Ecospace model (Steenbeek et al., 2013). This has enabled a host of new applications related to the spatial-temporal impact of change on the ecosystem. For each Ecospace layer that needs to receive time-varying maps, the user must supply one or more maps that represent the distribution and magnitude of external data over time. These maps can be provided in a number of Geographic Information System (GIS) file formats; the spatial temporal data framework uses on-board GIS engines to read and interpret the maps. Each map is time-stamped to tell Ecospace when the data is relevant, and any GIS processing steps that are needed to integrate the data are selected. Last, a time series of maps is connected to the Ecospace map layers of interest. When the Ecospace model is executed, external environmental maps are automatically integrated into the Ecospace model.

There are a few special complicating considerations to using the spatial-temporal data framework (Steenbeek et al., 2021):

- GIS data processing can significantly alter the quality of data if performed carelessly. The choice of rasterization and interpolation algorithms, strategies for dealing with missing data, unit conversions, and lack of data standards or poor adherence to these standards, can affect the quality of the data that Ecospace will ingest. Automatic data processing of large volumes of GIS data is not without risk and should always follow [FAIR principles](#);
- Different Ecospace layers have different data requirements (Table 1). This poses layer-specific challenges to GIS processing. The spatial-temporal framework contains the necessary processing tools to perform basic conversions to targeted Ecospace layers.

It is imperative that modelers first perform the GIS conversions outside Ecospace to ensure a good understanding of the data that Ecospace will be ingesting, including GIS processing artifacts that the conversion process may have created. This process can then be replicated by the STDF.

The STDF offers the means to bypass its internal GIS engine for data that has been pre-processed for a specific Ecospace spatial extent, projection and cell size (Steenbeek et al., 2021). Such data

must be provided as ESRI ASCII raster maps (<https://desktop.arcgis.com/en/arcmap/latest/manage-data/raster-and-images/esri-ascii-raster-format.htm>). This is the preferred method for those that wish to have full control over any GIS processing steps needed to develop the input layers. Table 1 provides an overview of the data needs for the various Ecospace layers.

Layer	Purpose	Format	Units	Observations
Depth	Bathymetry, identify ecosystem dynamics cells	Floating point	meters (implied), but can be anything	Cells with values $\geq 0$ have ecosystem dynamics
Excluded cells	Excludes cells from ecosystem dynamics	True/False	-	Exclude cells from ecosystem dynamics even when depth values are $\geq 0$
MPA	Prohibit specific fishing for a specific MPA	True/False	-	Blocks entire cells from fishing, not cell fractions. MPAs can overlap (EwE 6.4+)
Habitat	Suitable substrate, fishing limits	Floating point	[0,1]	Cell area fraction covered by substrate
Environmental driver	SST, salinity, bottom dissolved O <sub>2</sub> , pH, etc	Floating point	Any	Spatial distribution and magnitude of env. conditions
Relative PP	Distribute primary productivity	Floating point	[0, $\infty$ )	Weight layer for distributing PP. Applicable only to autotrophs
Relative contaminants	Distribute environmental contaminants concentrations	Floating point	[0, $\infty$ )	Weight layer for distributing base environmental contaminant concentrations
Biomass forcing	Affect Ecospace biomasses of a functional group	Floating point	[0, $\infty$ )	Override (absolute) or multiply (relative) biomass distributions of any functional group
Habitat capacity	Constrain niche model for a functional group	Floating point	[0,1]	Set capacity in HFC model. Multiplicative with niche calculations
Advection	Current velocities	Floating point	cm/s	u and v vectors from hydrodynamic models. Note that the Ecospace u direction is non-standard; positive currents flow South. Applied to groups identified as advected by the user

**Table 1. Ecospace layers and their data needs (reproduced with permission from Coll and Steenbeek, 2017)**

Layer	Purpose	Format	Units	Observations
Migration	Move species for reasons that Ecospace cannot predict	Floating point	$[0, \infty>$	Weight layer to specific migration target areas (EwE v 6.4+)

**Table 1. Ecospace layers and their data needs (reproduced with permission from Coll and Steenbeek, 2017)**

## Adaption

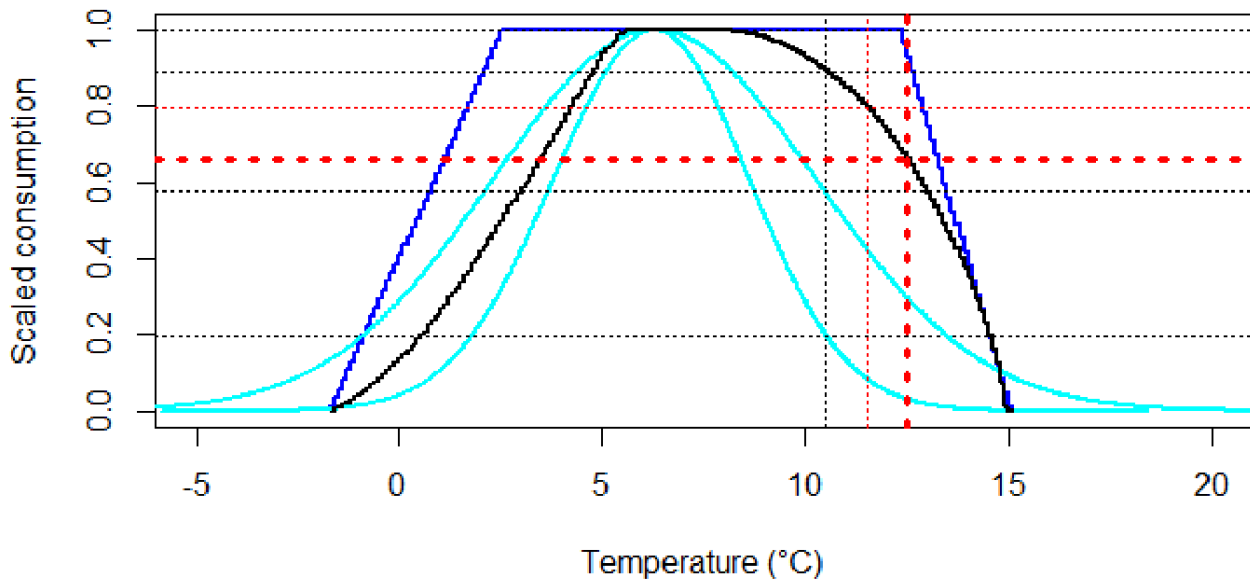
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# Response Curves

The species groups and life stages in any Ecospace model will only respond to environmental conditions and habitat features as discussed above via group-specific response curves (also known as environmental preference functions). The application of these response curves makes a cell more or less suitable for feeding by adjusting the size of the Ecosim and Ecospace foraging arenas and thus controlling the consumption rate of a species in that cell (Christensen et al., 2014).

Generally, the response curves are constructed from in-situ monitoring data, lab experiments, and through statistical analysis of species occurrences versus observed environmental conditions. In many fisheries independent monitoring programs, water quality and habitat data are collected at the time of sampling so creating these curves is a straightforward process but using local or regional data implies that the response functions will not be able to be used for other ecosystems (Coll et al., 2019; De Mutsert et al., 2021, 2017a, 2012). If current monitoring data are not available, published relationships between species and environmental parameters can also be a good resource. For example, responses to several environmental parameters are available worldwide from the free database AquaMaps (Kaschner et al., 2019). The use of AquaMaps response functions is ready to use in Ecopath with Ecosim models due to an AquaMaps-EwE link in the form of a plug-in freely distributed, and has been applied in several EwE applications (Bentley et al., 2020; Coll et al., 2020, 2016; Corrales et al., 2018, 2017). However, the limitation of this approach is that the response functions show a uniform distribution between the 10th and the 90th percentile, which can underestimate the impact of environmental change on consumption and thus deliver overly optimistic results.



**Figure 6** – Different shapes that response functions to temperature can take (reproduced from Serpetti et al., 2019)

Other options include using a Gaussian distribution (Bentley et al., 2019, 2017; Serpetti et al., 2017), which considers a more sensitive niche envelope but can overestimate the environmental effect. Finally, expert knowledge could also be used to develop functional responses to environmental conditions, but their application should be well documented in the methods (Bentley et al., 2019; Coll et al., 2019; Corrales et al., 2017). Additionally, AquaMaps response functions can be refined by using regional rather than global distribution of observations used to calculate the functions and building the functions to represent environmental values of a specific region (Ouled-Cheikh et al., 2022). A sensible approach can be to test the effect of various response shapes since these shapes have an effect on the modelling outputs (Burrows et al., 2019; Waldock et al., 2019; Fig. 6).

There are a few important considerations to keep in mind when applying environmental responses:

- Use environmental responses only when necessary, applying the most important driver to the most sensitive groups only, and test how the entire food web responds. Build up complexity gradually and only where absolutely warranted to make the ecosystem as a whole respond to (changing) environmental conditions;
- Be wary of auto-correlation between drivers;
- Be careful not to over-constrain functional groups;
- Do not assume that a response curve for a multi-stanza group necessarily applies across all stanzas. Response curves should be developed for each life stage, given that many species

have ontogenetic shifts in environmental preferences (De Mutsert et al., 2021, 2017a).

## Adaption

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# Spatial Distribution

In Ecospace, a modeled area is represented by a grid of equally sized cells, where each cell has the basic Ecosim trophic linkage dynamics and other components of ecosystem dynamics, and cells are linked through biomass flows associated with spatial mixing processes. Cells with ecosystem dynamics need a number of descriptors to define how specific ecosystem components and fishing fleets can utilize the cell.

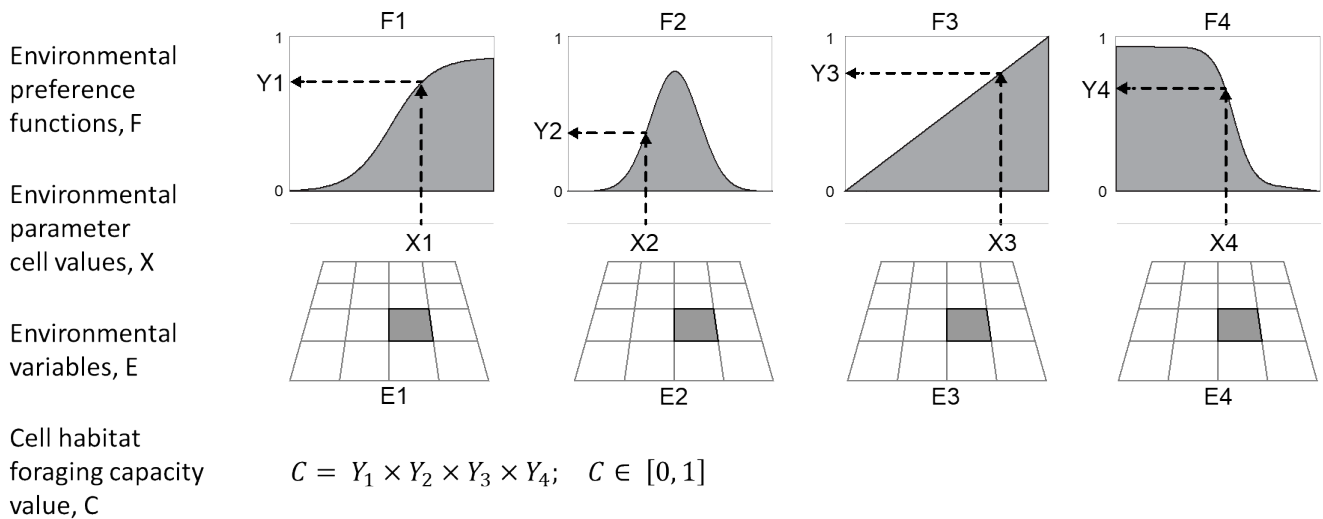
In the original 2008 version of the Ecospace model, each cell with ecosystem dynamics would be assigned to a single, discrete habitat type, and functional groups would be assigned to preferred habitats (Christensen and Walters, 2004; Pauly et al., 2000; Walters et al., 1999). Fishing fleets would be allowed to fish over specific habitats, or could be blocked from fishing in no-take zones (Walters, 2000). Moreover, relative variations of the primary productivity and of costs of fishing across space (but fixed in time) could be incorporated to influence the spatial distribution of the food web and fishing effort, while the model accounts for species movement and other behavioral aspects.

In the 2008 version, habitat structures with associated impact on biomass distributions and trophic interactions were represented by a binary habitat use pattern, with each spatial cell being either entirely suitable – or entirely unsuitable – for species/functional groups. Therefore, the original version of Ecospace assumed homogeneous conditions within each spatial cell, and local but possibly relevant variations within cells could not be represented (Christensen et al., 2014). In addition, a major shortcoming in this original Ecospace configuration was the limited support to include environmental variability as the model ran (Steenbeek et al., 2013).

Functional groups in Ecospace disperse throughout the map based on cell suitability, representing the tradeoff between being able to eat and the risk of being eaten, where differences in cell suitability define the likelihood of a species moving to a neighbouring cell (Christensen et al., 2014). In 2013, Ecospace version 6.3 introduced the Habitat Foraging Capacity (HFC) model that computes the foraging arena size in a cell (Christensen et al., 2014). The HFC contains two main methods, described below, that can be used to define the foraging arena size, or foraging capacity which can be used individually or in combination (Fig. 4).

The Habitat Foraging Capacity (HFC) model consider the cumulative effects of physical, oceanographic, and environmental conditions (such as depth, bottom type, temperature, salinity, oxygen concentrations and primary production) onto species distributions (Christensen et al., 2014). The HFC model defines a continuous relative habitat capacity for each functional group in each cell (Christensen et al., 2014), and the proportion of a cell that functional groups can use

became a continuous value from 0 to 1, allowing for the inclusion of as many environmental factors as needed to define the foraging capacity of a cell for a species (Fig. 1).



**Figure 1** – Schematic representation of the Habitat Foraging Capacity Model. The intercept of an environmental parameter value (X) with an environmental preference function (F) yields a foraging capacity (Y) for a given environmental driver, which multiply to express the total foraging capacity in the cell for a specific functional group (modified from Christensen et al. 2014).

## Habitat Affinity

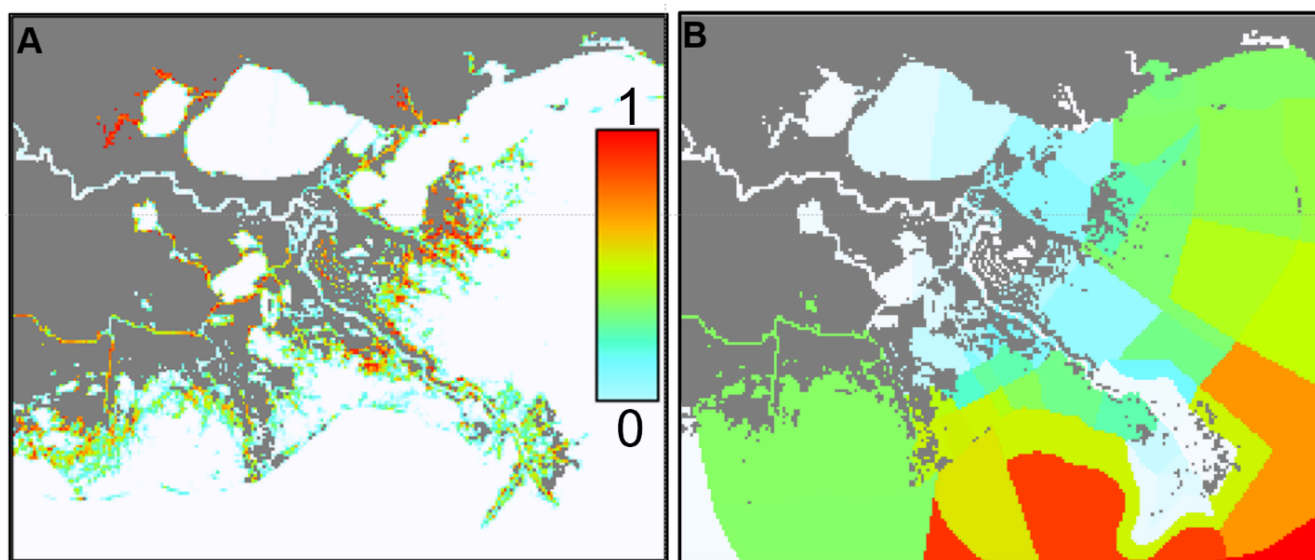
The first method is the legacy Ecospace habitat affinity modus, where the user defines habitat that typically relate to types of substrate relevant to the ecosystem, and how functional groups prefer each different type of habitat. Typically, 5-10 habitat types are used, although there can be many more. For each type of habitat (e.g., sand, rock, seagrass, mud, gravel, etc.) there is an accompanying habitat map that expresses the fraction of cell coverage by that habitat type on a scale of 0 to 1, where 0 indicates no presence and 1 indicates a cell covered entirely by that habitat.

Per functional group, users can quantify how preferred the habitat is for each given functional group that relies on habitats. Preference values range from 0 to 1, where 0 indicates no preference, and 1 optimal preference. Per cell, Ecospace can thus have patches of multiple habitats. The combined presence of habitats and individual habitat preferences leads to a total habitat suitability factor between 0 and 1 for any given functional group, across the map (Püts et al., 2020; Walters et al., 1999). Note that habitats can also be used to indicate vertical structures (e.g., Steenbeek et al., 2020). The sum of habitat areas used by group in a cell should sum to, and not exceed 1.

## Environmental Preferences

With the introduction of the Habitat Foraging Capacity model (Christensen et al., 2014), Ecospace gained a second option to calculate cell foraging suitability through the presence of environmental drivers and functional responses to these drivers. The “environmental preferences” model is similar to a habitat suitability index model that is widely used in spatial ecology (Rushton et al., 2004). Users can define any number of environmental drivers that are known to affect the distribution of parts of the modeled food web. For each defined environmental driver (sea surface temperature, wave action, low frequency noise, bottom dissolved oxygen, salinity etc.) Ecospace incorporates a spatial map that describes how the driver is distributed across the modeled area. A functional response curve, unique to each group and shared with Ecosim (see section 1.4.2), which defines the environmental effect of the driver to each impacted group also needs to be entered. One advantage of the “environmental preferences” model is that the same environmental driver data can be used across a number of functional groups, with response curves being used to specify group tolerances to, or preferences for, specific environmental conditions. The spatial-temporal framework added the ability to change the maps with environmental conditions over time (Steenbeek et al., 2013).

The HFC model considers “habitat affinity” and “environmental preferences” and solves most of the problems of the old habitat affinity (only) model. With the release of EwE 6.5, the combined use of habitats and environmental sensitivities is a per-group setting. This means that users have the freedom to control whether the utilization of space by a given group is driven by habitat affinity, by environmental preferences, or both (see Fig. 5 for example).



**Figure 5** – Examples of environmental preference maps included in Ecospace. A.) These data represent the environmental preference based on percent wetland occurring in each grid cell that was uploaded into the Ecospace module on an annual time step. B.) Example of an environmental preference map based on salinity that was uploaded into the Ecospace module on a monthly time step.

## Recommendations

As the user develops the habitat and environmental driver maps and response curves necessary to define how groups use the modeled space, it is advisable to start with the few environmental features that are most important for defining the distribution. Complexity can be built gradually, with less important environmental features being added subsequently until a realistic biomass distribution of groups is achieved. This is to avoid the problem of driver temporal and spatial correlation: their simultaneous application can result in an overemphasized effect on species distribution (Amodio, 2015; Serpetti et al., 2016). For example, temperature and depth may each play a role in establishing the spatial domain inhabited by a species or group, but these two environmental features are in many cases not independent. It is not trivial to disentangle these environmental effects, and some authors suggest the prior use of multivariate or spatial statistical approaches to determine appropriate coefficient weightings (Coll et al., 2019; Grüss et al., 2018) or selection and exclusion in case of strong correlation, a common practice for example in GAM modeling (Panzeri et al., 2021; Serpetti et al., 2016).

## Adaption

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# Setting Base Effort

CARL J. WALTERS

Ecospace attempts to predict the spatial distribution of fishing effort in relation to changes in profitability of fishing in different cells and policy changes such as marine protected areas and seasonal closures. It predicts the fishing effort  $E_{gij}$  by gear  $g$  in spatial cell  $ij$  at each time step by using a gravity<sup>1</sup> or logit choice model, which apportions total effort  $E_g$  for the gear using proportions by cell  $p_{gij}$

$$E_{gij} = E_g p_{gij} = E_g \frac{A_{gij}}{\sum_{ij} A_{gij}} \quad (1)$$

Here,  $A_{gij}$  is an attraction weight for cell  $ij$  that depends on the relative profitability of fishing in that cell. Profitability for cell  $ij$  is predicted from prices and abundances of species taken by the gear, spatial cost factors, whether the gear can operate in the habitat type set for the cell, and whether or not the cell is open to fishing by gear type  $g$ . Note that the proportions

$$p_{gij} = A_{gij} / \sum_{ij} A_{gij} \quad (2)$$

must sum to 1.0. Note also that total efforts  $E_g$  can be made to vary over time by supplying relative effort multipliers over time for each gear type in Ecosim, where a multiplier value of 1.0 represents the Ecopath base fishing impact.

When moving from Ecopath and Ecosim to Ecospace, it is important to set a base total effort value for  $E_g$  such that the Ecospace effort allocation calculation (eq. 1) results in overall (over all grid cells) fishing mortality rates that are as close as possible to the Ecopath base values  $F_{gk} = C_{gk} / B_k$  for each fishing gear and Ecopath biomass group  $k$ , where  $C_{gk}$  is the Ecopath base catch of group  $k$  by gear  $g$  and  $B_k$  is the Ecopath base biomass for group  $k$ . Note that replication of the Ecopath/Ecosim model over the  $n_w$  active (water) cells in a spatial grid results in total biomasses over the grid of  $n_w B_k$ , so base effort needs to be set so as to give total catches over the grid that are as close as possible to  $n_w C_{gk}$ , otherwise Ecospace will predict total fishing mortality rates that differ widely from  $F_{gk}$ . For gears that fish spatially concentrated species ( $p_{gij}$  high for only a few cells  $ij$ ), we cannot simply set total base effort to  $n_w$  (number of water cells times base effort of unity per cell), since allocation of such a high total effort to just a few cells with high  $p_{gij}$  can result in gross overestimation of by-cell fishing rates  $F_{kij}$  for those few cells. We also need to guard against such over-prediction of fishing mortality rates for groups that use the whole spatial grid, but are modelled to have migratory behaviour so as to be spatially concentrated in varying parts of the grid in different months of each simulation year.

Given the complex profitability calculations used to predict  $p_{gij}$  from attractivenesses  $A_{gij}$  (1), it is not in general possible to choose base efforts  $E_g$  so as to exactly predict Ecopath base fishing rates  $F_{gk}$  for all gears and species. For most models, about the best that we can do is to choose  $E_g$  so that it at least predicts the total Ecopath base catch  $n_w C_g$ , where

$$C_g = \sum_k C_{gk} \quad (3)$$

is the total catch by gear  $g$  summed over biomass groups that it catches (landings and discards). To achieve this prediction, we need to set  $E_g$  so that it satisfies the total catch condition,

$$n_w C_g = E_g \sum_{i,j} p_{gij} \sum_k q_{gk} \cdot B_{ijk} \quad (4)$$

Here,  $E_{gij}$  is the effort allocated to cell  $i,j$ ,  $q_{gk}$  is the catchability coefficient (Ecopath base fishing rate per unit of effort) for gear  $g$  on group  $k$ , and

$$\sum_k q_{gk} B_{ijk} \quad (5)$$

is the total catch per effort summed over groups  $k$  for gear  $g$  in cell  $i,j$ . Simply solving (2) for  $E_g$  results in the desired base effort:

$$E_g = n_w C_g / \left( \sum_{i,j} p_{gij} \sum_k q_{gk} \cdot B_{ijk} \right) \quad (6)$$

Note that if all gravity weights are the same, i.e. biomasses and costs are uniform over the spatial grid, each  $p_{gij}$  is just  $1/n_w$  and each grid cell's catch is  $C_{gij}=C_g$ , then (6) just predicts  $E_g=n_w$ . At the opposite extreme, if all fishing by gear  $g$  occurs in just one grid cell such that  $p_{gij}$  for that cell is 1.0, and all biomass available to gear  $g$  is also in that one cell ( $B_{ijk}=n_w B_k$  for every  $k$ ), then  $E_g$  will be set to 1.0. For intermediate cases in terms of spatial concentration of attractivenesses and biomasses, (6) generally predicts  $E_g$  values between 1.0 and  $n_w$ .

Application of (6) requires an initial assessment of the biomass distributions  $B_{ijk}$ , and of the attractivenesses  $A_{gij}$  that depend at least partly on the biomass distributions. Particularly for models that include migratory species, reasonable values for these distributions and attractivenesses are not available until at least a few time steps into each simulation, after enough time to allow for some spatial mixing and oriented movement. So the convention used in Ecospace is to initially set the  $E_g$  for each group to the number of spatial cells that the gear is physically able to fish, then simulate a few time steps and reset  $E_g$  to the value implied by the spatial biomass distribution after those steps. In some cases, it may still be necessary to adopt an iterative approach and to use total effort multipliers (Ecospace > Input > Ecospace fishery > Fleet dynamics > Tot. eff. multiplier) to increase or decrease efforts for some gears after initial simulation trials indicate persistent over- or under-prediction of fishing mortality rates.

## Notes

1. Caddy, J.F. 1975. Spatial model for an exploited shellfish population, and its application to the Georges Bank scallop fishery. *J. Fish. Res. Board Can.* 32: 1305–1328. <https://doi.org/10.1139/f75-152>

# Model Type Options

Ecospace has three options for modeling the movement and survival-growth of multi-stanza groups – groups that represent ontogenetic stages of a species, such as larvae, juvenile and adult fish: the Basic Partial Differential Equations (PDE) model applied to split pools of biomass in the original Ecospace model, the EwE6 multi-stanza model and the Individual-Based Model (IBM; Walters et al., 2010, 1999).

## Basic PDE

This is the original implementation of multi-stanza accounting in Ecospace and is included for legacy reasons (Walters et al., 1999). This option does not account for size-age structure within each life stages of the multi-stanza group, but links one species related to different pools of biomass. Instead, it treated each life stage as its own functional group that assumed the size-age structure was at equilibrium for the life stage. Because of this, the PDE does not give an accurate accounting for numbers at age, and body weight is calculated on a grid averaged value. If a model contains multi-stanza groups, it is recommended that one of the other options are used.

## EwE6 Multi-Stanza Model

The EwE6 multi-stanza model is the default option. This model includes a single spatially averaged size-age structure model that is used to populate the Ecospace grid cells. Spatial distributions are handled by the diffusion model in the same manner as the non-multi-stanza biomass pool groups. Weighted, spatially averaged consumption and total mortality rates are calculated across the map for each model time step (Walters et al., 2010). These spatially averaged values update numbers- and weights-at-age of the single size-age structure model. Once this is done, the map-averaged biomass for each life stage of the multi-stanza group can be integrated from the numbers- and weight-at-age. These averaged biomasses are then populated back into the grid cells based on the original biomass weighting of each cell. This algorithm maintains the Ecosim style numbers and weights at monthly ages accounting, with fecundity rates based on body weight above weight at maturity, and size-number dependent monthly egg production used to predict recruitment rates to age 0 fish. However, because it is based on spatially averaged values, any local differences in consumption and/or mortality rates are lost. For example, the consumption and mortality rates

inside an MPA will be the average across the modeled area, not just the values inside the MPA. Similarly, local effects on consumption and mortality of habitat restoration will be averaged over the model domain (Walters et al., 2010).

## IBM

In the IBM Ecospace predicts spatial changes in consumption and mortality rates by dividing each multi-stanza population into a user-controlled number of packets (a.k.a. cohorts or super-individuals). Each packet is assumed to represent a group of identical individuals of the same age and each packet maintains its own multi-stanza size-age structure. At initialization of a run, each packet is populated with the same monthly numbers-at-age and weight-at-age, then uniformly distributed over the grid cells with a habitat capacity greater than 0.1. At each monthly time step, each packet is tracked independently as it moves around the grid cells. This allows each packet to derive its consumption and mortality rates from the conditions in the local cell it finds itself in at the beginning of the time step. By doing this, each packet can respond to local ecological conditions as it moves through both space and time (Walters et al., 2010). Monthly recruitment creates new IBM packets with initial age 1 month, spatially distributed in proportion to the distribution of spawning biomass.

Due to the way the number of packets that is used to represent a single month in a multi-stanza life stage is calculated, multi-stanza life stages that span a shorter time frame (or number of months), are represented by fewer packets. An implication of this is that if the number of packets is too low, the spatial distribution will be unrealistically patchy, and the life stage's survival-growth will be dominated by the ecological conditions of only the few cells that the packets happened to find itself in due to random movement. The package multiplier used to scale the total number of packets needs to be high enough to give realistic spatial distribution for the shortest-lived life stages of multi-stanza groups. However, if it is too high the computational speed may be slow. Setting the number of packets is a tradeoff between computational speed and the need to be high enough that it will predict realistic spatial distributions (Walters et al., 2010).

The movement in the IBM model is controlled by the same parameters as the non-multi-stanza species base dispersal rate, relative vulnerability to predation in bad habitat, relative movement speed to cell fitness, relative dispersal in bad habitat, advection, migration and the foraging capacity of neighboring grid cells. The base dispersal rate and grid cell size are the main drivers of the IBM dispersal rates with foraging capacity, advection and migration weighting the direction of the movement. Monthly movements are a series of incremental steps with each step being no larger than half a cell. The direction for each move can only be in one of the cardinal directions (N, S, E, W). If a packet cannot escape the grid cell from its current location, because it can only

move a maximum of half a cell, then it will move in a uniform random direction in one of the four directions. Otherwise, if it can escape the current cell in one move, the probability of it moving in any one direction will be a random choice weighted by the foraging suitability of the neighboring cells (Walters et al., 2010).

While a packet can move through multiple grid cells in a time step, the consumption and mortality rates are derived from the grid cell it finds itself in at the start of a time step, and these rates are not integrated across the cells it traveled through during the time step to get to its current location. This assumes the grid cell size and dispersal rates are such that a packet can only move over a few grid cells in a time step, or the spatial distribution of food availability and mortality rates does not vary greatly over the grid cells a packet traveled through in a single time step. As with other Ecospace model configurations, when using the IBM one needs to make sure that the spatial resolution of the basemap, the spatial distribution of habitat or foraging capacity and dispersal rates capture the behavior of the multi-stanza life stages.

The initial spawning location of each packet can be set to either recruit where spawned, current location of the spawner, or to be moved to randomly selected nursery cells, a grid cell with habitat capacity greater than 0.1 for the age 0 life stage of the multi-stanza group. This allows the habitat of spawning adults and start-age recruits to be spatially separated in such a way that the movement model could not transport them across the grid cells in a single time step. This prevents the recruits from incurring unrealistically high mortality rates as they move into better foraging capacity. Packets that age from one life stage to the next can also be randomly moved at stanza entry into cells that have a foraging capacity of greater than 0.5 for the life stage they are aging into. Again, this prevents the life stage from incurring unrealistic mortality rates as it moves into areas of better foraging.

The multi-stanza plus IBM model has not been intensively featured in publications yet (but see Espinosa-Romero et al., 2011; Grüss et al., 2016; Püts et al., 2020). There are many potential applications that can benefit from these capabilities, including the evaluation of MPAs and MPA connectivity, the effects of climate change or the impacts of invasive species. The current IBM model application correctly incorporates current velocities to move advected multi-stanza packets. This makes Ecospace especially useful for studying protected area connectivity.

## Adaption

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# Addressing Uncertainty

## General Practices

It is generally a good practice – if not mandatory – to explicitly acknowledge sources of uncertainty in data and modeling exercises, make reasonable attempts to quantify it, and caveat the model results as appropriate.

An ever-increasing body of literature categorizes the various types of uncertainty related to the development and operation of ecosystem models (Cariboni et al., 2007; Harwood and Stokes, 2003; Payne et al., 2016; Spence et al., 2016; Steenbeek et al., 2021). A useful typology is: (1) model / structural, (2) stochastic-, (3) data-, and (4) parameter uncertainty (GREGG and Chan, 2015). Model uncertainty occurs due to potential incomplete or inaccurate abstractions embedded in the structure of the model. Ensemble modeling approaches can be an effective approach to better understanding uncertainty due to implicit architecture of a model: multiple models are used, each representing a different method of abstracting and representing the ecosystem, e.g., Scales et al. (2016), Spence et al. (2018), Lotze et al. (2019) and Tittensor et al. (2021). Structural uncertainty can also be explored using a single model by modifying model equations, for example by aggregating/disaggregating compartments, changing functional relationships and/or modifying basic function process, e.g., linear fishing mortality (Coll et al., 2020; Hansen et al., 2019; Pantus, 2007). Stochastic uncertainty occurs due to chaotic or ‘noisy’ process signals, non-stationary patterns and relationships between variables (Deyle et al., 2016; Litzow et al., 2018; Walters, 1987), or uncertainty in processes represented by the model (e.g., recruitment, (Spence et al., 2016). Data uncertainty results from measurement and observation error and can be propagated through a model due to the model fitting procedure. Parameter uncertainty arises due to non-unique parameter values that the modeler must choose from, as well the large number of parameters typically needed for ecosystem models.

The EwE approach provides some means to execute parameter uncertainty analysis (e.g., (Coll and Steenbeek, 2017; Heymans et al., 2016; Steenbeek et al., 2018). As the Ecospace module inherits model structure, parameters, and associated uncertainty from both Ecopath and Ecosim, we recommend using a formal fitting routine and sensitivity analysis in Ecopath and Ecosim (e.g., (Scott et al., 2016) before tackling uncertainty in Ecospace. To assess Ecospace model sensitivity due to the underlying parameterization of Ecopath / Ecosim, the Ecosampler module described in section 3.2 can be used (Steenbeek et al., 2018). The Ecoranger module in EwE 5 was a pseudo-Bayesian approach to search for parameters (Christensen et al., 2005; Christensen and Walters, 2004; Walters et al., 1997), though no Bayesian uncertainty analysis tool is currently built into EwE

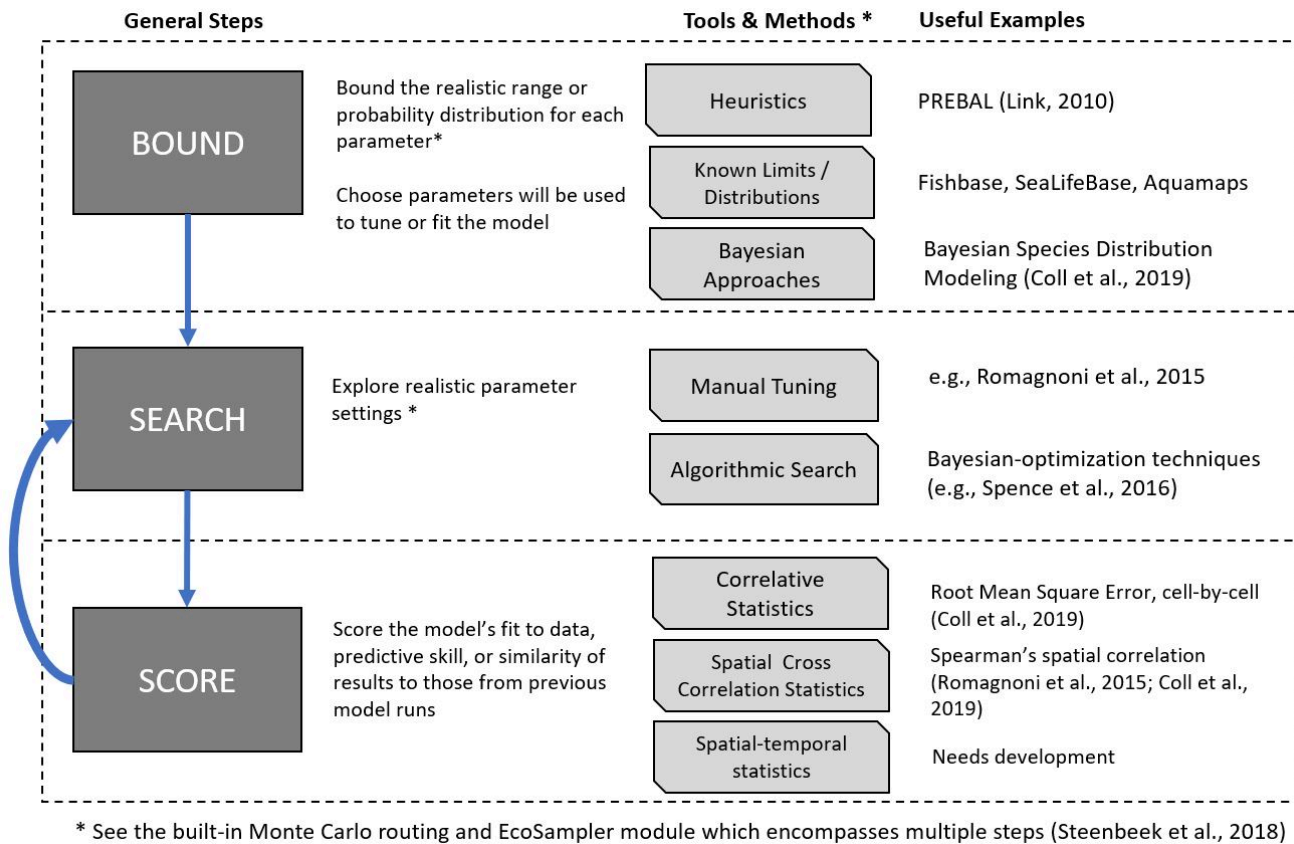
6. One promising alternative is Bayesian-Species Distribution Models (B-SDM), which implicitly considers uncertainty in spatial distributions and environmental niches. This type of model can be used in a complementary manner with Ecospace to incorporate uncertainty in plausible habitat capacity, response functions or both (see Coll et al., 2019).

A ‘bound, search, and score’ generalized approach for tackling uncertainty due to data and parameter uncertainty may be intuitively familiar to most modelers and help to contextualize the various methods, tools, and statistics available to Ecospace users (Fig 9). This simple framework captures the general approach used in a previous ad hoc effort to parameterize Ecospace (Romagnoni et al., 2015).

The ‘bound’ step addresses issues related to computational cost associated with running Ecospace, a typical challenge with the complexity of most ecosystem models. In Ecospace, this must currently be done manually. We recommend selecting Ecospace parameters for sensitivity analysis based on: (a) importance to the questions, patterns, or processes being investigated, (b) those that are most frequently tuned, and (c) computational limitations and model run time. Common non-spatial parameters used to tune Ecospace models are the “vulnerability exchange rate”, “base dispersal rate”, “relative vulnerability to predation in bad habitat”, and “effective power of fishing fleets”. Key spatial parameters (those that vary between raster cells) may also be bounded using the spatial-temporal framework by importing raster data prepared in advance that represent habitat capacity (Coll et al., 2019; Steenbeek et al., 2013).

In Ecospace, the ‘search’ step is currently limited to a manual search, since Ecosampler and the Monte Carlo routine are not yet able to access Ecospace parameters. However, the spatial-temporal framework makes it possible to easily run and re-run Ecospace using different spatial parameterizations, and the ability to run EwE directly from code greatly facilitates the repeated execution of model exercises to perform structural uncertainty analyses.

‘Scoring’ the Ecospace runs may be done in several ways. A simple approach is to use comparisons between Ecospace results from multiple runs. Currently, Spearman’s spatial correlation, which can be calculated using the ‘raster’ package in R using the “corLocal” function (R Core Team, 2018) is popular (Coll et al., 2019; Piroddi et al., 2022; Romagnoni et al., 2015; Subramaniam et al., 2022), while (Lynam et al., 2017) used Mantel spatial correlation with 999 permutations to test the significance level. To best address the task of comparing Ecospace outputs, a spatial-temporal statistical measure of similarity, or spatial-temporal cross correlation, is required. Unfortunately, spatial cross-correlation statistics in Ecospace are still under development and present computational and theoretical challenges (Chen, 2015). In the lack of such statistics, Püts et al. (2020) utilized a set of metrics for the temporal (Pearson correlation and root mean squared error) and spatial fit (Schoener’s D index) separately, finally combining them using a Taylor diagram.

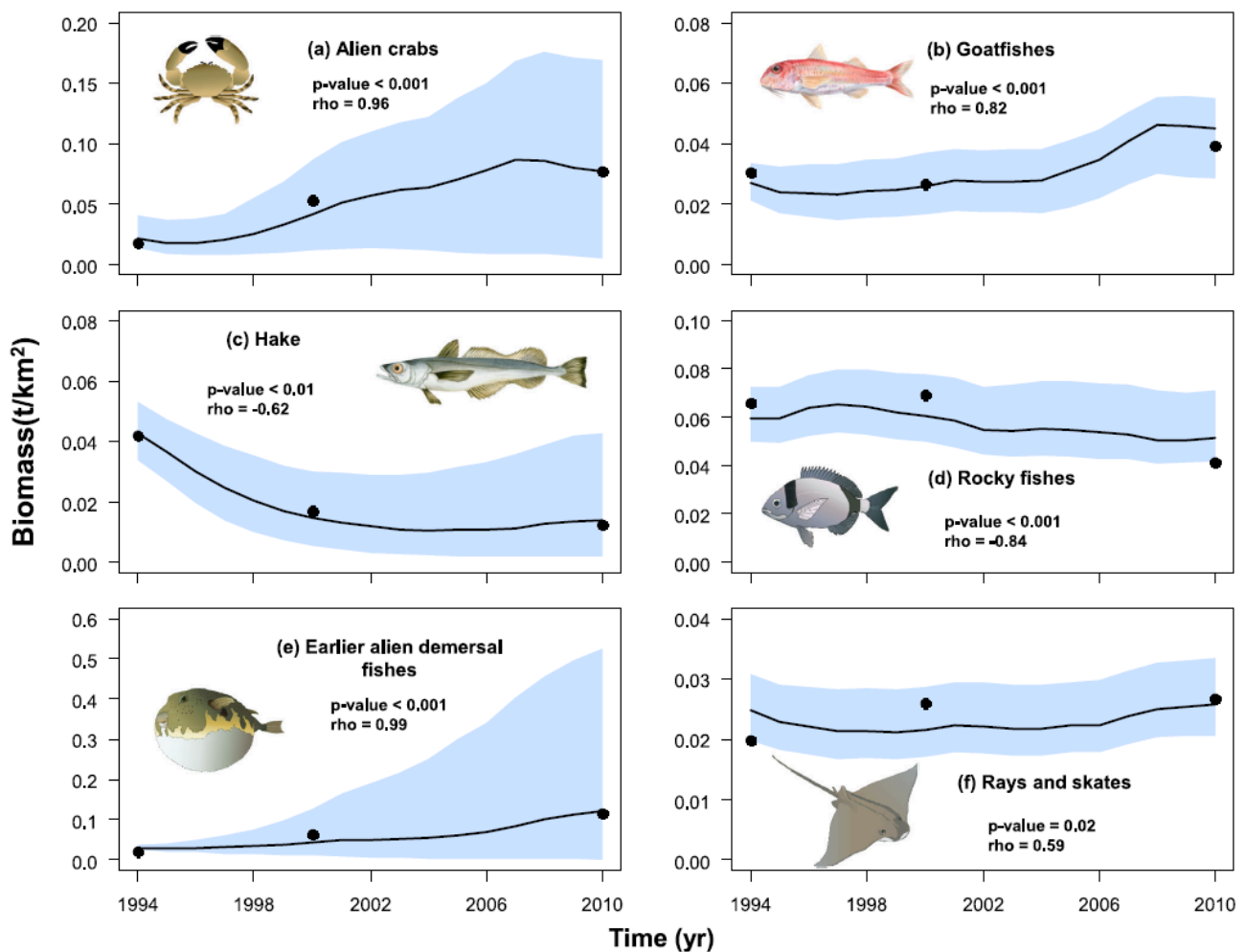


**Figure 9** – Diagram of the ‘bound, search, and score’ framework for tackling uncertainty which captures the general approaches used to parameterize Ecospace

Spatially-temporally explicit uncertainty assessments are a challenging priority for future development (Steenbeek et al., 2021). The development plans for EwE includes extending the parameters that can be perturbed by the Monte Carlo routine (and subsequently sampled by Ecosampler) to Ecospace (Steenbeek et al., 2021, 2018). Given the high computational cost of running a spatially resolved model such as Ecospace, the parameter search space (i.e. the range of the parameters to be explored, and their combinations) must be limited to a local instead of a global search (Hansen et al., 2019; Pantus, 2007; Püts et al., 2020), with the caveat of reducing the possibility of exploring extreme values and combination of parameters. Iterative, ad-hoc process for space reduction (e.g., see Romagnoni et al., 2015) are time-consuming when manually implemented, and automated procedures are not available at present. Preliminary understanding of parameter space is thus critical to make the analysis tractable.

# Ecosampler

Ecosampler is a module within EwE to measure the impact of Ecopath input parameter sensitivity on its results (Steenbeek et al., 2018). Ecosampler records samples – alternate mass-balanced parameter sets for a food-web model – from the built-in Monte Carlo routine, and replays these samples through all of the EwE modules and any loaded plug-in. Ecosampler can capture output variation due to base input parameter sensitivity of any computational component including the temporal module Ecosim, the spatial-temporal module Ecospace, and plug-ins such as Ecological Network Analysis, Value Chain, and Ecological Indicators (Fig. 10).



**Figure 10** – Predicted (solid lines) versus observed (dots) biomass for various functional groups of the model for the Israeli Mediterranean continental shelf ecosystem model for the period 1994–2010. Blue shadows represent the 5th and 95th percentiles obtained from Ecosampler–perturbed model outputs. Rho and p-values were obtained from Spearman’s rank correlation test (modified with permission from Corrales et al., 2017)

Image attributions?

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## Adaption

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De Mutsert K, Marta Coll, Jeroen Steenbeek, Cameron Ainsworth, Joe Buszowski, David Chagaris, Villy Christensen, Sheila J.J. Heymans, Kristy A. Lewis, Simone Libralato, Greig Oldford, Chiara Piroddi, Giovanni Romagnoni, Natalia Serpetti, Michael Spence, Carl Walters. 2023. [Advances in spatial-temporal coastal and marine ecosystem modeling using Ecopath with Ecosim and Ecospace](#). Treatise on Estuarine and Coastal Science, 2nd Edition. Elsevier.

# Ecospace Output

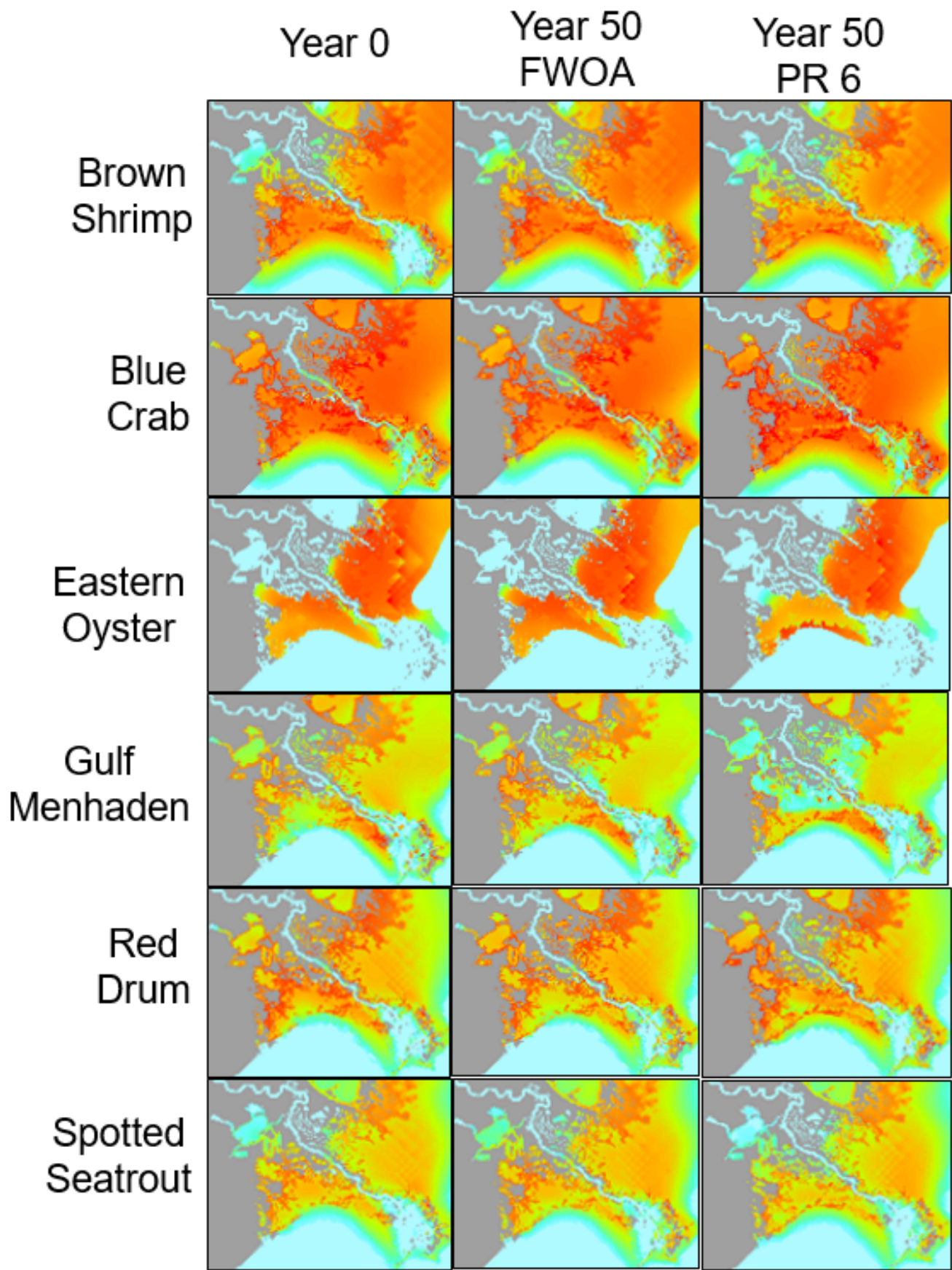
Ecospace offers a number of facilities to write model outputs to storage for subsequent analysis.

## Basic Ecospace Output

The most basic form of Ecospace output are spatially-temporally explicit distributions of biomass, fishing effort and catches in a range of file formats (Fig. 7). Ecospace can also write maps per time step, of computed habitat foraging capacity, contaminant concentrations, and discards, which can help to better understand the model's behavior and address specific management questions. The EwE plug-in system (Steenbeek et al., 2016) allows the user to expand the list of standard outputs.

Be aware that writing output to hard-drive can amount to large volumes of data, especially when writing spatial output for every monthly time step.

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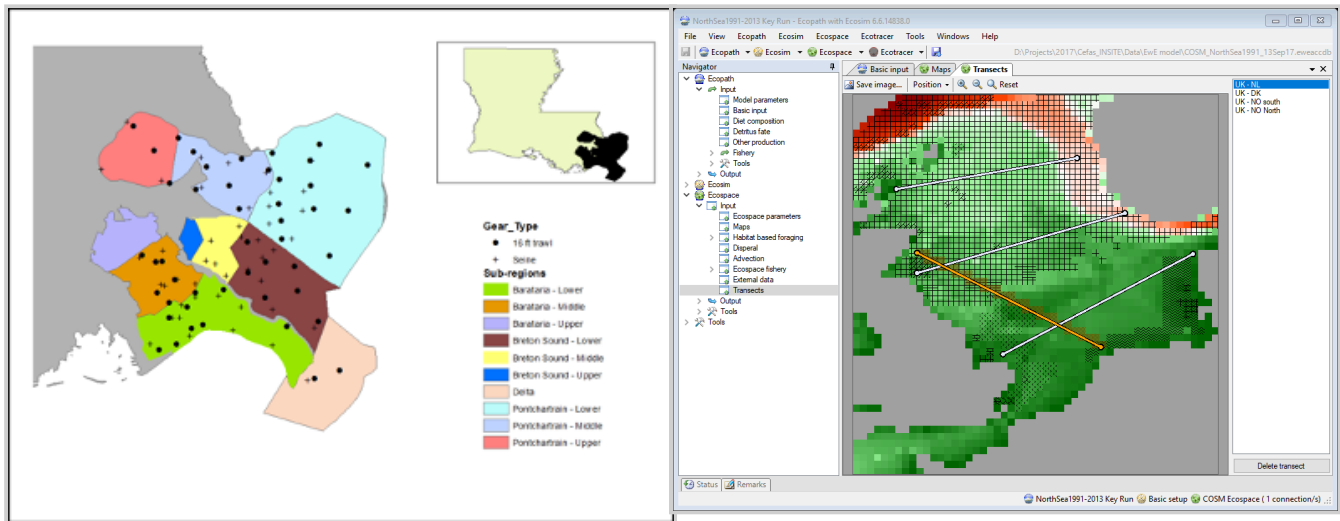


**Figure 7** – Spatial distribution of biomass of groups in the Delta Management model. Year 0 of the model run is compared with year 50 in a future without action (FWOA) and a chosen scenario (PR 6). Reproduced with permission from De Mutsert et al. (2017a)

## Regions and Transects

Ecospace can automatically summarize outputs over the whole model area by group and fleet. In addition, it is often useful to have information summarized by specific regions within the model area, for example when there are separate ecological regions or management units within the model domain (Fig. 8A). This is possible by loading a map with these sub-areas indicated in the ‘Maps’ interface in the specified ‘Regions’ location of the Ecospace interface. Note that a given cell can at most belong to one region. The program then summarizes the output by region as well.

Additionally, Ecospace can automatically extract information from a predefined transect. Transects are defined as input data on top of the Ecospace base map and after the runs are finished, values of the transects are extracted according to the depth, biomass, catch and MPAs intersected along the transect, per time step (Fig. 8B).



**Figure 8** – A: The Mississippi River Delta Model partitioned in regions relevant to Louisiana coastal managers (reproduced from K. De Mutsert et al., 2016).

B: using the transect extraction tool to define transects for extracting time-varying Ecospace values (reproduced from the Transect plug-in user guide)

### Adaption

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# ECOSPACE ADVANCED

# Cumulative Impacts

The impact of various anthropogenic activities and other drivers that influence the spatial distribution of organisms in the system can be assessed through Ecospace to understand their ecosystem-wide effects. Similarly to other impact assessment tools (e.g., Halpern et al., 2007; Halpern and Fujita, 2013; Hammar et al., 2020), formulating the representation of impacts undergoes a stepwise approach:

1. identification of a set of potentially impacting activities (e.g., windfarm construction, artificial reef placements, aquaculture settings);
2. translation of each activity into corresponding stressors, for example noise (Harvey, 2018; Serpetti et al., 2021), bottom disturbance (Steenbeek et al., 2020) or nutrients release (Piroddi et al., 2011);
3. condensation of the multiple stressors into a ‘cumulative impact’ metric; and
4. quantification of each stressor effect, or of the cumulative impact metric, on determinate species or for the whole ecosystem, in a determinate area.

In Ecospace, a straightforward approach for including spatially explicit, and time dynamic, cumulative impacts is through the HFC model (section 1.5.1). Layers of stressors, at the same spatial resolution of the model, are loaded and associated to functional groups through response curves, in the same way as environmental drivers such as depth or temperature.

When multiple stressors occur in an individual cell, the cumulative impact is represented as the product of the individual stressors (Christensen et al., 2014). Predator-prey interactions can buffer or enhance the effects of stressors: for example, in an area closed to fisheries due to another human activity (e.g. a wind farm and aquaculture site), cetaceans could be displaced by the negative effect of the stressor “noise”, but attracted due to increasing food availability driven by the fishing closure and the locally higher primary productivity (Serpetti et al., 2021). The actual emerging net effect is thus dependent on the cumulative effect of multiple stressors on the prey and on the predator, as well as on other dynamics (fishing, protection, environmental drivers), resulting in complex and in some cases counterintuitive dynamics (Wedding et al., 2022).

The application of multiple pressures can be particularly important when assessing Marine Spatial Planning options and trade-offs, and the effects of de facto MPAs driven by e.g., renewable energy installation (e.g., Alexander et al., 2016; Noguez et al., 2022, 2021; Serpetti et al., 2021; Steenbeek et al., 2020). Ecospace can provide a support platform that enables tracking the effects of impacts on each trophic group and its propagation through the food web: this is a great added value compared to other spatially explicit tools for cumulative impact assessment (Depellegrin et al., 2021), which

mostly address direct effects of stressors on ecosystem components, and do not consider trophic dynamics.

It is important to note that simulation of impacts through the HFC model has the effect of changing habitat suitability, thus the feeding ability, which changes cell suitability. This, in turn, increases the chance that groups relocate to nearby areas that are more suitable. Survival is affected when groups cannot relocate fast enough to keep up with changing environmental conditions. The HFC model is less efficient in capturing direct localized mortality events such as harmful algal blooms, hypoxia, temperature extremes, pollution, or mortality associated with shipping and other destructive anthropogenic activities. In these cases, a different solution has been recently provided through direct influence of natural mortality (Section 6.6). In EwE version 6.6 mortality response curves can be included to describe the proportion of biomass killed in each grid cell as a function of the stressor value in that cell (e.g., contaminant concentration, temperature, dissolved oxygen, Vilas et al. 2020), or by knowing the probability of the occasional event occurring (e.g., co-occurrence within cetaceans and shipping tracks and the probability of a fatal collision, Harvey 2018). However, long-term impacts of e.g., persistent pollutants within the organisms might not be well captured by the habitat capacity model if the mortality associated with specific concentrations of these pollutants is not incorporated in the model.

The assessment of the ecosystem effects of cumulative human activities is a challenging scientific task. Many studies have considered the impact of fishing activities and a second or even a third factor (such as eutrophication, pollution, aquaculture, loss of habitat, climate change, or invasive species), mostly using time-dynamic modeling (Ainsworth et al., 2011; Booth and Zeller, 2005; Corrales et al., 2018; Guénette et al., 2006; Serpetti et al., 2017). The assessment of cumulative impacts using spatial-temporal dynamic modeling is growing but has thus far been limited by the original configuration of Ecospace. Recent developments in Ecospace are allowing an exponential increase in such applications (see section 6.)

## Adaption

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# Ecoengineer Plug-In

JEROEN STEENBEEK

## Introduction

The Ecoengineer plugin is designed for predicting the spatial spread of functional groups in benthic ecosystems with at least one autogenic ecosystem engineer: an animal or plant that uses its own body to change an environment and affect the access of other species to resources <sup>1</sup>. Ideally, the engineering species should be hard in structure. In the accompanying publication Sadchatheeswaran et al. <sup>2</sup>, mussel and barnacle beds, which dominated the intertidal area considered, were used.

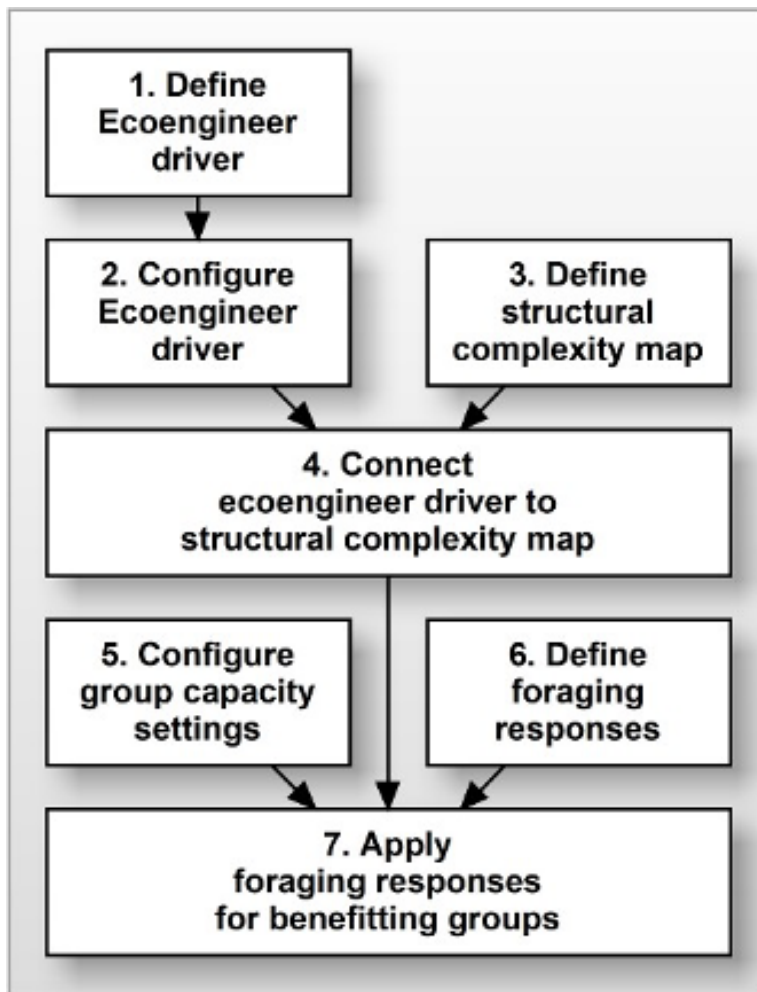
The Ecoengineer plugin for Ecospace, the spatial-temporal modelling routine of Ecopath with Ecosim or EwE (Christensen and Walters 2004), is publicly available with EwE version 6.6.5 and onward.

## Using Ecoengineer

Setting up Ecoengineer dynamics in a EwE model thus requires the following:

- A balanced Ecopath model, with an Ecosim and Ecospace scenario
- One or more eco-engineer functional groups present in the ecosystem model
- Definition of the empirical relationship between ecoengineer biomass and structural complexity
- Definition of an Ecospace environmental driver map that will receive the amount of structural complexity
- Definition of functional responses for all functional groups that are affected by this new environmental driver

Figure 1 outlines how to achieve this in the EwE desktop software. The steps are described in detail, below.



**Figure 1.** Outline of Ecoengineer procedure.

## Preparation: Set Up a Temporal-Spatial Model

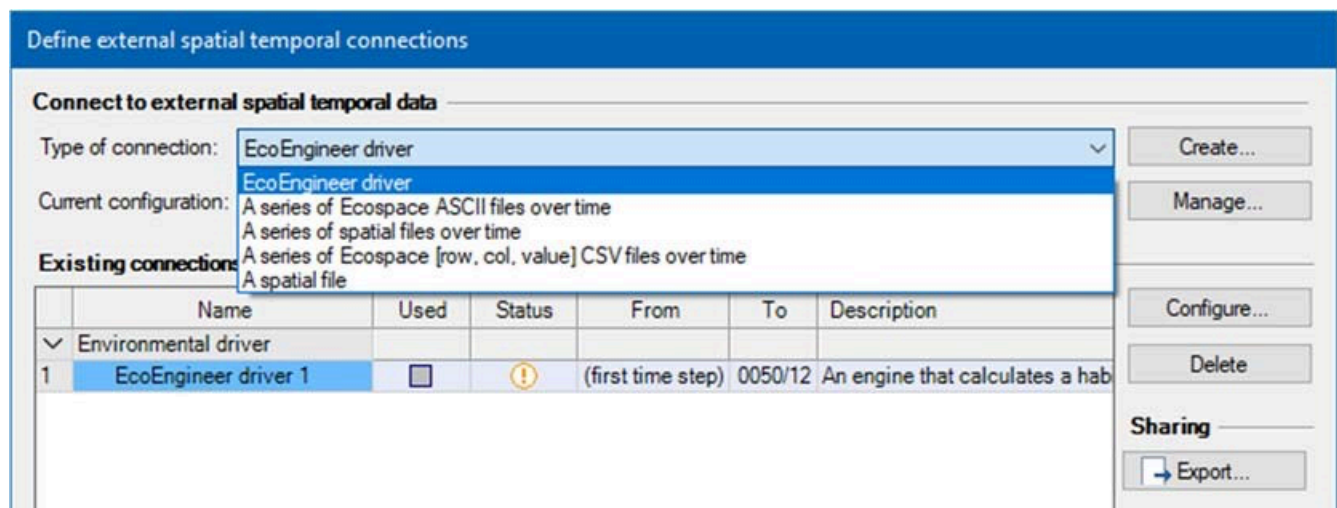
In EwE, create a balanced Ecopath model of the ecosystem that represents the first year of biomass time series of ecosystem engineers. Make sure ecosystem engineers are explicitly represented by at least one functional group. Run the model for a set number of years in Ecosim, with a time series to drive the biomass of functional groups over time. In Sadchatheeswaran et al.<sup>3</sup>, the time series was run for 35 years (1980 to 2015), and the initial biomasses of the alien ecosystem engineer groups started low and were forced at each annual time step, rather than use fitted data, as per the recommendations of Langseth et al.<sup>4</sup>. The biomasses of the native functional groups in the time series can be used to fit the model to observed data. The model is then ready for Ecospace, the spatial-temporal modelling routine.

In Ecospace, open and name a new scenario that should automatically run for the total number

of years dictated in Ecosim. In Maps (Ecospace>Input), create a base map that matches the size of the study area<sup>5 6</sup>. If possible, also create depth (or zonation) and habitat layers on this map to drive functional group biomass to preferred areas on the map, based on observational data.

## Step 1: Enable Ecoengineer Dynamics

The first step to enabling ecosystem engineer dynamics is to define the empirical relationship between engineering species biomass and derived structural complexity. We implemented this connection through the Ecospace ‘external data connections’ system (Steenbeek 2021), where the Ecoengineer plug-in acts as an intermediate calculator that calculates structural complexity while Ecospace executes<sup>7</sup>.

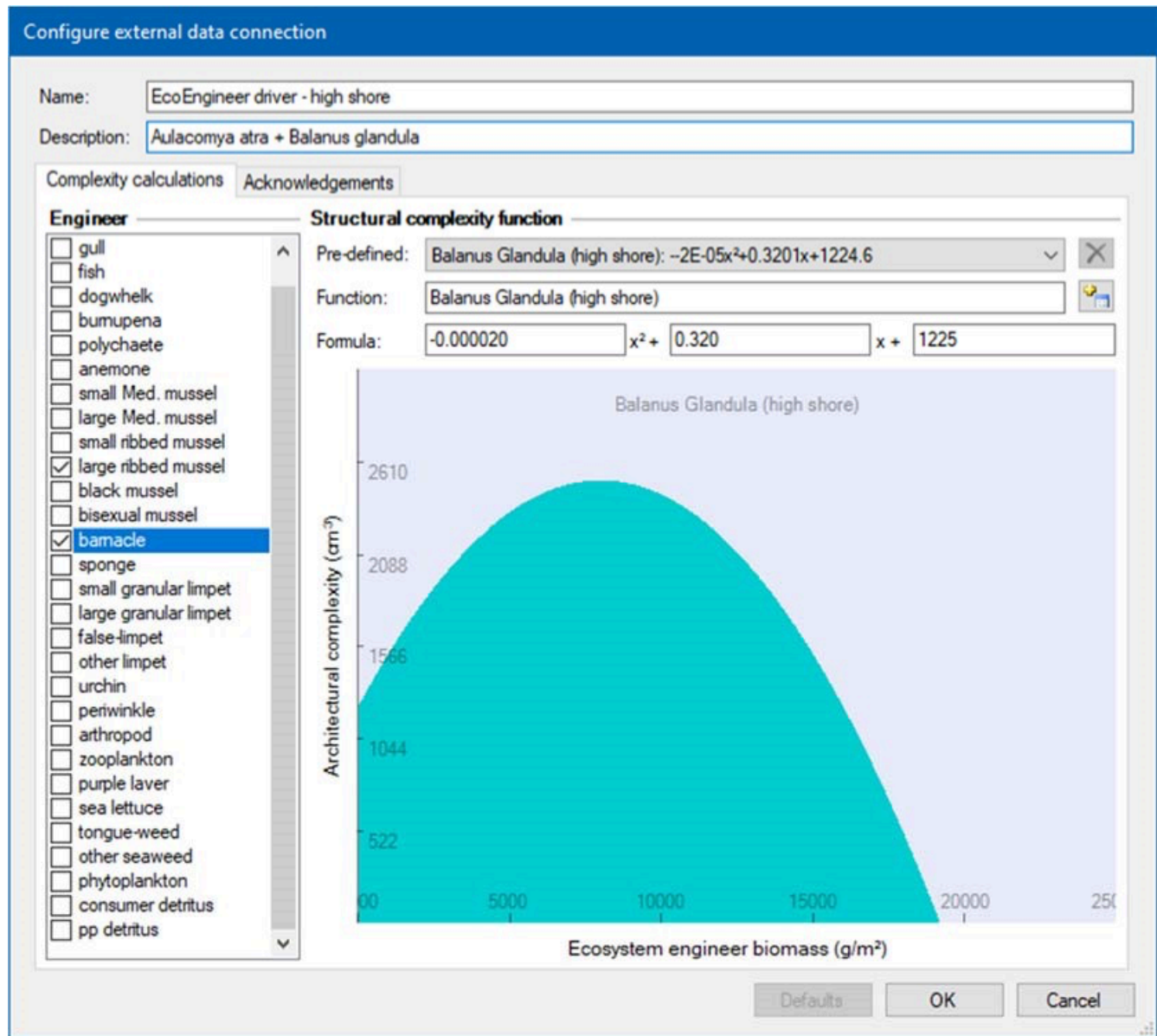


**Figure 2** – Define Ecoengineer as an external data connection

From the menu bar, go to Ecospace > Define External Data Connections. Under Connect to external spatial temporal data select the EcoEngineer driver and press Create. This new connection should now be present under the Existing connections.

## Step 2: Set Up Engineer Biomass – Structural Complexity Relationship

The next step is to parameterize the relationship between the ecosystem engineer biomasses and the structural complexity (Figure 3).



**Figure 3** – Configure the external data connection between the ecosystem engineer biomasses and the structural complexity.

Make sure the new connection is selected and press Configure.

First, provide your Ecoengineer set-up with an intuitive name and an optional description.

In the Complexity calculations tab, choose an ecosystem engineer in the left frame. In the right frame, select a predefined function of how structural complexity changes as a function of ecosystem engineer biomass (if suitable). Otherwise define formulae based on observational data, by entering parameters for a, b and c of  $y = ax^2+bx+c$ , where y is structural complexity (cm<sup>3</sup>) and x is engineering biomass (g m<sup>-2</sup>). Derivation of these calculations is discussed in Sadchatheeswaran et al. <sup>8</sup>. Repeat for all ecosystem engineers.

### Step 3: Define Ecoengineer as an Environmental Driver Map

Once empirical relationships between habitat building biomasses and structural complexity are defined, Ecospace needs to be informed of how individual functional groups respond to structural complexity. First, a new environmental driver map is needed to receive the spatial- and temporally varying structural complexity to drive structural complexity-related functional responses.

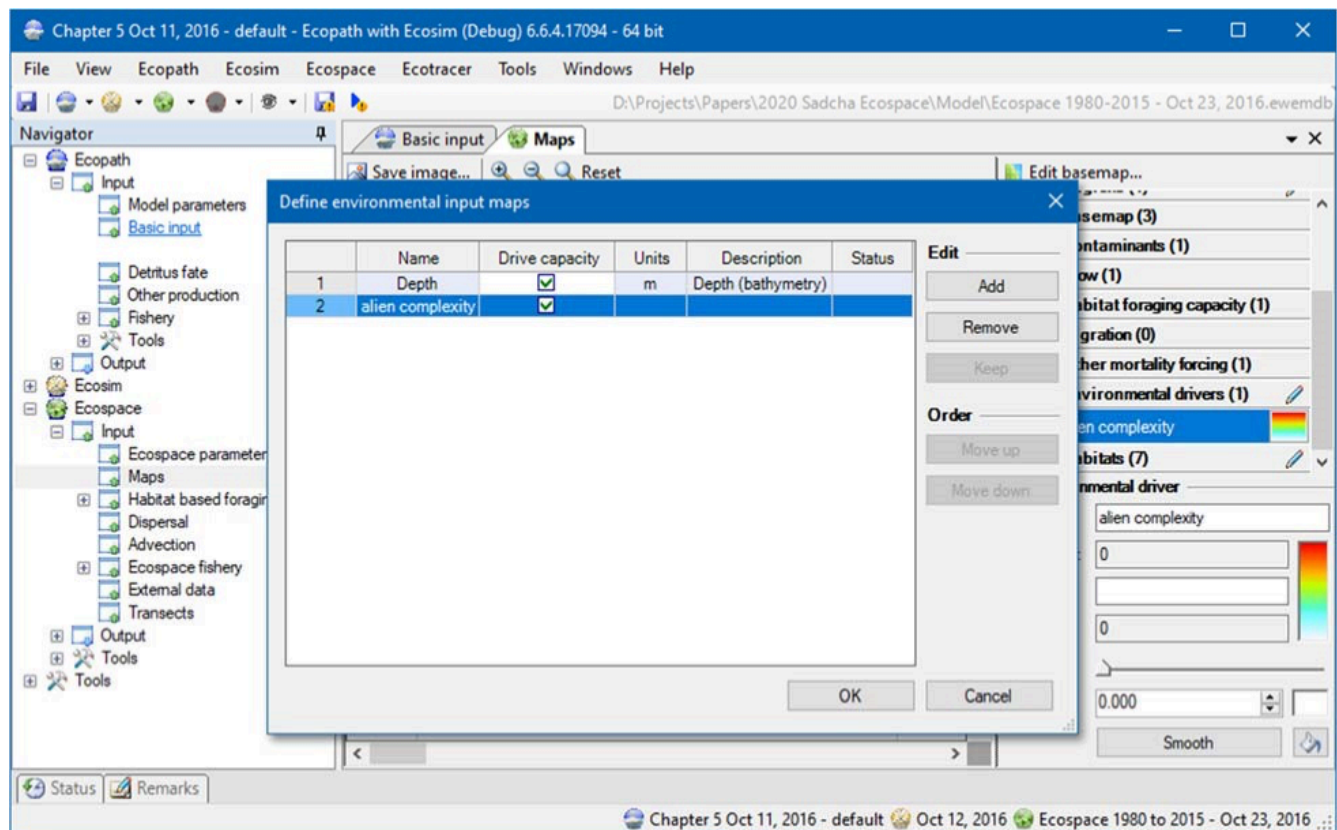


Figure 4 – Define environmental input maps.

In the Menu bar, select Ecospace > Define Environmental Driver maps. Add and name a new environmental driver. For illustration, in Figure 4, the driver was named 'alien complexity'. The driver will show up under Environmental drivers in the Map window of Ecospace.

## Step 4: Connect Ecoengineer Driver to the Environmental Driver Map

The environmental driver map, defined in Step 3, must receive the ecosystem engineer calculated complexity, defined in Steps 1 and 2. This is achieved by connecting the external driver (defined in step 2) to the environmental driver (defined in step 3). This will make the alien complexity map vary in response to changing habitat-building biomasses.

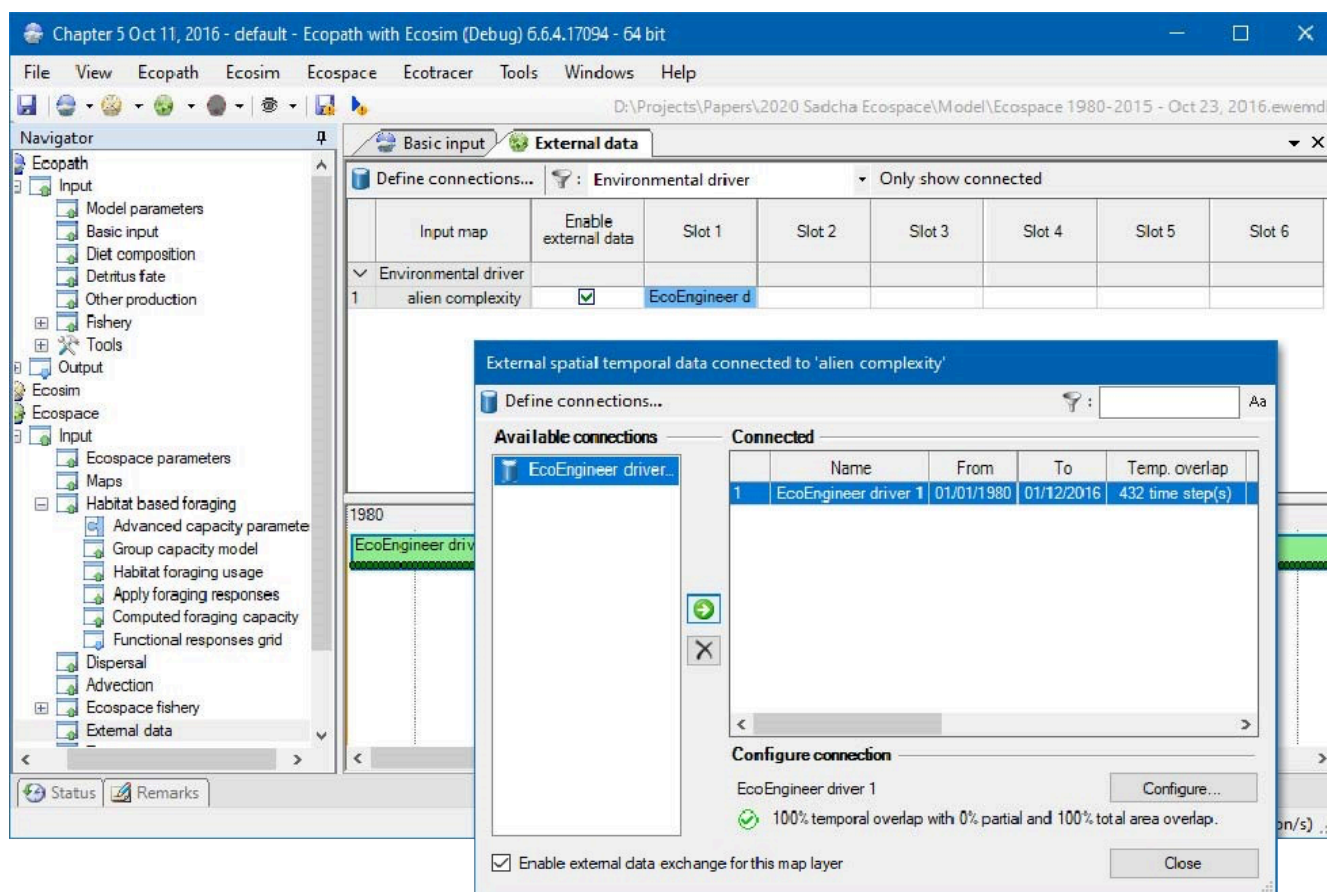


Figure 5 – External data connection setup.

In the Navigator window, select Ecospace > Input > External data. In the main window, there will

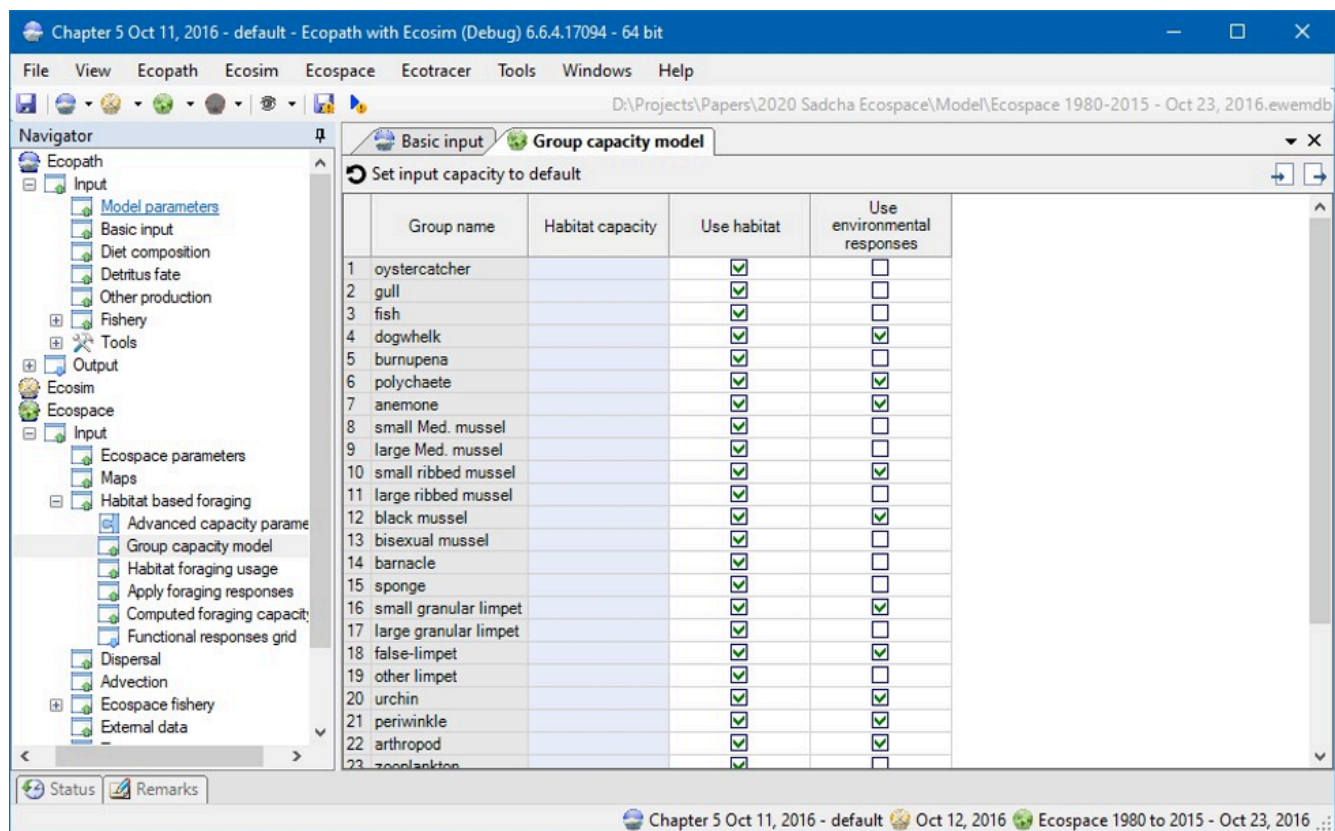
be several input maps; select Environmental drivers. Click on the column marked Slot 1 in the row marked alien complexity (for illustration) (Figure 5).

In the window that pops up, under available connections, select the Ecoengineer driver that you created and configured in steps 1 and 2, and click the right arrow button to connect the driver to the alien complexity map. Close the window.

The Ecoengineer driver is applied properly when a green time series line is present in the external data window.

## Step 5: Configure Group Capacity Model Settings

Make sure that Ecospace niche model, the habitat foraging capacity model, knows which functional groups must respond to environmental drivers.



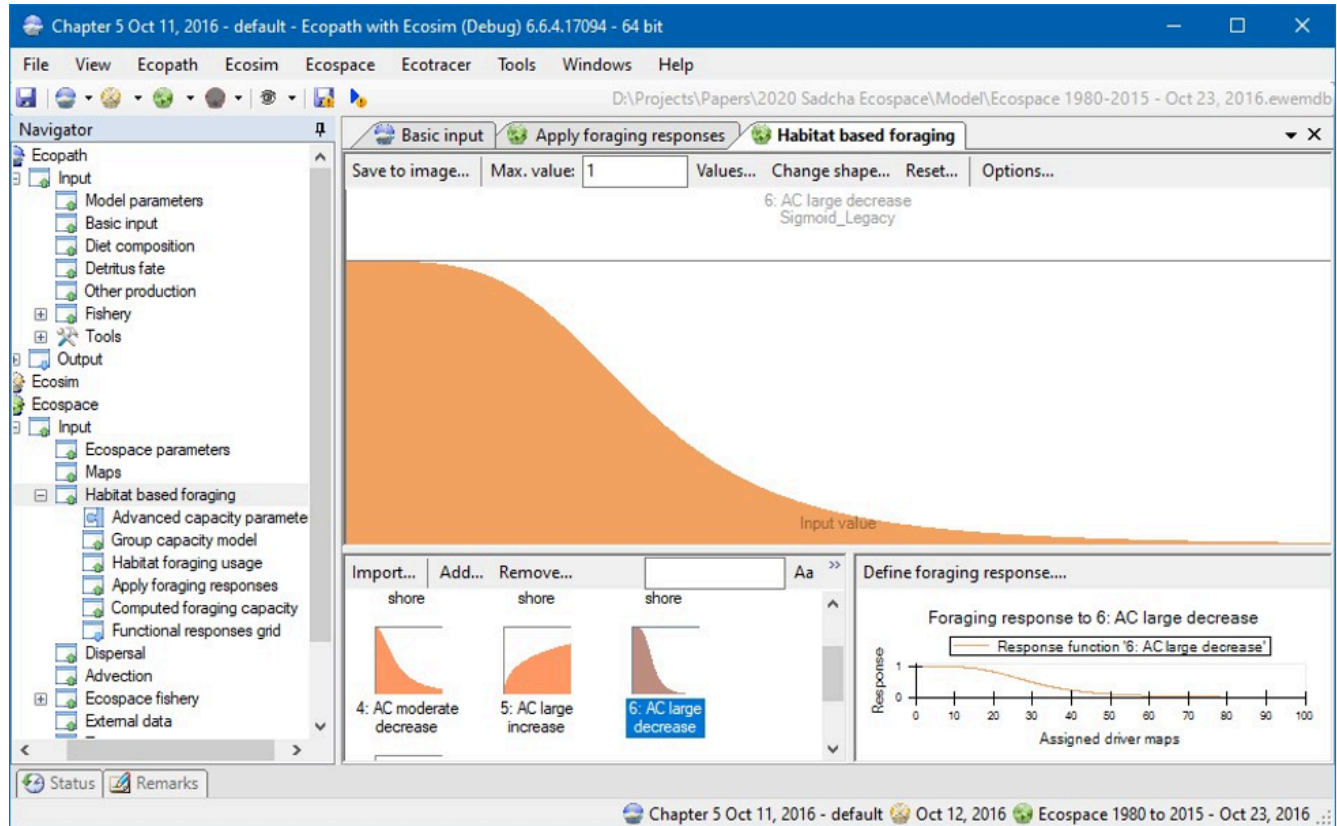
**Figure 6** – Enable Ecospace > Input > Habitat based foraging > Use environmental responses for relevant groups.

In the Navigation window, choose Ecospace > Input > Habitat based foraging > Group capacity

model. Ensure that the option “use environmental responses” is checked for all functional groups that are affected by structural complexity (Figure 6).

## Step 6: Create Foraging Responses

Next, define how individual functional groups are affected by structural complexity.

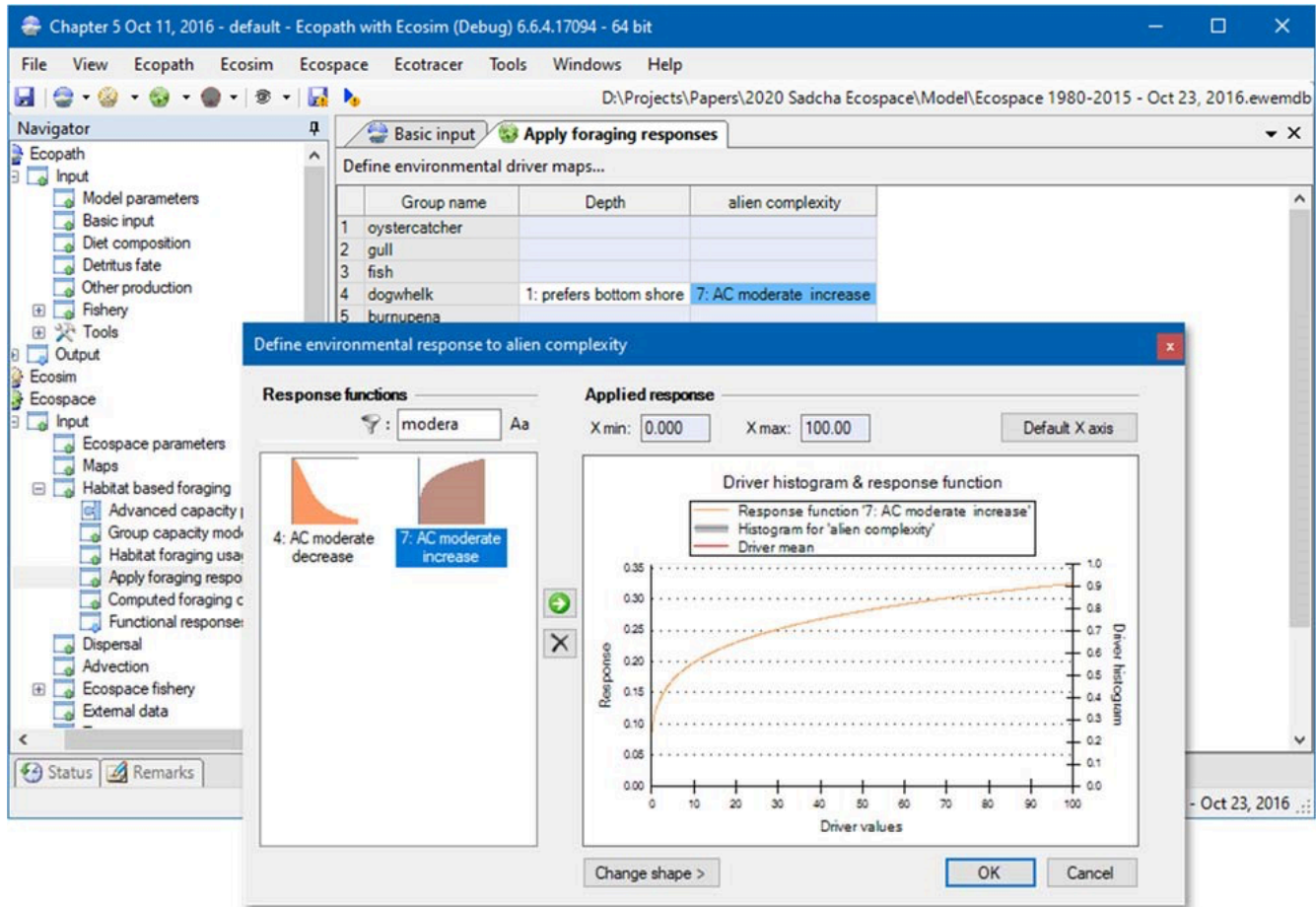


**Figure 7** – Definition of habitat based foraging response functions.

In Ecospace > Input > Habitat based foraging, create and define foraging responses that can be applied to the relevant functional groups in Apply foraging response window. These foraging responses dictate how the foraging arena of a functional group will vary in size as a function of changing structural complexity in the Ecospace habitat capacity model<sup>9</sup>.

## Step 7: Apply Foraging Responses

The last step is to make the functional groups sensitive to environmental conditions, as defined in Step 5, so that they respond to structural complexity using the functions defined in Step 6.



**Figure 8** – Definition of habitat based foraging response functions (next step).

Make sure that sensitive groups are configured to derive foraging capacity from environmental drivers in Ecospace>Input>Habitat based foraging>Group capacity model.

When Ecospace next runs, this environmental driver will be used to help drive functional groups around the map, as dictated by the foraging capacity computed by the functional responses to ecosystem engineer-computed structural complexity.

Make sure that sensitive groups are configured to derive foraging capacity from environmental drivers in Ecospace > Input > Habitat based foraging > Group capacity model (Figure 8).

When Ecospace next runs, this environmental driver will be used to help drive functional groups

around the map, as dictated by the foraging capacity computed by the functional responses to ecosystem engineer-computed structural complexity.

## References

Concept: S. Sadchatheeswaran, Biological Sciences, University of Cape Town, South Africa

Coding: J. Steenbeek, Ecopath International Initiative, Spain

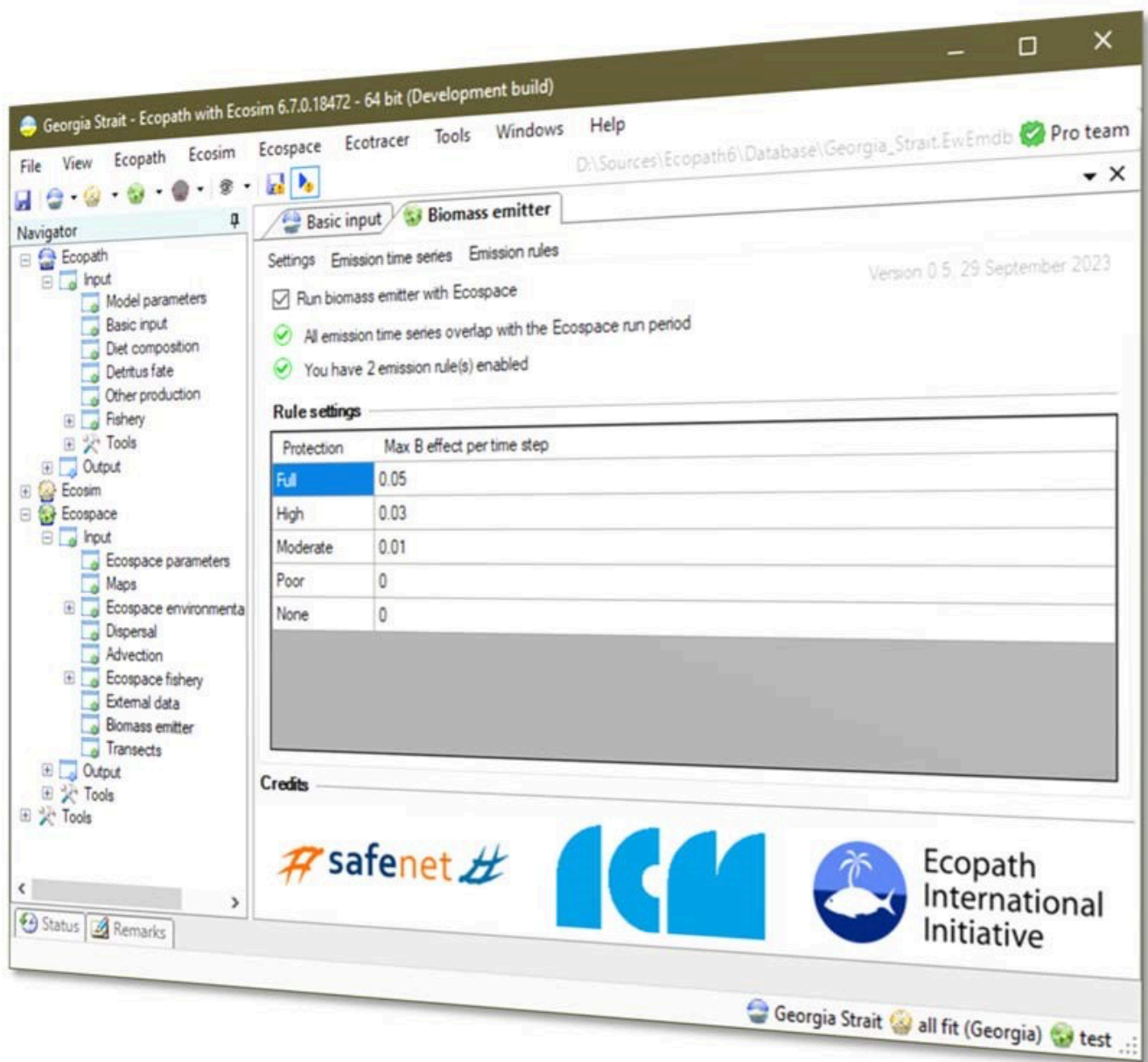
Financial contributions from the University of Cape Town, the Andrew Mellon Foundation, the South African Research Chair Initiative (funded through the South African Department of Science and Innovation (DSI) and administered by the South African National Research Foundation (NRF)), and the DSI-NRF Centre of Excellence for Invasion Biology are gratefully acknowledged.

## Notes

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# Biomass Emitter

JEROEN STEENBEEK AND MARTA COLL



## How Does it Work

Dedicated models of Marine Protected Areas (MPAs) can only be used to adequately represent

the local effects of MPAs, as these models are created at sufficient spatial scales to allow species to thrive and disperse within the MPA. Coarser models do not have the cell resolution needed to reflect these dynamics, which has been a limiting factor to deciding on spatial scales of EwE models.

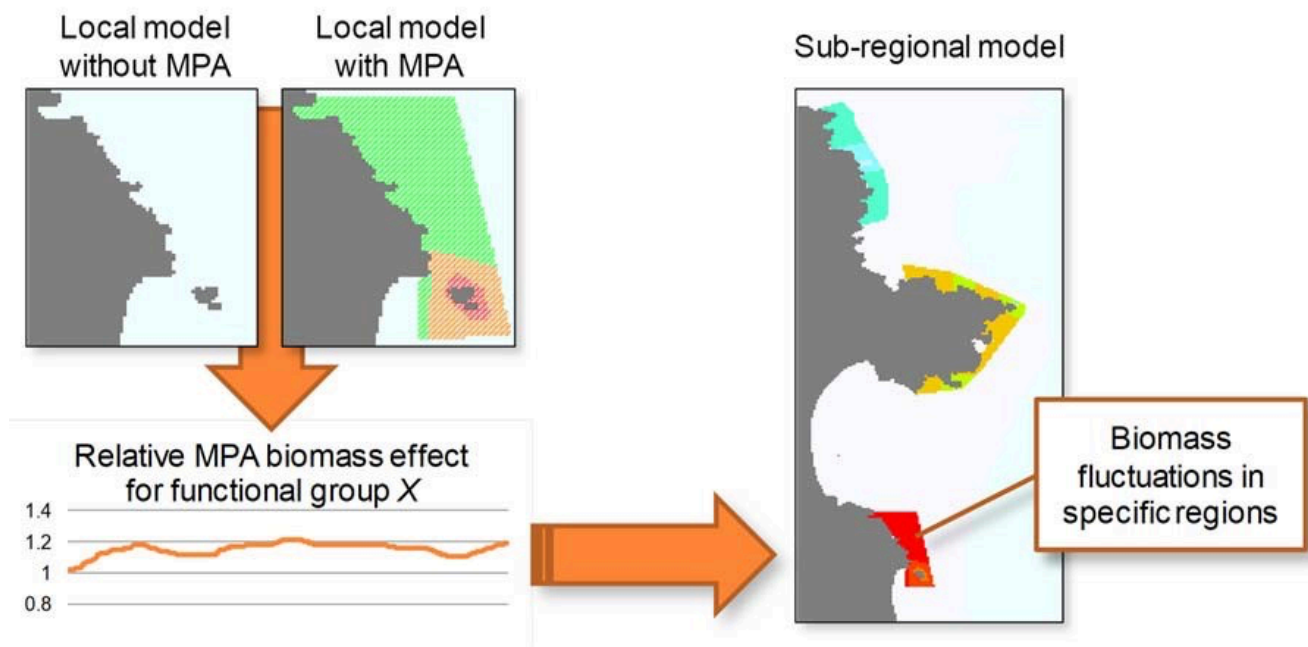
The Biomass Emitter is a lightweight plug-in to the Ecopath with Ecosim food web modelling desktop software, intended to incorporate MPA biomass effects into models with insufficient spatial resolution to properly calculate the workings of the MPAs.

The Biomass Emitter's plug-in provides two pathways to incorporate fine-scale dynamics into larger models:

1. from finer-scaled models where MPAs are explicitly modelled, or
2. from empirical rules that emulate the workings of the MPAs in absence of detailed MPA models.

We describe each of these options in the following.

## Using Detailed Models



**Figure 1** – The Biomass Emitter plug-in transfers biomass trends from regions in fine-scaled models to those same regions in coarse-scaled models. This enables regional models to integrate local predictions. The emitter can apply relative biomass trends (as depicted above) or absolute biomass trends.

To the transfer biomass effects of local features, obtained from dedicated fine-scale spatial models, the emitter uses time series of biomass effects for selected functional groups (Figure 1). These time series capture either relative or absolute change in biomass within the area of an MPA as computed by a dedicated MPA model:

1. Relative biomass trends for use in the Biomass Emitter are calculated as follows,

$$\Delta B_t = \bar{B}_t^1 / \bar{B}_t^0 \quad (1)$$

where  $\Delta B_t$  is the relative change in biomass within an MPA area at time step t;  $\bar{B}_t^1$  is the mean biomass of this group within the same MPA area at time step t extracted from an Ecospace where the MPA was active; and  $\bar{B}_t^0$  is the mean biomass of the same group within the same MPA area at time step t extracted where the MPA was not enforcing any fishing limitations.

2. Absolute biomass trends can be obtained directly from regional average-saved data.

The biomass trends needed to parameterize the Biomass Emitter can be calculated from Region Averaged CSV files, a data format natively produced by the EwE software, through a utility included with the Biomass Emitter plug-in (see below). Emission files have the following layout:

group	1	1	1	...
target	1	2	3	...
2015-01	2			
2018-01		2		
2020-01			2	
...				

**Table 1** - an example of a biomass emission data file

Each column identifies biomass fluctuations for a single group and target area over time, where the target area can identify either a region number or the sequential index of an MPA in the coarse scale model where the data is applied. Time is entered in absolute terms as ‘year-month’, and similar to Ecosim time series, emission values are allowed to be missing. When Ecospace runs, for every time step that a biomass emission value is defined, biomasses of the target group in all cells that fall within the target area will be multiplied by (relative), set to (absolute) or increased by (additive) the emission value.

## Using Emission Rules

When local MPA models are not available, and biomass trends thus cannot be obtained from localscale dedicated MPA models, the Biomass Emitter offers the ability to include biomass effects of the fine-scaled MPAs as follows:

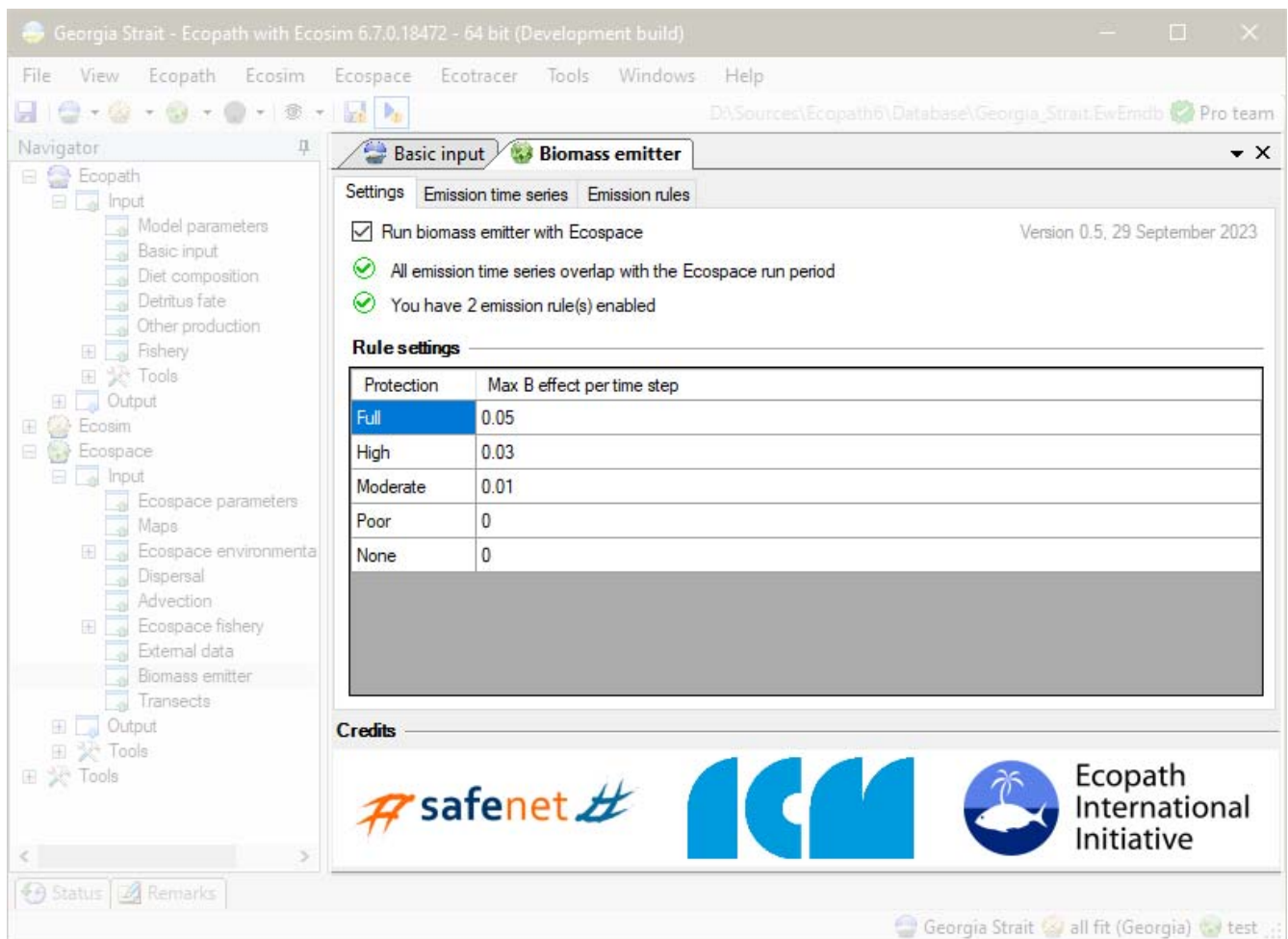
$$\Delta B_t = 1 + m \cdot \min(1, \max(0, \frac{9 - n}{5})) \quad (2)$$

where  $\Delta B$  is the relative change in pool biomass at time step  $t$ ;  $m$  is the maximum biomass effect that the MPA can achieve based on the MPA protection category as defined by e Costa et al. <sup>1</sup>;  $n$  is the cluster size (e.g., the number of connected target cells) of the target MPA. The cluster size correction dampens the emission effect when the MPA cluster increases in size, accounting for the fact that Ecospace requires at least 9 cells to mathematically represent the workings of an MPA. The max cluster size assumption is rather crude, and may need refining in the future. The maximum biomass effect  $m$  defaults to 5% biomass increase for fully protected areas, 3% biomass increase for highly protected areas, and 1% biomass increase for moderately protected areas, per month. Values of  $m$  can be customized.

## Using the Biomass Emitter

### Settings Page

Once the Biomass Emitter plug-in is installed, it can be launched from Navigator > Ecospace > Input > Biomass emitters. This brings up main settings page of the plug-in (Figure 2):

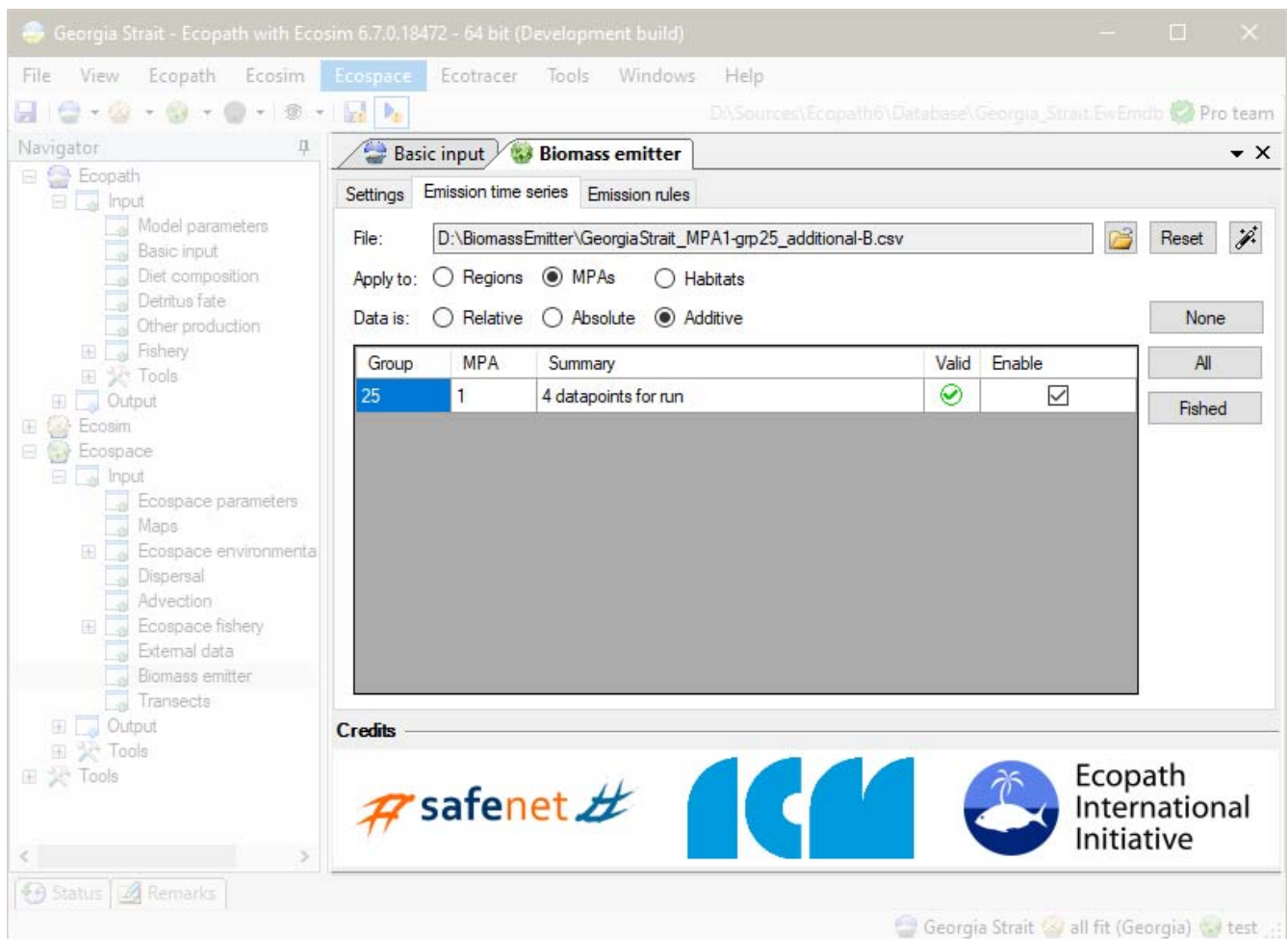


**Figure 2** – Biomass Emitter’s main settings interface.

The settings page is where the biomass emitter is enabled or disabled, where to check for possible conflicts, and where one can enter custom values of  $m$  (2) for different categories of protection. Custom values of  $m$  are stored with the system-wide settings for EwE.

## Using Emission Time Series

This emission time series configuration page shows all controls for loading (open folder symbol), unloading (Reset), and generating (magic wand) model-derived biomass emission time series (Figure 3). Loaded biomass emission time series can be applied to target Ecospace Regions, MPA or Habitats, and can be applied as relative (e.g., multiplied onto per-cell biomasses), absolute (e.g., overwriting per-cell biomasses) or additional (e.g., adding to per-cell biomasses).



**Figure 3** – Emission time series configuration page

For all loaded time series, the interface shows whether target group and area index are valid for the currently loaded Ecospace scenario, how many emission values fall within the current Ecospace run, and which emission time series are enabled. Emission time series data points are matched by absolute dates. Biomass emissions can be applied per time step, presuming that the Ecospace time step size is left at monthly defaults.

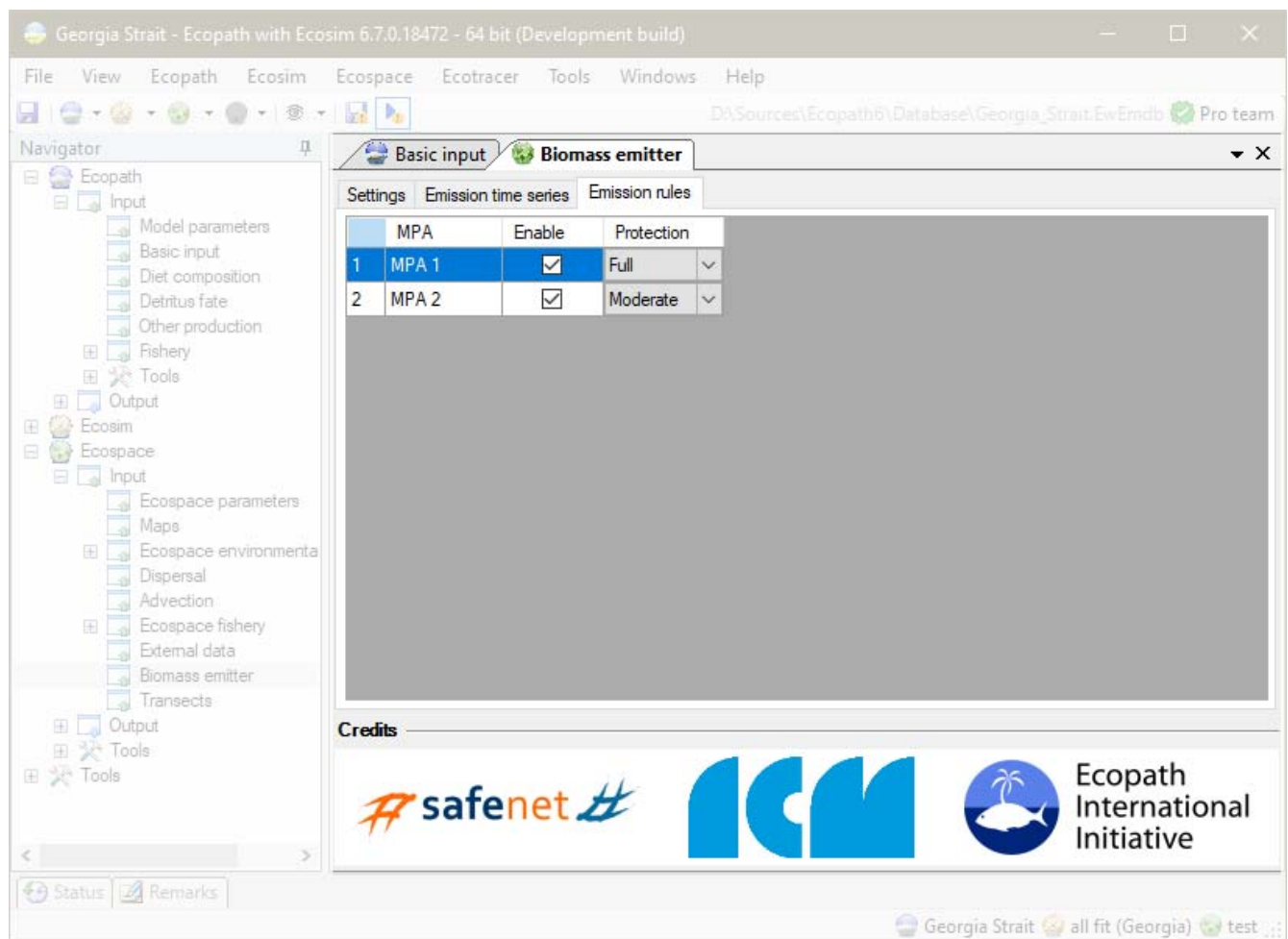
The buttons labelled None, All, and Fished are used to quickly enable or disable emission time series. Note that the fished option functions differently depending on the type of area the time series emissions will be applied to. When applying time series to regions or habitats, the fished option will enable all emission time series for fished groups.

- When applying emission time series to MPAs, the fished option will enable only those time series that apply to groups that are fished by at least one fleet that is restricted by the indicated MPA.

- When applying time series to habitats, the emission amount is scaled to the habitat cell area coverage [0,1].

## Using Emission Rules

The emission rules page requires users to specify, for each MPA in the loaded Ecospace scenario, the level of enforcement and whether a biomass emission rule needs to be applied to that MPA (Figure 4). The assigned enforcement level effectively selects one of the pre-defined  $m$  values for use in equation 2. Just like time series-based emissions, emission rules are applied at every time step.



**Figure 4** – Rule-based emission configuration page.

Note that rule-based emissions are applied to MPA cells only, and within each MPA, only to those

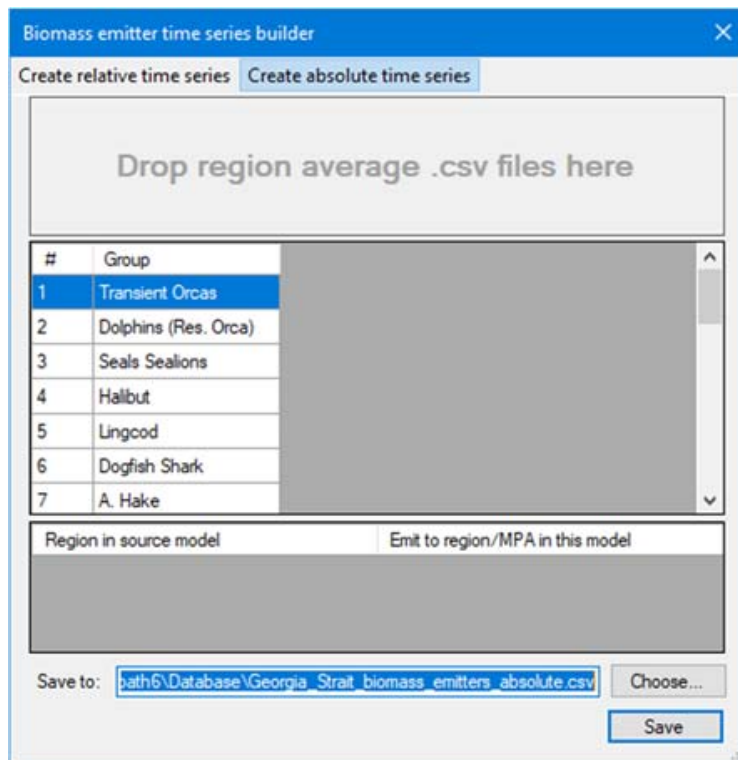
species that are being caught or discarded by fleets prohibited from fishing at the specific time step.

## Generating Biomass Emission Time Series CSV Files

Biomass emission time series CSV files can be created by hand, or can be generated from regional average CSV files that Ecospace can auto-save on demand with a utility provided with the Biomass

Emitter plug-in according to the following workflow:

1. In EwE, load the model for the dedicated MPA, load Ecospace, and enable auto-saving of Region Averaged CSV files;
2. Define regions for every MPA in the Ecospace model (Menu > Ecospace > Define Regions);
3. Run Ecospace with protection measures ENABLED (e.g., all relevant MPAs are configured to enforce some kind of protection scheme onto at least one fleet in the model for at least one month of the year);
4. If you wish to generate Relative Biomass Emission time series, continue with step 5. If you wish to generate Absolute Biomass Emission time series, skip to step 8;
5. Change the Region Averages folder name so that it starts or ends with “after” (e.g., Subregional\_01667dd\_region\_averages\_after);
6. Disable all MPAs, and run Ecospace with protection measures DISABLED;
7. Change the Region Averages folder name so that it starts or ends with “before” (e.g., Subregional\_01667dd\_region\_averages\_before);
8. In EwE, load the model where emissions need to be sent to. Load Ecospace, and launch the Biomass Emitter Time Series Builder (either by clicking in the Biomass Emitter plug-in settings page, or by selecting EwE > Menu > Tools > Biomass Emitter Time Series Builder). This brings up a form as shown in Figure 5;



**Figure 5** - Biomass Emitters time series builder interface for generating relative (left or top) or absolute (right or bottom) time series.

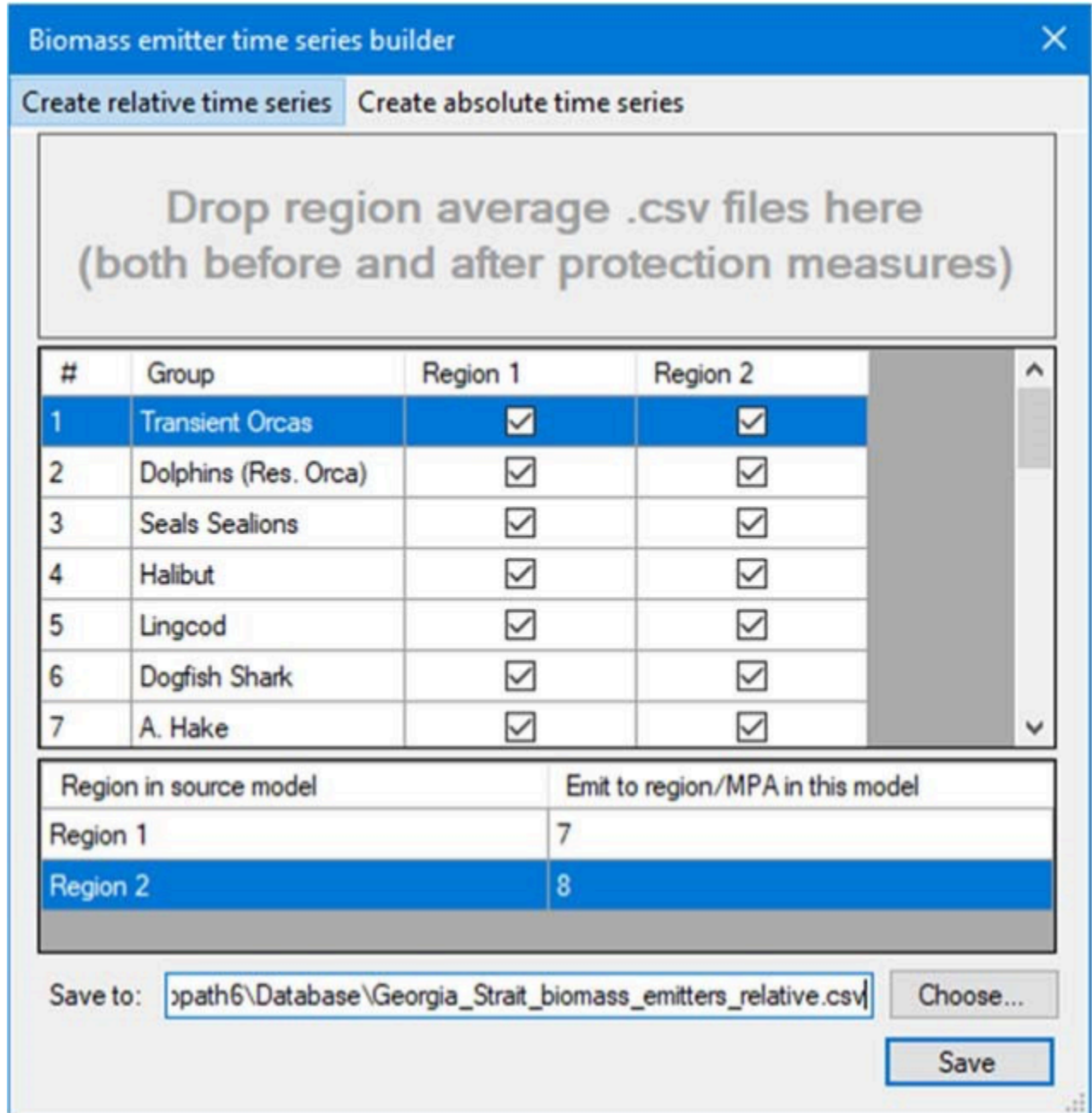
9. Drop the single region averages folder for creating Absolute Biomass Emission time series, or both the “before” and “after” folders for creating Relative Biomass Emission time series, onto the target area in the time series builder utility;
10. Select which target area the emissions need to be sent to. This can be either a region number or the sequential number of an MPA;
11. Select an output folder and file name, and click Save.

When dropping the folders with region averaged CSV files, the time series builder performs a number of checks:

- Only monthly averaged biomass files for specific regions are processed (e.g., files with names such as “Ecospace\_Average\_Region\_\*\_Biomass.csv”. Files for annual averages, files not specific to a region, and non-biomass averages are ignored;
- Group names from the fine MPA model (as written into the column headers in the region average biomass CSV files) are resolved to groups with the same name in the coarser model for which the emission time series are being created. Group name checks are not case sensitive, but spelling must be identical;

- For relative time series, both before and after folders are checked if they contain averages for the same regions. Only then can relative time series be computed.

Figure 6 shows the biomass emitter time series builder, ready to generate relative biomass emission time series, where source regions are mapped to desired target emission regions.



**Figure 6** – Biomass emitter time series builder interface, ready to create a relative time series file where source data from region 1 in the original MPA model will be mapped to region or mpa 7 in the target model, and data from region 2 to target region 8.

Note that the EwE status panel shows a history of generated emission time series files.

Also note that when the biomass emitter time series builder is launched from the EwE menu, it will act as a stand-alone utility used for generating any number of emission time series files for a EwE model in general. When launched from the biomass emitter plug-in, the time series builder will launch to deliver one specific emission file that can be directly integrated into the emitter plug-in.

## References

The biomass emitter was built under 2015-2019 DG Mare funded project SafeNet: Sustainable fisheries in EU Mediterranean waters through network of Marine Protected Areas.

## Notes

1. Bárbara Horta e Costa, Joachim Claudet, Gustavo Franco, Karim Erzini, Anthony Caro, Emanuel J. Gonçalves. 2016. A regulation-based classification system for Marine Protected Areas (MPAs), Marine Policy 72: 192-198, <https://doi.org/10.1016/j.marpol.2016.06.021>

# Spatial Optimizations (Edit)

EwE6 incorporates two routines for optimum placement of marine protected areas (MPAs) so as to maximize a user-defined objective function. This routine is implemented at Ecospace > Tools > Spatial optimizations. In order to use this routine you must have defined both an Ecosim scenario and an Ecospace scenario, and have verified the behaviour of your model.

An early version of an Ecospace routine for spatial optimization was developed as part of a thesis project at UBC <sup>12</sup>. That approach was subsequently expanded and incorporated in EwE along with an additional spatial optimization module, which uses the same objectivity function as the updated seed cell, but where the spatial cell selection process is influenced by spatial reference layers, typically of conservation interest.

Two alternative approaches to running the routine have been developed: (i) ‘Seed cell’ selection, based on the original approach of Beattie (2001) and Beattie et al. (2002); and (ii) ‘Conservation feature’ sampling, an approach, which allows the user to incorporate other forms of spatial information in the selection of protected areas.

All methods for evaluating efficacy of MPAs are crucially dependant on dispersal rates.

## Seed Cell Selection Procedure (‘Seed Cell’ Method)

This optimization method (user selects ‘Seed cell’ method) is based on a previous study (Beattie 2001; Beattie et al. 2002), in which we use a very simple optimization scheme to evaluate the trade-off between proportion of area protected and the value of the objective function. We have modified the previous approach by securing a better program flow, and by changing the objective function from considering only profit from fishing and existence value of biomass groups to a more detailed objective function described in the EwE textbook chapter on [Spatial optimization](#).

The procedure takes as its starting point the designation of one, more, or all spatial cells as ‘seed cells’, i.e. cells that are to be considered as potential protected cells in the next program iteration. The procedure will then run the Ecospace model repeatedly between two time steps, closing one of the seeds cells in each run, while storing the ecosystem objective function value. The seed cell that results in the highest objective function value is then closed for fishing, and its four

neighbouring cells (above, below, left, right) are then turned into seed cells, unless they are so already, or already are protected, or are land cells. This procedure will continue until all cells are protected. Finally, the routine will return the set of cells to be protected that would maximize the objective function.

The time over which the selection procedure is run is dependent on the application. Typically, an ecosystem model is initially developed and tuned using time series data to cover a certain time period, e.g., from 1950 to 2005. Subsequently, the model is used in a scenario development mode to evaluate, for instance, protected area placement covering the period 2006-2020.

The major result from the seed cell selection procedure is an evaluation of the trade-off between size of protected area, and each of the objectives in the objective function. This can, for instance, be used to consider what proportion of the total area to close in subsequent, more detailed analysis based on conservation feature layer sampling (see next section).

## Conservation Feature Sampling

An advantage of the seed cell modelling approach described above is that it allows a comprehensive overview of the trade-off between proportion of area closed to fishing, and the ecological, social, and economical benefit and costs of the closures. This is done, based on the information already included in the EwE modelling approach, with no new information being needed. While this may be an advantage from one perspective, it does not allow use of other form for information, notably in form of spatial information, e.g., critical fish habitat layers from GIS.

To address this shortcoming, there is a conservation feature layer optimization routine in Ecospace. This approach uses spatial layers of conservation interest to set likelihoods for spatial cells being considered for protection. The optimizations are performed using a Monte Carlo approach where the conservation feature layers are used for the initial cell selection in each MC realization. The Ecospace model is then run, the objective function is evaluated, and the results, including which cells were protected, are stored for each run.

It is important to note that the conservation feature layers are not used to evaluate the objective function. The information in these layers is used only to influence initial cell selection.

The conservation feature layers are defined as raster layers, with dimensions similar to the base map layers in the underlying Ecospace model, i.e. they are rectangular cells in a grid with a certain number of rows and columns. Each cell in a given layer has a certain importance for conservation, expressed, e.g., as the probability of occurrence of an endangered species. For each conservation

feature layer  $l$ , we initially scale the importance layer values to sum to unity, and then calculate an overall cell weighting  $w_c$  for each cell  $C$  from

$$w_c = \sum_l w_l C_{c,l} \quad (1)$$

where  $w_l$  are the conservation feature layer weightings, and the  $C_{c,l}$  cell-specific, scaled conservation feature layer values.

Similar to the seed cell selection procedure, we typically develop and tune the model to an initial time period, and then use the sampling procedure to evaluate scenarios for protected areas for a subsequent time period.

Ecospace can import raster files with spatial information such as conservation feature layers or other Ecospace base map layers. The reading is possible from comma separated text files (.csv), ESRI ASCII files (.asc), and ESRI shape files (.shp). The files need to have layers or columns with row and column numbers matching the Ecospace model (see below for details).

Further information can be found in the EwE textbook [Spatial optimization](#) chapter, and it is strongly recommended you read that chapter before running analysis with the approach.

## Implementing Spatial Optimizations in Ecospace

The Spatial optimizations form is divided into two sections. Inputs are entered in the top half of the form in the Configuration and Map Input tabs. Results are displayed on the bottom half of the form on the Progress and Results tabs.

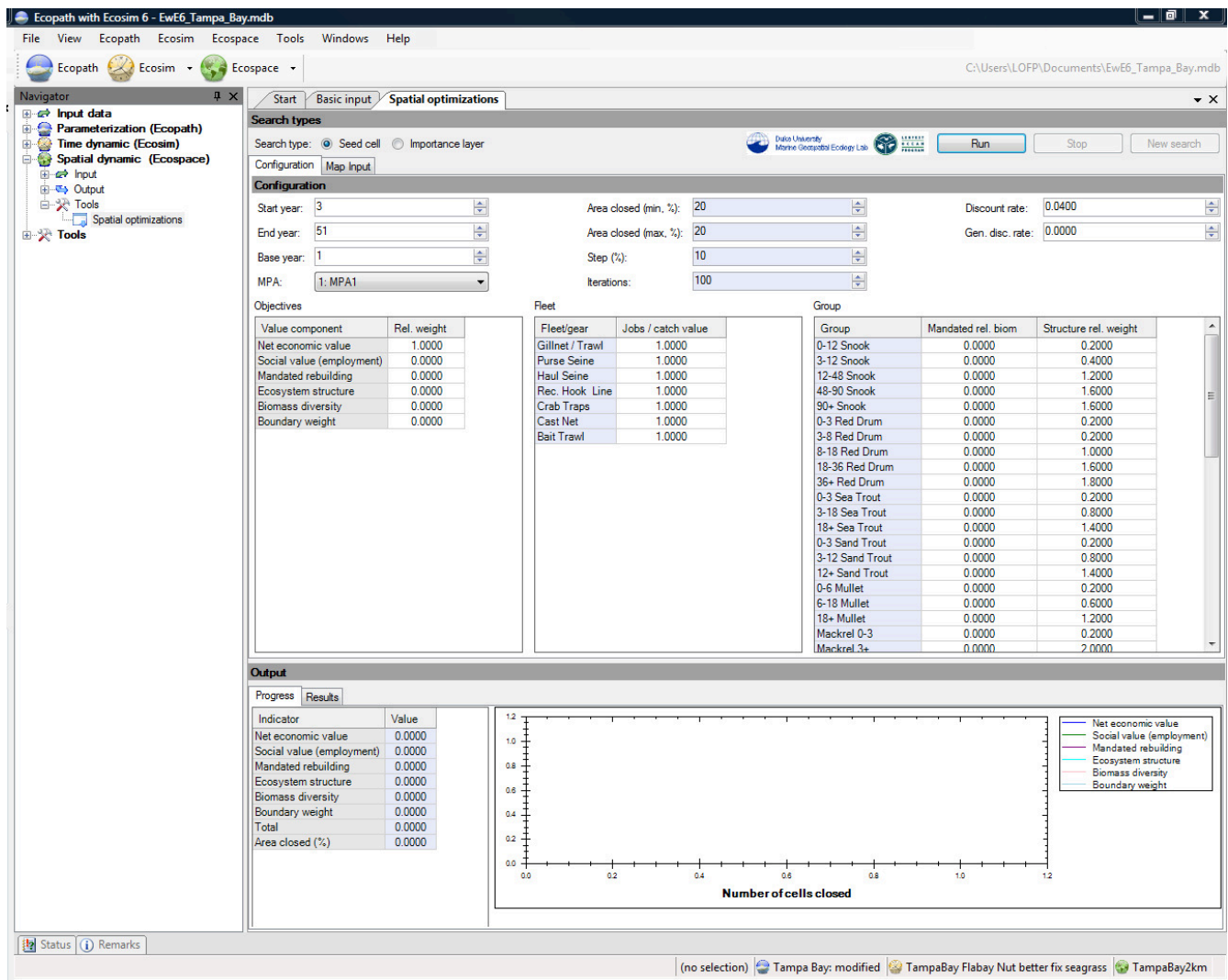


Figure 1 – The Spatial optimizations form, Configuration tab.

## Configuration Tab

Users can choose between two methods of implementing the spatial optimisation routine: Seed cell or Importance layer (see [\\_Ref493389844](#) above). Before proceeding with the optimization routine, users should first select one of these two options in the Search box on the Parameters panel of the form (Figure 11.3). Selection of one of these methods will determine the inputs required.

In both cases, users must set the Start year and End year for the optimization search. If Start year is set to 1, the routine will start running Ecospace and evaluating the objective function from the first year of simulations. However, in many cases, users will wish to run Ecospace for a period of time, perhaps to allow the model to fit historic trends, before optimization begins. It is generally

not a good idea to start the optimizations at year 1, as Ecospace as a rule needs to react to initial imbalance in how groups are distributed spatially. If for instance a predator has little spatial overlap with its main prey in an Ecospace scenario, then the biomass of the predator will likely fall initially, even under constant fishing pressure, and the prey increase.

To proceed, set Start year to the first year that the objective function is to be evaluated, e.g., if Start year is set to five, Ecospace will run for four years and then start the search routine in year five. Set End year to the year in which the search routine is to stop. The appropriate length of time over which to run the optimization routine will depend on the time horizon of the particular management question and the life span of the species affected by the MPA. When running, Ecospace will only run up to the Start year once,

save all information in memory, then run iteratively from Start year to End year, jump back to Start year, and so on.

In both cases, users can also select an MPA previously defined on the Ecospace Basemap (see also Define Ecospace habitats). The cells bordering the MPA will then also be used as seed cells and the selected MPA may be modified during the search. Any other MPAs will be unaffected by the search.

Additionally, if Importance layer is selected, the user defines the minimum and maximum area (Min area % and Max area %, with step size Step %, all expressed as percentage of water cells, i.e. ignoring land cells) to be set aside as MPA. The percentage area to be protected can be set to a fixed value by setting Min area % and Max area % to the same value. Users also set the number of Iterations that will be implemented in the Monte Carlo search routine (see above).

The search routine is initialized using the Run button. It can be stopped using the Stop button.

NOTE: If you initialize a search then stop the search, you cannot restart it or change input parameter values. You must use the New Search button to start a new search.

## Objectives

The objective function used in the routine is analogous to that used in Ecosim's Policy optimization routine. It is strongly recommended you read Spatial optimization procedures for detailed description of the objective function.

Use the Objectives table (Figure 11.3) to define objective function weights for Net economic value (total landed value of catch minus total operating cost); Social value (employment), i.e., a social indicator, assumed proportional to gross landed value of catch for each fleet with a different jobs/landed value ratio for each fleet; and two ecological objectives: 1. Mandated rebuilding of

one group (value of the objective function is measured by departures of biomasses over time from target biomass levels specified by entering ratios of target to Ecopath base biomasses); and 2. Ecosystem structure, which favours biomasses of large, long-lived organisms. See Policy objectives in Fishing policy search and Christensen and Walters (2004b) for more details about these objectives.

Use Boundary weight to adjust the weight given to size/border ratio of the protected area in the objective function. This is estimated as protected area size over the total boundary length, and captures spatial connectivity of protected areas.

Note that you may initially need to play with different values for the objective function weight for each factor to find ranges that produce contrast in the final value of the objective function.

You may also need to set extra parameters for these using the two tabs on the Configuration panel. Use the Fleet table to set the number of jobs relative to the catch value. The default is 1 for each fleet, implying that if the catch doubled, the number of jobs would also double. For economic objectives, you may wish to adjust the Discount rate and Generational discount rate. The discount rate is the annual rate (entered in %) applied to discount the present value of future catches relative to present base value. See Ainsworth and Sumaila (2005) for description of intergenerational discounting.

The Group table has two columns:

Mandated rel. biomass

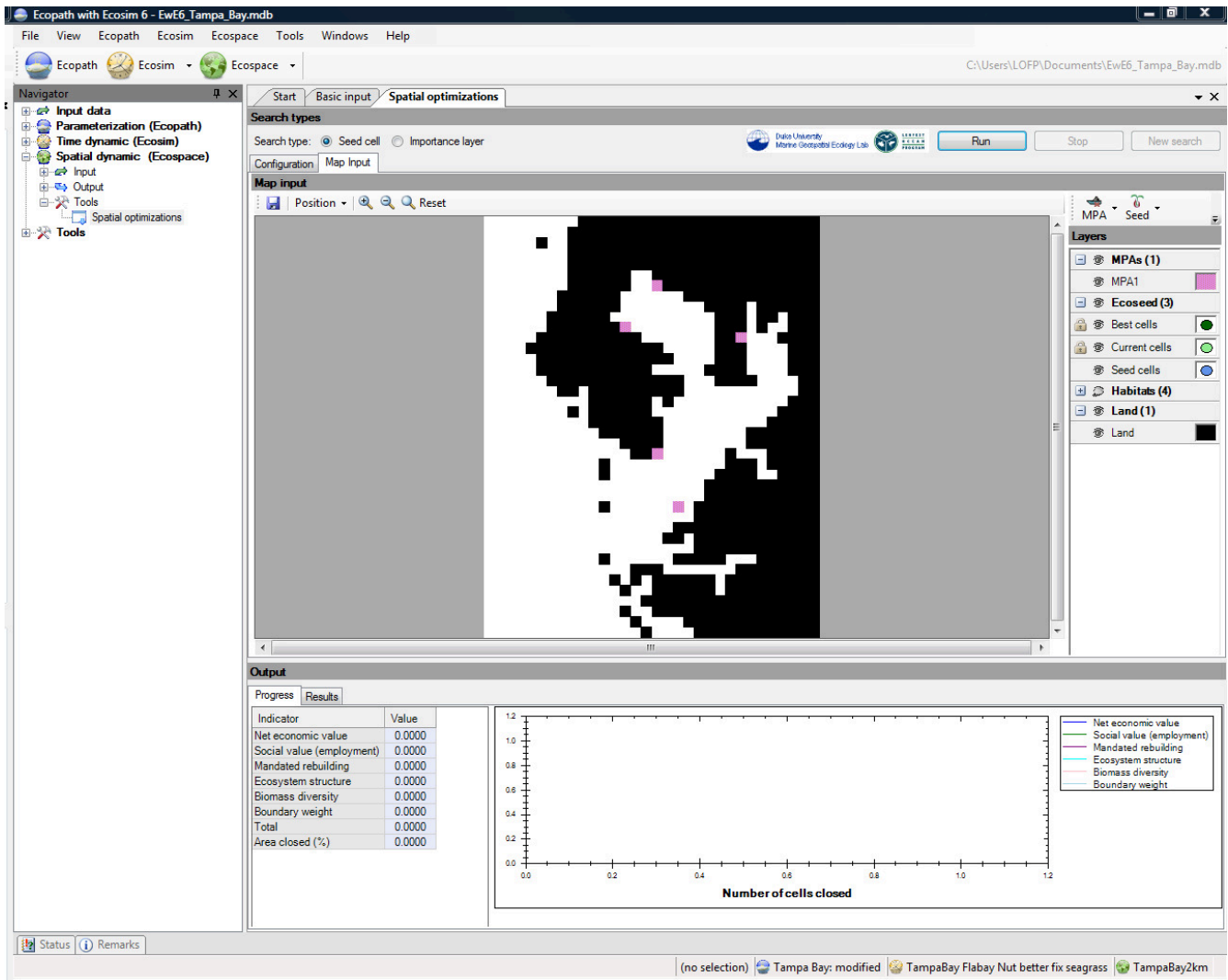
Use this column to set a threshold biomass (relative to the biomass in Ecopath) for the species or group of interest.

Structure rel. weight

When Ecosystem structure is included in the objective function, the search routine favours larger biomasses of long-lived organisms, indicated by B/P (i.e., P/B-1). These values are listed in the Structure rel. weight column and can be changed if users wish to place more or less weight on some groups than indicated by their B/P or if the user wishes to optimize for something other than B/P under the ecological objective.

## Map Input tab

The Map Input tab displays the Ecospace basemap associated with the Ecospace scenario that has been loaded. It displays progress of the search and the final results of the analysis.



**Figure 11.4b** – The Spatial optimizations form, Map Input tab.

## Layers


The Layers panel is also found on the Map Input tab. Available options will change, depending on whether the Seed cell or Importance layer search is selected. Note that the Layers panel has a root directory format, which can be collapsed or expanded using the plus and minus icons. Use the eye symbols

to show [  ] or hide [  ] layers on the Map.

## Seed Cell



When Seed cell has been selected on the Configuration tab, use the Layers panel (see image below) to set seed cells.


You cannot set Best cells or Current cells, as these are output results, but you can edit their appearance (i.e., colour) by clicking once on the symbol (coloured circles in the image below). This will open a dialogue box (the Edit layer dialogue box, see image below) where the colour of the symbol can be set. You can also change the appearance of Seed cells in this way. Once you have set the appearance of seed cells, click OK to close the dialogue box.

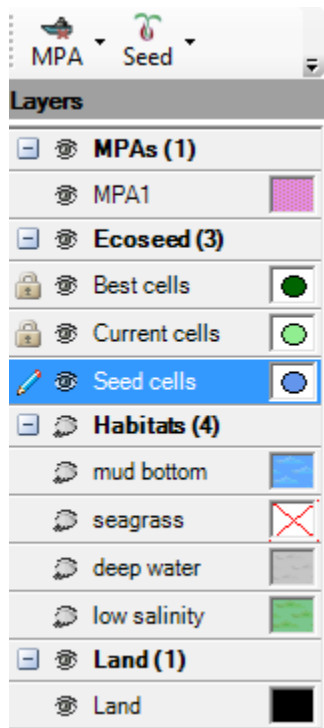
Click to the left of the Seed cells eye symbol to pick up the pen tool [  ]. You can now click on the Map to select cell(s) to be used as seed cells. These will be indicated by a coloured circle (blue in this example). Note that you can use the Seed button at the top of the panel (see image below) to Clear all seed cells or Set all cells as seed cells.

Note also that if you now click on the Seed cells symbol (blue circle in the image below) the Edit layer dialogue box will now display the location of the seed cell(s) in the Description and Appearance tab. The Data tab of the Edit layer dialogue box displays the map as a spreadsheet of numbered cells corresponding to the cells on the map. Seed cells are indicated by 1 and all other cells are indicated by 0. Note that 1s and 0s relate only to the layer currently being edited. These data can be exported to a csv file using the Export

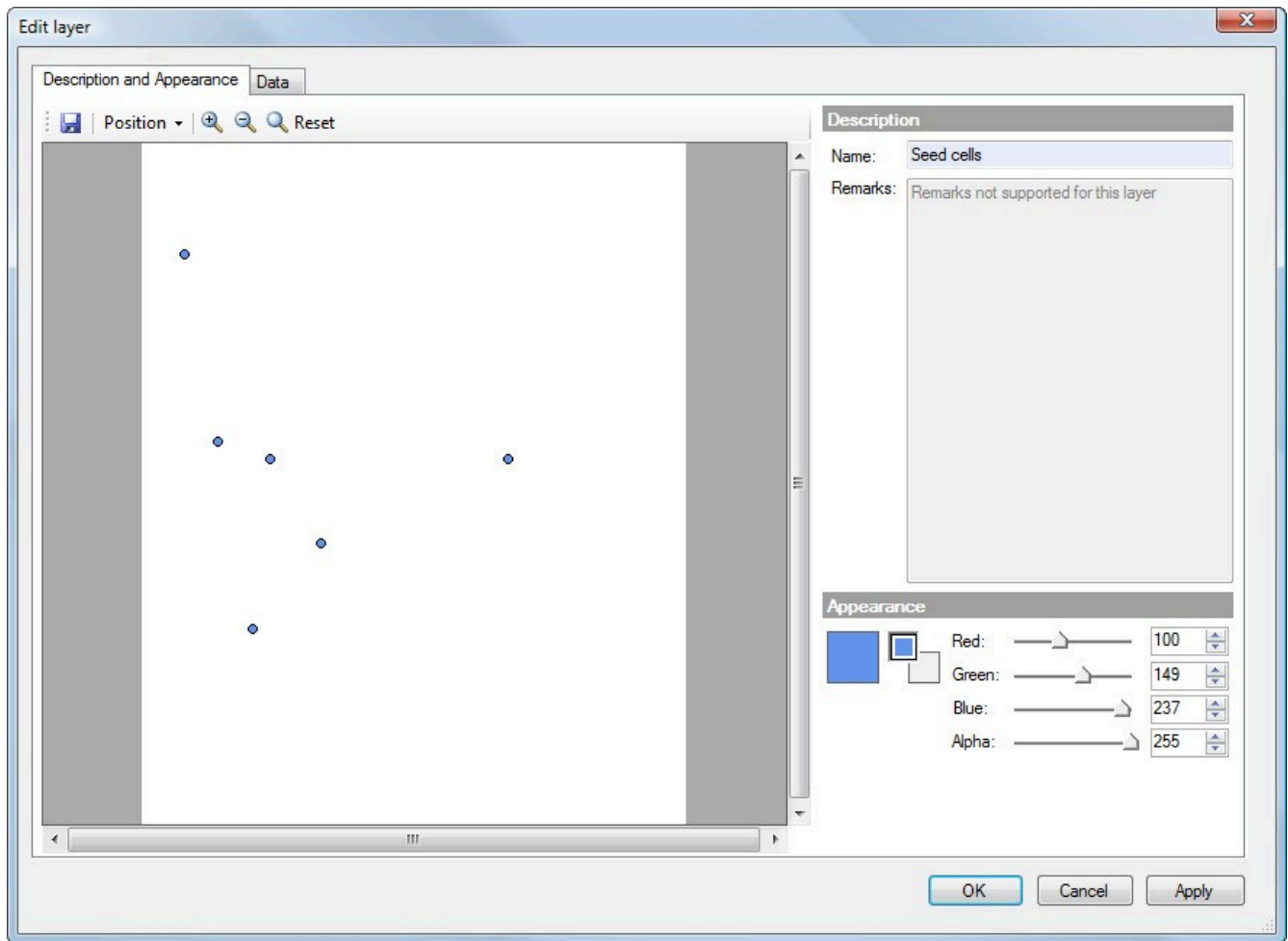
... button on the Data tab.

 Habitats, MPAs and Land can also be modified using the Layers panel. Again, use the eye icon [  ] to

show or hide layers. Use the pen tool [  ] to modify location of these layers on the Map. Note that you can use the MPA button at the top of the panel (see image below) to Clear all MPAs or Set all cells as MPAs.



The Layers panel on the Map Input tab (Seed cell configuration).

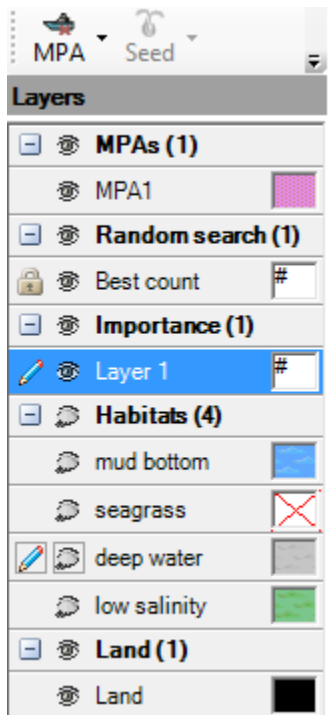


The Edit layer dialogue box.

### *Importance layer*

When Importance layer has been selected on the Configuration tab, the Layers panel (see image below) is used to set Importance layers (users do not set seed cells). Note that importance layers are not used in calculation of the objective function, but rather are used to give greater importance to certain cells during random selection of seed cells. There are a number of ways to read in data for setting or importing importance layers. See [Setting importance layers](#) for full details on importing data importance layers. See [Spatial optimization procedures](#) for more on Importance layers.

After you have imported the importance layers, they will be displayed in the Layers panel.

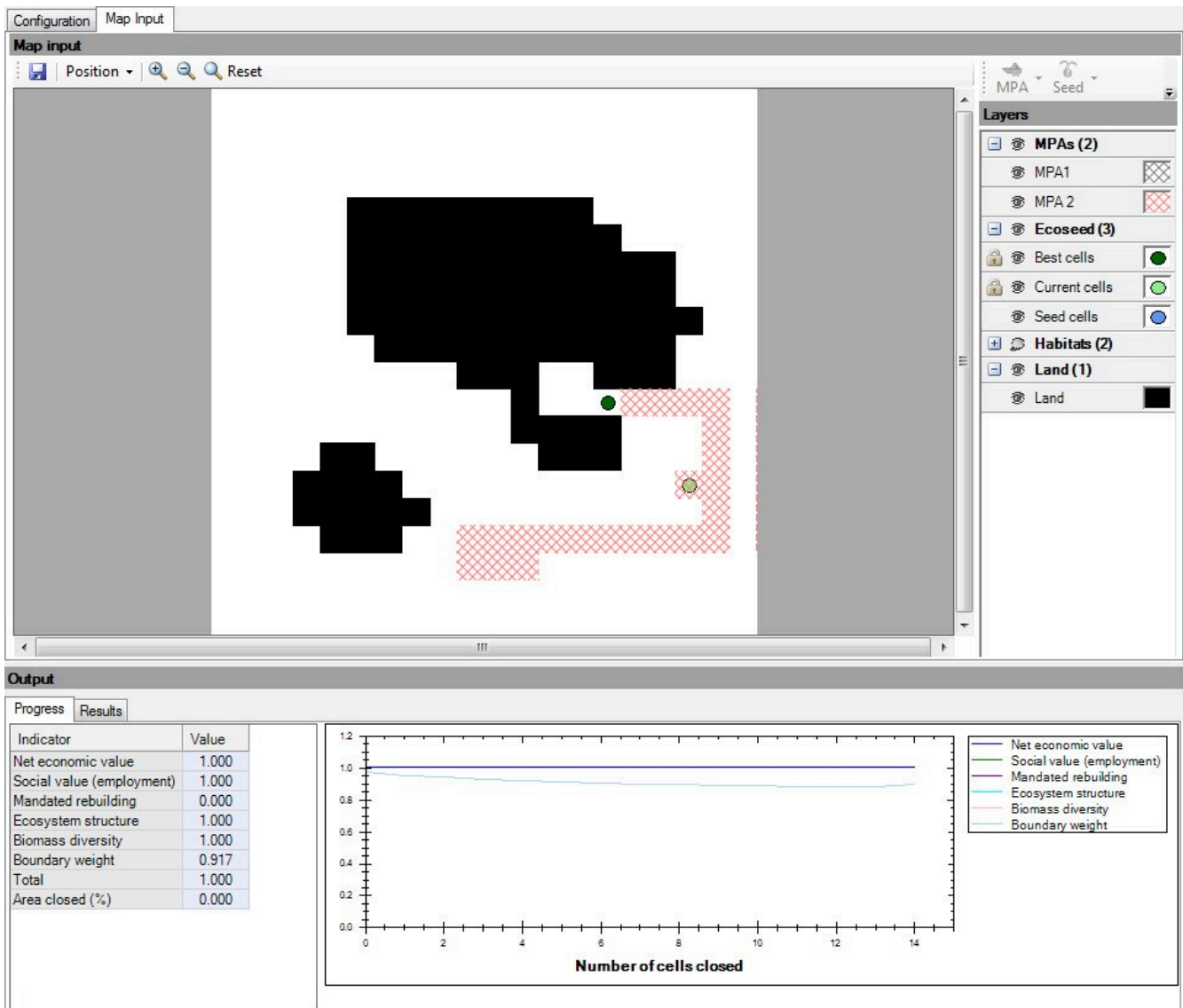


The Layers panel on the Map Input tab (Importance layer configuration).

## Output

### *Progress Tab*

As the search algorithm proceeds, progress is displayed on the Progress tab of the Output window (image below). On the left of the Progress tab, relative values of the components of the objective function are displayed. On the right, relative values of the components of the objective function are shown as a function of number of cells closed.



## Results Tab

When the algorithm has finished, results are shown on the Results tab. Results are displayed graphically, as on the progress tab, as relative values of the components of the objective function, and are displayed as a function of the number of cells closed. Results are also shown in tabular form at the right of the Results panel and as MPAs on the Map Input panel.

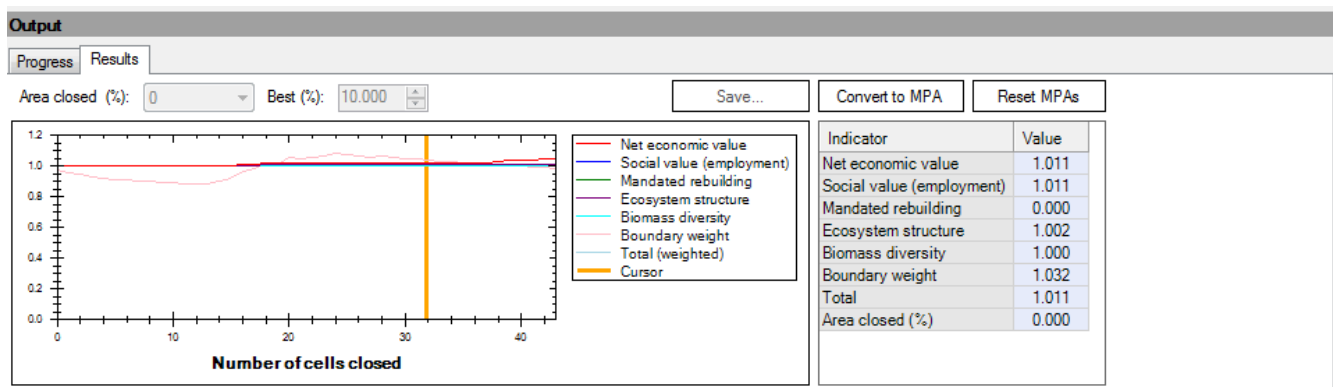
Results can be filtered in three ways.

- You can hover with the mouse over the final results graph to display results at that location on the graph (vertical orange line below). Results at this location are displayed in tabular form on the right of the panel.

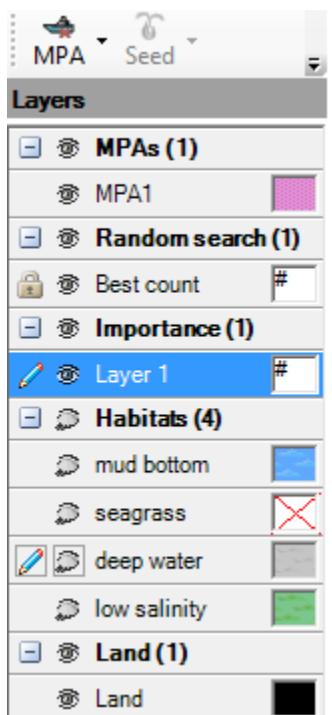
- You can also use the Area closed (%) window, above the graph, to select results to display.
- You can also use the Best (%) window on the Results tab to filter which results are displayed on the map (e.g., if 10% is selected, only results that produced the top 10% of objective function values will be displayed).

Final filtered results can be saved to csv file using the Save... button. The final filtered results can be converted to MPAs on the base map using the Convert to MPA button. This will result in MPAs with the highest count in the selected Best (%) being placed on the Basemap for the current Ecospace scenario.

Original MPAs can be reset using the Reset MPAs button.



## Setting Importance Layers

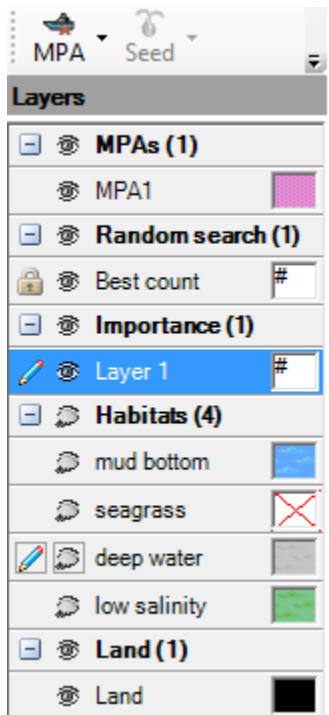


When Importance layer has been selected on the Spatial optimizations form, the Layers panel on the Map Input tab is used to set Importance layers. Importance layers are used to give greater importance to certain cells during the random selection of seed cells as part of the Spatial optimization procedure.

NOTE: Values in importance layers have no effect on calculation of the objective function (see Spatial optimizations procedures). There are a number of ways to read in data for setting importance layers, listed here.

## Reading in Importance Layers

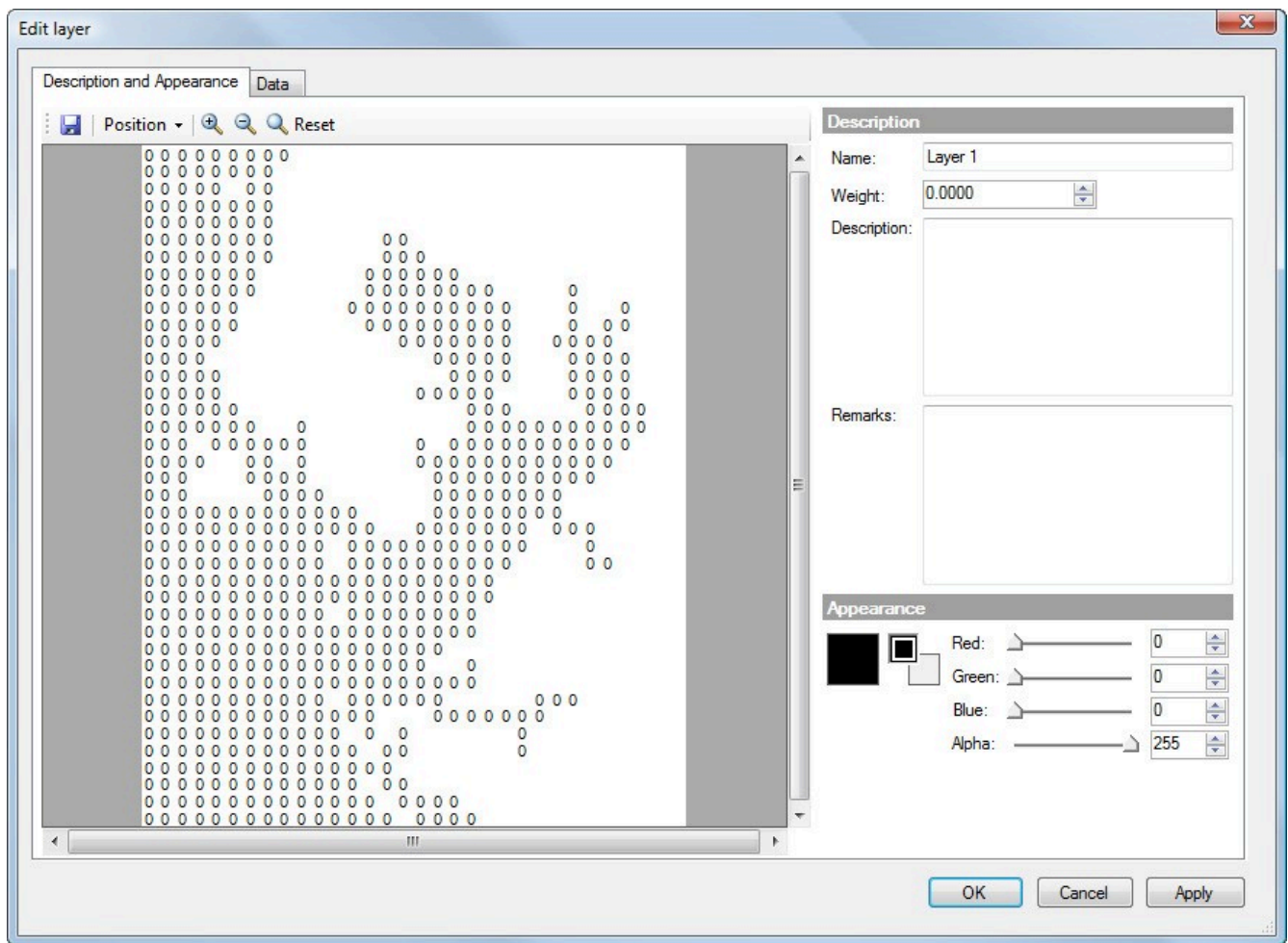
- To read in importance layers, make sure you have first, loaded an Ecosim and Ecospace scenario, and opened the Spatial optimizations form. After setting input parameters and selecting Search type: Importance layer on the Configuration tab, go to the Map Input tab.



The Layers panel on the Map Input tab of the Spatial optimizations form (Importance layer configuration).

- In the Layers panel, double click on the layer for which you want to import data (highlighted in the image above). This will open the Edit layer dialogue box. You can use this dialogue box to edit the description and appearance (i.e., display colour) of the importance layer.

IMPORTANT NOTE: You must also assign the layer a Weight on the Description and Appearance tab (see image below). Importance values are normalised within each importance layer. Therefore the Weight assigns relative importance of layers relative to one another.



The Edit layer dialogue box (Description and Appearance tab), before data entry.

- Next, click on the Data tab (image below). The tab contains a spreadsheet with exactly the same row and column configuration as the Ecospace Base map. Numbers entered into the cells on the Data tab represent relative importance weights for each cell within the layer. Note that the routine will normalise all values on the sheet, so only relative values are required (i.e., units are unimportant).

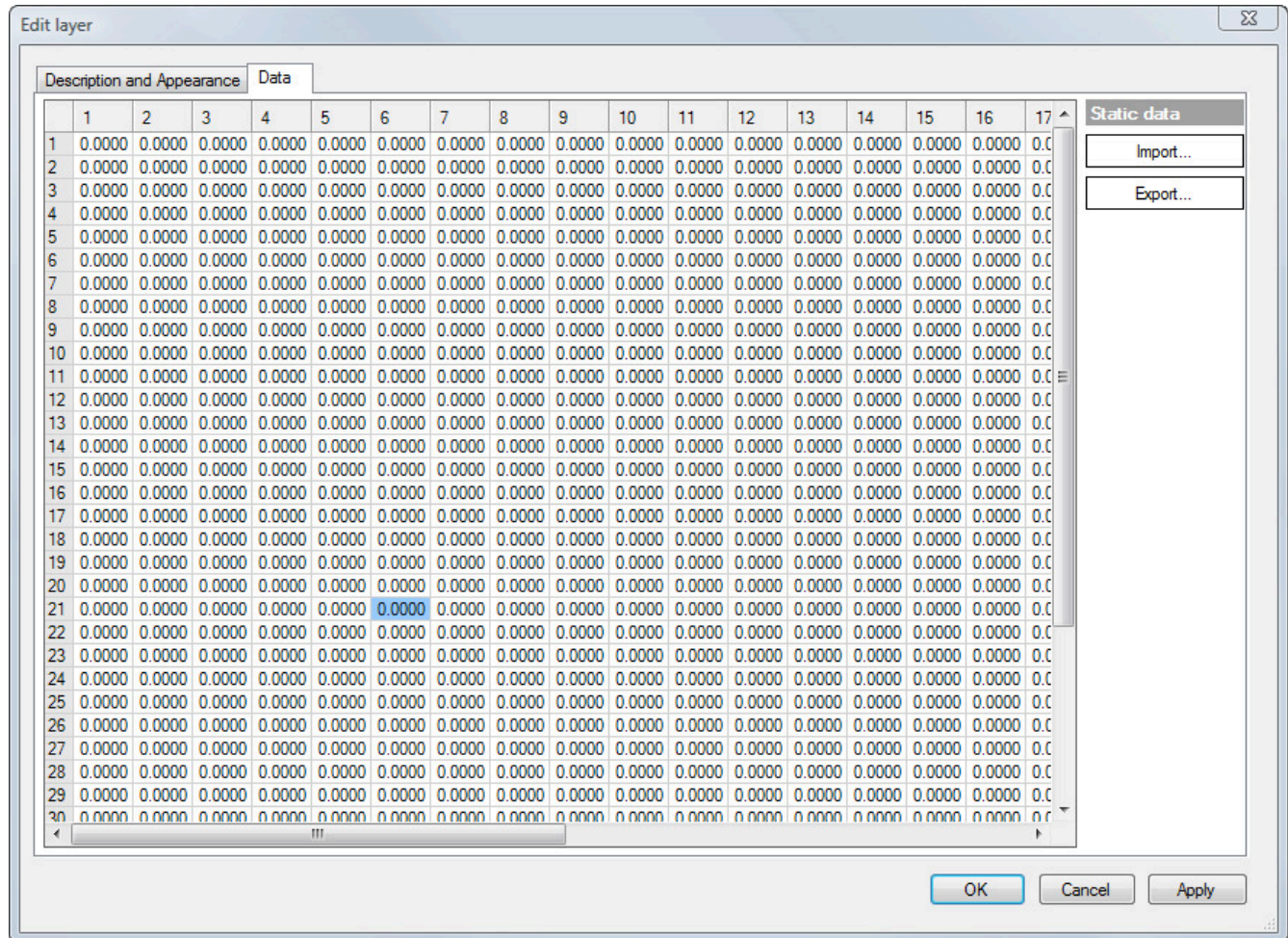
NOTE: There are two methods to enter data into the Data tab.

In the first method, copy and paste cells directly from a spreadsheet into the cells on the Data tab. Note that the data must be in exactly the same configuration as the cells in the base map. Assign greater importance to the cells of conservation interest (e.g., marine mammal breeding habitat; fish nursery areas; known habitat of rare species). Assign zero importance to cells of no

conservation interest and land cells. After entering data this way, close the dialogue box and return to the Spatial optimizations form.

In the second method, Ecospace can read in raster files with spatial information such as importance layers or other Ecospace base map layers. It is possible to read from comma separated text files (.csv), ESRI ASCII files (.asc), and ESRI shape files (.shp).

To use this method, first click on the Import ... button on the Data tab. This will open the Import layer data dialogue box. Proceed to Step 4 below.



The Edit layer dialogue box (Data tab), before data entry.

- Click on the Open icon  on the Import layer data dialogue box (image below) and navigate to the location of the data file.

NOTE: at the bottom right of the Open dialogue box, there is a pull-down menu labelled Comma

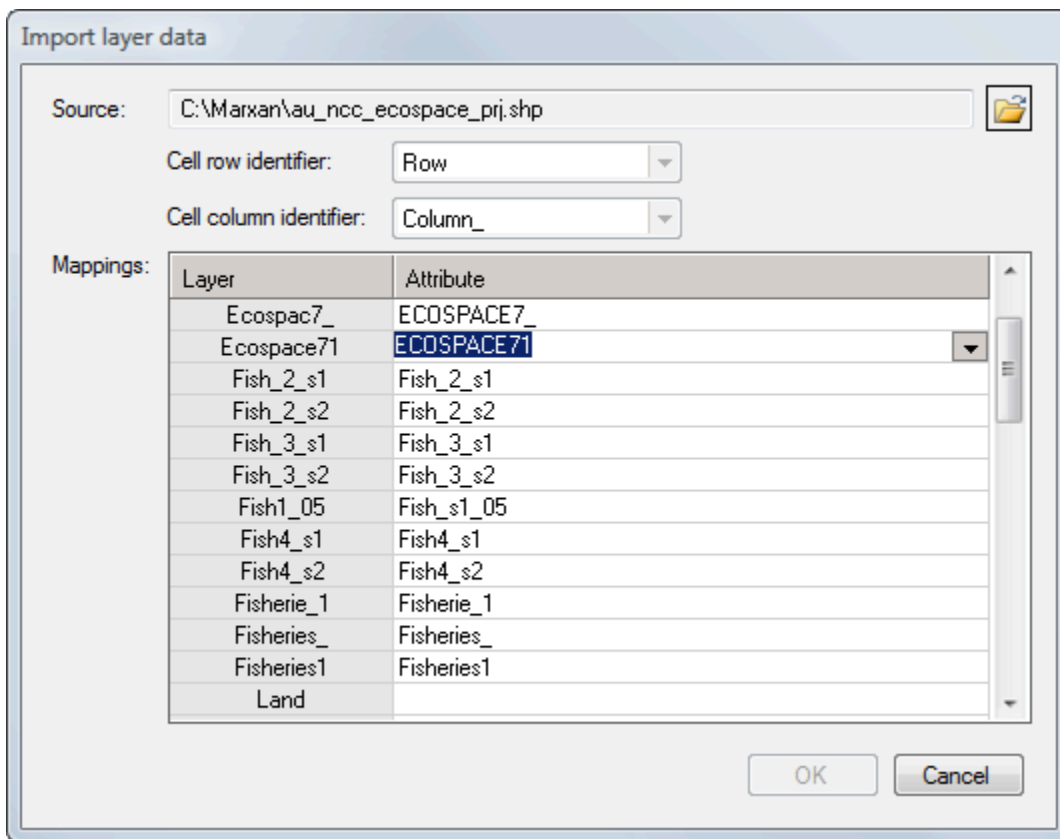
separated text file (see bottom image below). Use this pull-down menu to select the type of file (.csv, .asc, .shp) you will be importing. Click Open to open the file you wish to import.

**IMPORTANT:** To correctly import shape files, files must have row and column attributes identified and must have the same dimensions as the base map.

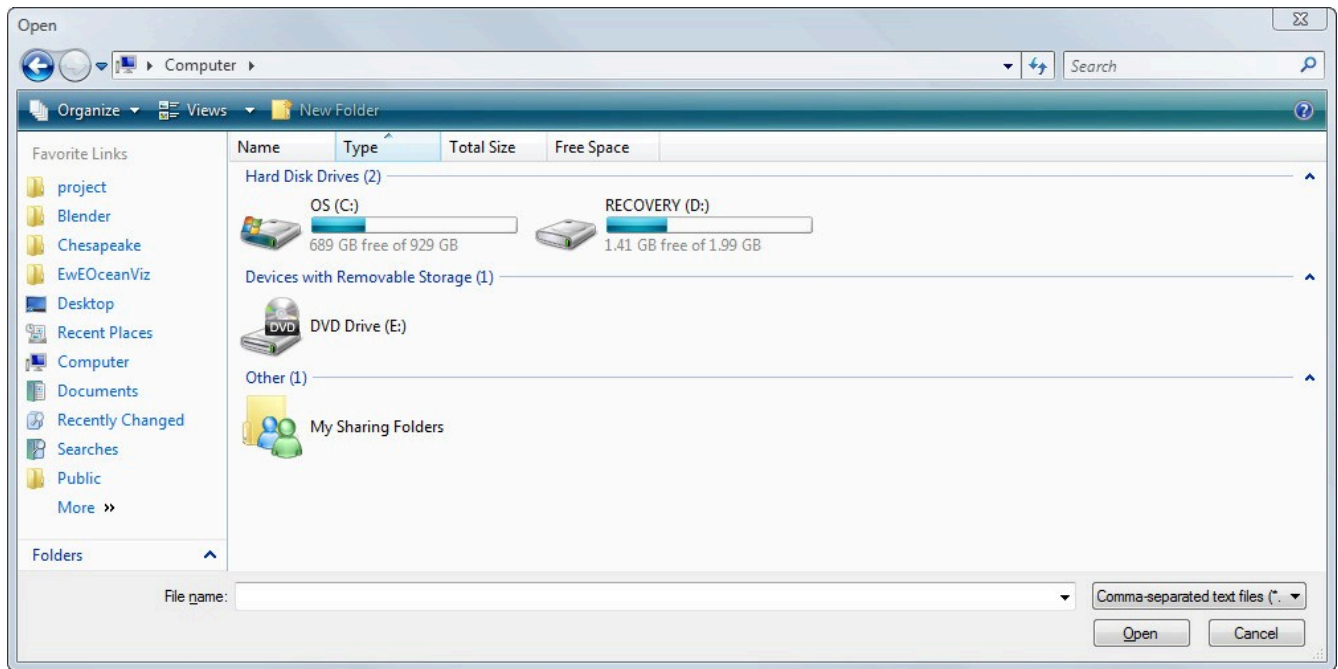
Use Cell row identifier and Cell column identifier to select the attributes of the rows and columns in the shape file. Note that shape files may have several layers (e.g., see image below). These will be displayed in the Mappings panel of the dialogue box.

Select OK to close the Import layer data dialogue box. Select OK again to close the Edit layer dialogue box. Imported layer(s) will now be visible on the Layer panel of the Map Input tab.

[Click here to return to the Spatial optimizations documentation.](#)



The Import layer data dialogue box.



The Open dialogue box. Note the Comma separated text file pull-down menu at the bottom right.

## Notes

1. Beattie, A., 2001. A new model for evaluating the optimal size, placement, and configuration of marine protected areas. M.Sc. University of British Columbia, Vancouver.
2. Beattie, A., Sumaila, U.R., Christensen, V., Pauly, D., 2002. A model for the bioeconomic evaluation of marine protected area size and placement in the North Sea. *Natural Resource Modeling* 15, 413–437. <https://doi.org/10.1111/j.1939-7445.2002.tb00096.x>

# Ecological indicators: EcoIND

Ecological indicators are useful tools to analyze and communicate changes in ecosystems and for evaluating environmental status (Coll and Steenbeek, 2017). The ECOIND plug-in added to the EwE modeling approach, is applicable to Ecopath, Ecosim and Ecospace models. ECOIND calculates a series of widely-used ecological indicators in a standardized way, including biomass-based, catch-based, trophic-based, size-based and species-based indicators. The plug-in includes a new taxonomy input database and species traits, where each functional group can be broken down into its composing species, and species traits can be added to characterize each species (Table 2).

ECOIND broadens the EwE modeling approach into biodiversity and conservation-based frameworks to contribute to integrated ecosystem analyses, also in a spatial-temporal mode (Table 3). ECOIND also adds the ability to analyze input uncertainty on output results, from Ecopath, Ecosim and Ecospace, by linking the indicators' plug-in with the Monte Carlo routine (see section 3 below). This plug-in can be easily modified to add new indicators and species traits to the computations, which can be used to provide indicators dedicated to specific management contexts, such as the Marine Strategy Framework Direction (MSFD) of the EU (Piroddi et al., 2015).

Indicator	Description	Units	a.1978	b.2010	b/a
Total C	Total Catch (C) (a)	t·km <sup>-2</sup> ·year <sup>-1</sup>	3.97	2.52	0.63
Fish C	Catch (C) of all fish species (a)	t·km <sup>-2</sup> ·year <sup>-1</sup>	3.75	1.92	0.51
Invertebrate C	Catch (C) of all invertebrate species (a)	t·km <sup>-2</sup> ·year <sup>-1</sup>	0.23	0.59	2.63
Invertebrates / Fish C	Catch (C) of invertebrates over fish (a)		0.06	0.31	5.12
Demersal C	Catch (C) of demersal species (a)	t·km <sup>-2</sup> ·year <sup>-1</sup>	0.23	0.59	2.63
Pelagic C	Catch (C) of pelagic species (a)	t·km <sup>-2</sup> ·year <sup>-1</sup>	3.95	2.21	0.56
Demersal / pelagic C	Catch (C) of demersal over pelagic species (a)		0.06	0.27	4.71
Predatory C	Catch (C) of predatory organisms with trophic level $\geq 4$ (i)	t·km <sup>-2</sup> ·year <sup>-1</sup>	0.11	0.16	1.42
Discards	Total discarded catch (i)	t·km <sup>-2</sup> ·year <sup>-1</sup>	0.28	0.27	0.96

**Table 3 B. Biomass based: Ecological indicators included in ECOIND plug-in where a. are present values of the Mediterranean food web model in 1978 and b. in 2010, and b/a is the ratio of values from 2010 in relation to 1978 (modified with permission from Coll and Steenbeek, 2017)**

Indicator	Description	Units	a.1978	b.2010	b/a
TL catch	Trophic level (TL) of the catch (i)		3.07	3.12	1.02
MTI	Marine trophic index, trophic level (TL) of the catch (including organisms with TL $\geq$ 3.25) (i)		3.78	3.91	1.03
TL co.	Trophic level (TL) of the community (including all organisms) (i)		1.44	1.39	0.97
TL co. 2	Trophic level (TL) of the community (including organisms with TL $\geq$ 2) (i)		2.42	2.40	0.99
TL co. 3.25	Trophic level (TL) of the community (including organisms with TL $\geq$ 3.25) (i)		3.69	3.91	1.06
TL co. 4	Trophic level (TL) of the community (including organisms with TL $\geq$ 4) (i)		4.12	4.11	1.00

**Table 3 C. Trophic-based: Ecological indicators included in ECOIND plug-in where a. are present values of the Mediterranean food web model in 1978 and b. in 2010, and b/a is the ratio of values from 2010 in relation to 1978 (modified with permission from Coll and Steenbeek, 2017)**

Indicator	Description	Units	a.1978	b.2010	b/a
ML of fish co.	Mean length (ML) of fish in the community (a)	cm	16.74	17.66	1.06
ML of fish C	Mean length (ML) of fish in the catch (C) (a)	cm	12.09	15.85	1.31
MW of fish co.	Mean weight (MW) of the fish in the community (a)	kg	170.99	164.19	0.96
MW of fish C	Mean weight (MW) of fish in the catch (C) (a)	kg	89.11	158.30	1.78
MLS of fish co.	Mean life span (MLS) of fish in the community (a)	year	4.47	4.61	1.03
MLS of fish C	Mean life span (MLS) of fish the catch (C) (a)	year	3.34	4.52	1.35

**Table 3 D. Size-based: Ecological indicators included in ECOIND plug-in where a. are present values of the Mediterranean food web model in 1978 and b. in 2010, and b/a is the ratio of values from 2010 in relation to 1978 (modified with permission from Coll and Steenbeek, 2017)**

Indicator	Description	Units	a.1978	b.2010	b/a
Intrinsic Vul. Index	Intrinsic Vulnerability Index of the catch (a)		49.29	47.97	0.97
Endemics B	Biomass (B) of endemic species in the community (a)	t·km <sup>-2</sup>	1.E-04	2.E-04	1.73
Endemics C	Endemic species in the catch (C) (a)	t·km <sup>-2</sup> ·year <sup>-1</sup>	2.E-08	6.E-07	33.07
IUCN species B	Biomass (B) of IUCN-endangered species in the community (a)	t·km <sup>-2</sup>	1.07	0.72	0.67
IUCN species C	IUCN-endangered species in the catch (C) (a)	t·km <sup>-2</sup> ·year <sup>-1</sup>	0.09	0.14	1.61
Mammals, birds & reptiles B	Biomass (B) of marine mammals, seabirds and reptiles (a)	t·km <sup>-2</sup>	0.42	0.29	0.71
Mammals, birds & reptiles C	Catch (C) of marine mammals, seabirds and reptiles (a)	t·km <sup>-2</sup> ·year <sup>-1</sup>	0.42	0.29	0.70

**Table 3 E. Species based: Ecological indicators included in ECOIND plug-in where a. are present values of the Mediterranean food web model in 1978 and b. in 2010, and b/a is the ratio of values from 2010 in relation to 1978 (modified with permission from Coll and Steenbeek, 2017)**

## Adaption

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De Mutsert K, Marta Coll, Jeroen Steenbeek, Cameron Ainsworth, Joe Buszowski, David Chagaris, Villy Christensen, Sheila J.J. Heymans, Kristy A. Lewis, Simone Libralato, Greig Oldford, Chiara Piroddi, Giovanni Romagnoni, Natalia Serpetti, Michael Spence, Carl Walters. 2023. [Advances in spatial-temporal coastal and marine ecosystem modeling using Ecopath with Ecosim and Ecospace](#). Treatise on Estuarine and Coastal Science, 2nd Edition. Elsevier.

[1 https://www.un.org/bbnj/content/background](https://www.un.org/bbnj/content/background)

[2 https://iaac-aeic.gc.ca/050/evaluations/proj/80054](https://iaac-aeic.gc.ca/050/evaluations/proj/80054)

[3 https://ditto-oceandecade.org/](https://ditto-oceandecade.org/)

[4 https://marine.copernicus.eu/news/ocean-and-its-digital-twin-whats-copernicus-marine](https://marine.copernicus.eu/news/ocean-and-its-digital-twin-whats-copernicus-marine)

# Geospatial Considerations

Configuring Ecospace requires making choices and trade-offs to best address the research questions at hand. One will have to decide on grid cell size, the factors that drive the spatial distribution of ecosystem components, how to implement fisheries measures and fishing effort allocation, whether currents and migratory patterns are important for the question asked by the model, etc. These decisions are guided by functional group and fishing fleet structure, but are often limited by the resolution and quality of available spatial (and temporal) data. Here we provide some general guidelines to making these decisions.

The choice of the spatial domain to set the Ecospace basemap is the first step in the configuration of the model. As a rule of thumb, it should correspond to the domain used for the parameterizations of the Ecopath and the Ecosim models.

The choice of grid cell size is more challenging. Ecospace operates on a uniform raster grid of cells, where cell size directly determines the number of rows and columns that Ecospace will compute over. Higher number of cells generally mean more detail in model output but also increased demands in computational time and required memory, and do not necessarily provide better predictions. In general, the choice of cell size should be fine enough to answer research questions – but not finer. Other questions that need to be answered include: How do species relevant for the research questions utilize space, and what features affect their distributions? Are the ecological mechanisms that you want to address relevant considering the spatial extent of the modeled area? Are focal groups moving fast or slow? What are the spatial extents of fisheries management options? Are currents and/or migration patterns important? Do you have data of sufficient spatial detail to parameterize your Ecospace model? The answers to these kinds of questions may yield a range of sensible cell sizes. As an indication, most Ecospace maps fall within the 25×25 to 100×100 cell range (though an Ecospace map does not have to be square). A pragmatic approach is to use three sets of resolutions for Ecospace: one at the cell size that makes the most sense to the user, one set twice as coarse for rapidly building and testing the Ecospace scenario, and one set with cells that are twice as fine as the optimal cell size to assess whether a finer spatial scale significantly increases model predictive power. The coarse resolution offers quick runtime advantages and may help support some treatment of uncertainty. When satisfied, duplicate the entire Ecospace model, supply it with the intermediate resolution maps, and fine-tune as needed. This step is then repeated with the highest resolution maps to validate if this further improves the model.

Geospatial projection may be another consideration. If not instructed otherwise, Ecospace assumes that its grid is expressed using a World Geodetic System projection (WGS). Ecospace assumes that the Ecospace cell size is expressed in decimal degrees, and translates this to cell

length in km at latitude, thus accounting for cell width tapering with latitude. Ecospace uses these cell lengths to translate species dispersal rates to actual movement (see Movement section, here below). If this default behaviour is undesired, for instance, when modeling an area using a local map projection where cell tapering is negligible (e.g., at lower latitudes) or when the coordinate system is expressed in meters, one can set Ecospace to Assume square cells, which makes Ecospace treat its grid as a uniform grid without cell tapering and where the user is responsible for entering the cell length (in km) to correctly drive species movement.

## Accounting for Effects of Latitude in Ecospace Models

Ecospace models are typically developed for grids of latitude-longitude spatial cells, with biomasses represented as densities (e.g., t km<sup>-2</sup>) within each cell. But for models of high latitude grids or grids that span a wide range of latitudes, cell widths over which biomass densities are predicted can vary considerably.

Thus, for cell  $i,j$  where  $i$  is map row (latitude) position and  $j$  is longitude position, relative width (width/height,  $W_i$ ) across the top of the cell varies with map row  $i$  as:

$$W_i = \cos(Lat_i) \quad (1)$$

where  $Lat_i$  is latitude in degrees at the cell top; thus  $\cos(Lat_i)$  varies from 1.0 at the equator to about 0.7 at 45 degrees north or south latitude to 0 at the poles. The Ecospace cell tapering logic assumes that the Ecospace map is projected to the World Geodetic System (WGS 1984) coordinate system with latitude and longitude are expressed in decimal degrees.

Variation in  $W_i$  requires three corrections in Ecospace calculations:

- dispersal rates across north-south cell faces need to be multiplied by  $W_i$  to account for differences in the odds of randomly moving creatures crossing those faces as opposed to east-west faces;
- fishing effort  $E_{i,j}$  allocated to each spatial cell using gravity models needs to be proportional to  $W_i$ , while fishing mortality rates need to vary with effort density (effort/ $W_i$ ); and
- catch and discards from each cell need to be set to the model predicted catch per area times  $W_i$ .

The first and third of these corrections are trivial to implement (simply scale mixing rates  $m$  by  $W_i$  for north-south cell faces, multiply catches and discards  $C_{i,j}$  by  $W_i$ ). The effort allocation and effort density calculations require a bit more care.

For Ecospace fishing mortality rate calculations, fishing mortality rate needs to be set proportional

to the effective effort density per unit area  $E_{i,j}$  predicted for each spatial cell. At each time step, we make that prediction by assuming a total fishing effort  $E_t$  for the step, then allocating that total over the cells using a logit choice or gravity model with the attractiveness of each cell being proportional to the profitability (revenue/cost per unit effort) of fishing in that cell,  $p_{i,j}$ . The total effort for each cell also needs to be adjusted for relative cell area as measured by  $W_i$ . That is, the total effort  $ET_{i,j}$  that is allocated to each cell should be calculated as,

$$ET_{i,j} = \frac{E_t p_{i,j} W_i}{\sum_{i,j} p_{i,j} W_i} \quad (2)$$

But the effort density  $E_{i,j}$  per unit area varies as  $E_{i,j} = ET_{i,j} W_i$ , implying that the gravity prediction of effort density should be,

$$E_{i,j} = \frac{E_t p_{i,j}}{\sum_{i,j} p_{i,j} W_i} \quad (3)$$

Using this model, two cells with equal profitability will be allocated the same effort density (calculated with the same denominator in the last equation, but the cell with larger  $W_i$  will then give higher total catch when catch per area is multiplied by  $W_i$  (correction factor 3 above).

Note that application of (3) requires care in setting the total effort  $E_t$  so as to make total fishing mortality rates over the spatial grid have the same averages as assumed in the Ecopath/Ecosim model setup. In past Ecospace versions, we have not been careful in setting  $E_t$ , assuming it to be  $ngE_{\text{Ecosim}}$  where  $ng$  is the number of water spatial cells fished by gear  $g$ . This calculation of  $E_t$  needs to be modified (Ecospace routine `SetEffortParameters`) by summing total effort over  $W_i$  times base effort per cell, so as not to generate total efforts that are unrealistically high. This is implemented via a Total efficiency multiplier for each fleet. The basic assumption for fleets in Ecospace (as described above) is that each functional target group is distributed across the map, and that the baseline effort (from Ecopath) is distributed across cells. If the effort is concentrated in a few cells only, this will result in a very high fishing effort being allocated to such a target group. In such a case the Total efficiency multiplier should be reduced from the unity level. A check for this is that with constant effort a fleet should not deplete a target species, other things being equal.

## Adaption

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Villy Christensen, Sheila J.J. Heymans, Kristy A. Lewis, Simone Libralato, Greig Oldford, Chiara Piroddi, Giovanni Romagnoni, Natalia Serpetti, Michael Spence, Carl Walters. 2023. [Advances in spatial-temporal coastal and marine ecosystem modeling using Ecopath with Ecosim and Ecospace](#). Treatise on Estuarine and Coastal Science, 2nd Edition. Elsevier.

# Geospatial Projections

JEROEN STEENBEEK

The Ecospace module of the (EwE) software applies the ecological dynamics of a marine food web across a grid of cells. Traditionally, this grid is geo-referenced to decimal degrees longitude [-180, 180] and latitude [-90, 90], where cells taper at higher latitude ranges – the common WGS84 or EPSG:4326 projection. In its functional groups dispersal calculations Ecospace automatically takes this into account.

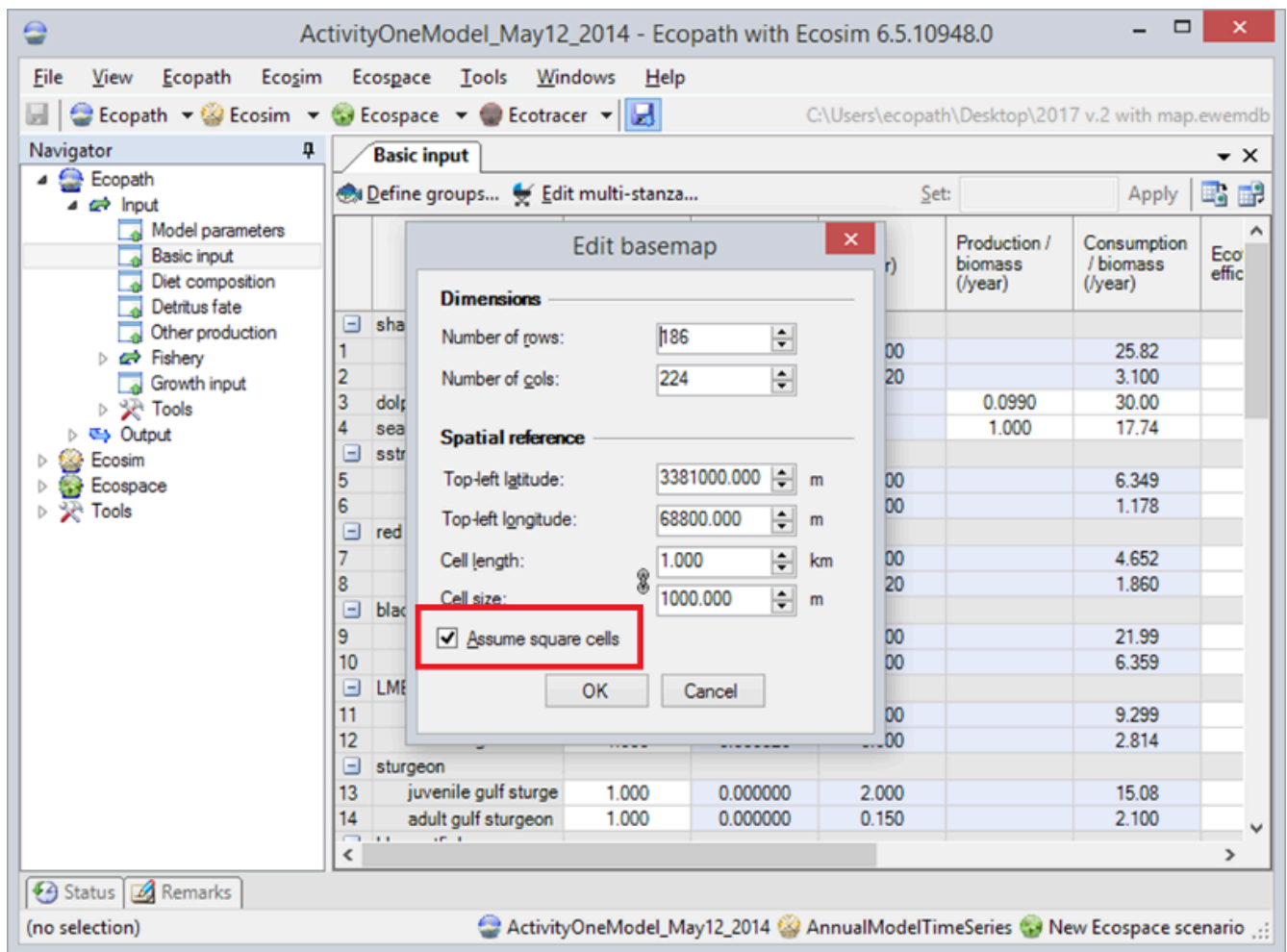
To enable environmental driver data input to Ecospace to be mapped to a local UTM spatial projection with highest positional accuracy, these calculations need to be modified.

Re-projecting the UTM data to the traditional Ecospace projection would cause irrevocable changes to driver data since UTM grid cells do not perfectly align nor perfectly overlap with the Ecospace grid. Driver data would thus not arrive in its accurate form in Ecospace, calling for modifications as described in this chapter.

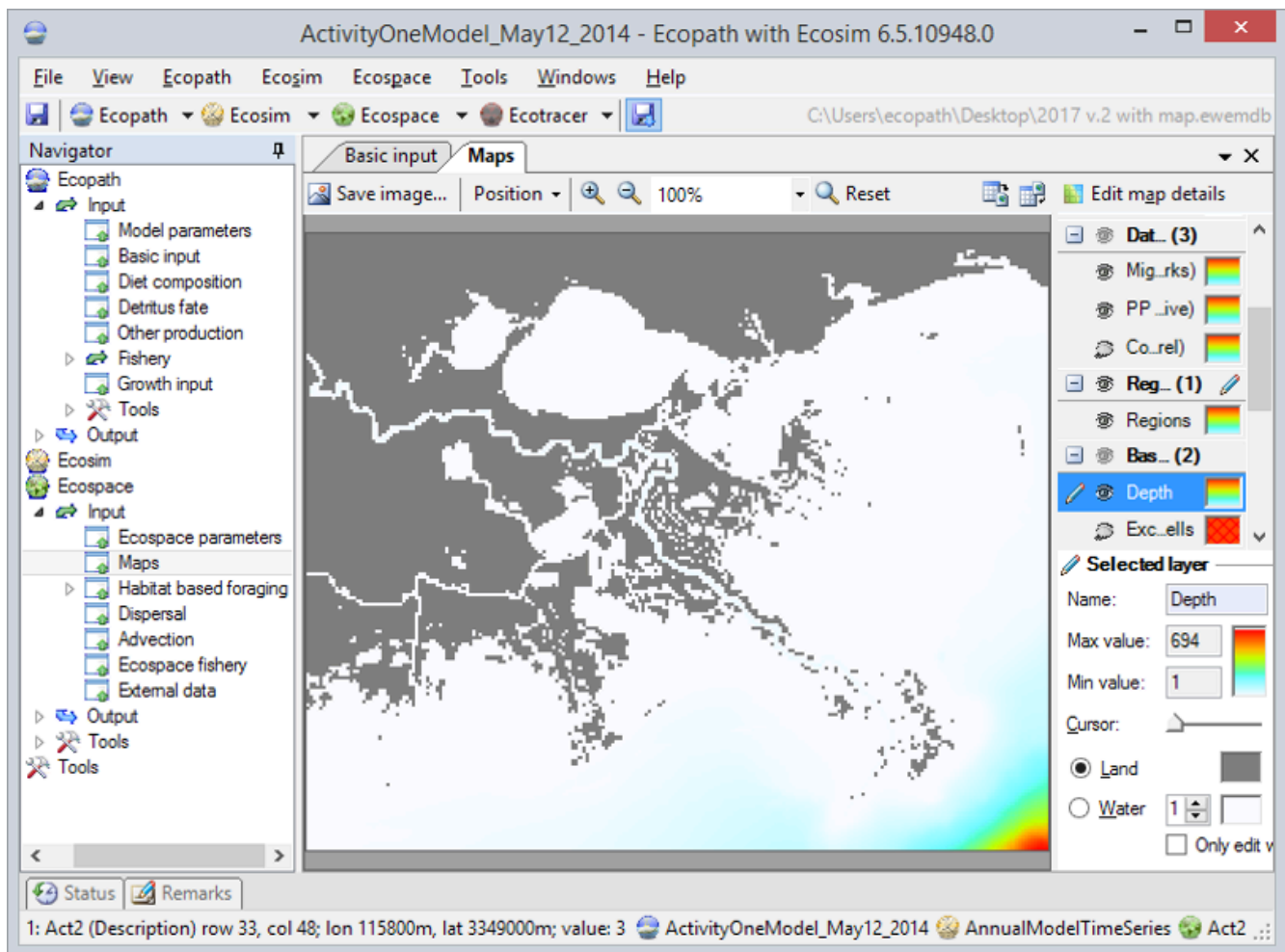
The following changes have been made to the EwE software to satisfy this requirement in three aspects of the EwE source code:

1. The Ecospace model has gained an Assume square cells flag. When this flag is turned off, Ecospace will operate in traditional fashion assuming cell tapering by latitude, and assumes that cell coordinates and dimensions are specified in decimal degrees. When turned on, Ecospace assumes that its grid is geo-referenced to a relatively small local area where cells can be considered square, and cells coordinates and dimensions are specified in meters. This required changes to the EwE database format, and changes to Ecospace dispersal computations and sailing cost calculations, which both perform key distance calculations that need to take different geo-spatial projections into account.
2. The Ecospace user interface has been adjusted to correctly translate between cell size (stated in projection units) and cell length (stated in km, used for functional group dispersal purposes).
3. Ecospace data import and export routines have been adjusted to use the correct map projection units.

Users can toggle the square cells flag in the Edit Basemap form, found in the Ecospace menu, where map units and the cell length / cell size translations change with the value of the Assume Square Cells flag (Figure 1). The Ecospace map provides correct location feedback to the mouse cursor when hovering over the Ecospace map (Figure 2).



**Figure 1** – Toggling the Assume Square Cells setting to switch between WGS84 / EPSG:4326 projections (when the setting is turned off) and a local UTM projection (when the setting is turned on).

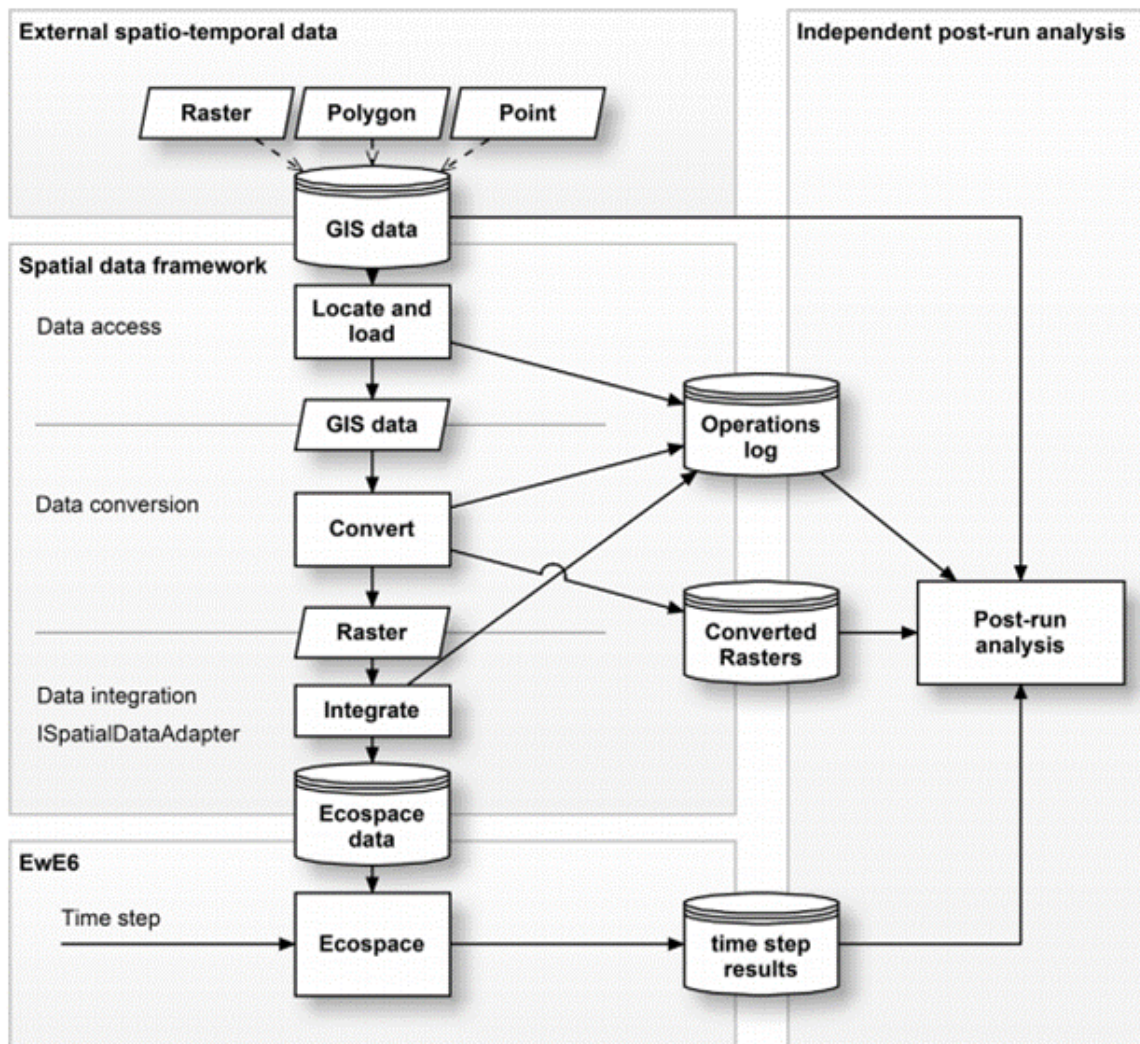


**Figure 2** – The Ecospace map interface providing geo-spatial location feedback for a local UTM grid in the EwE status bar, at the bottom left.

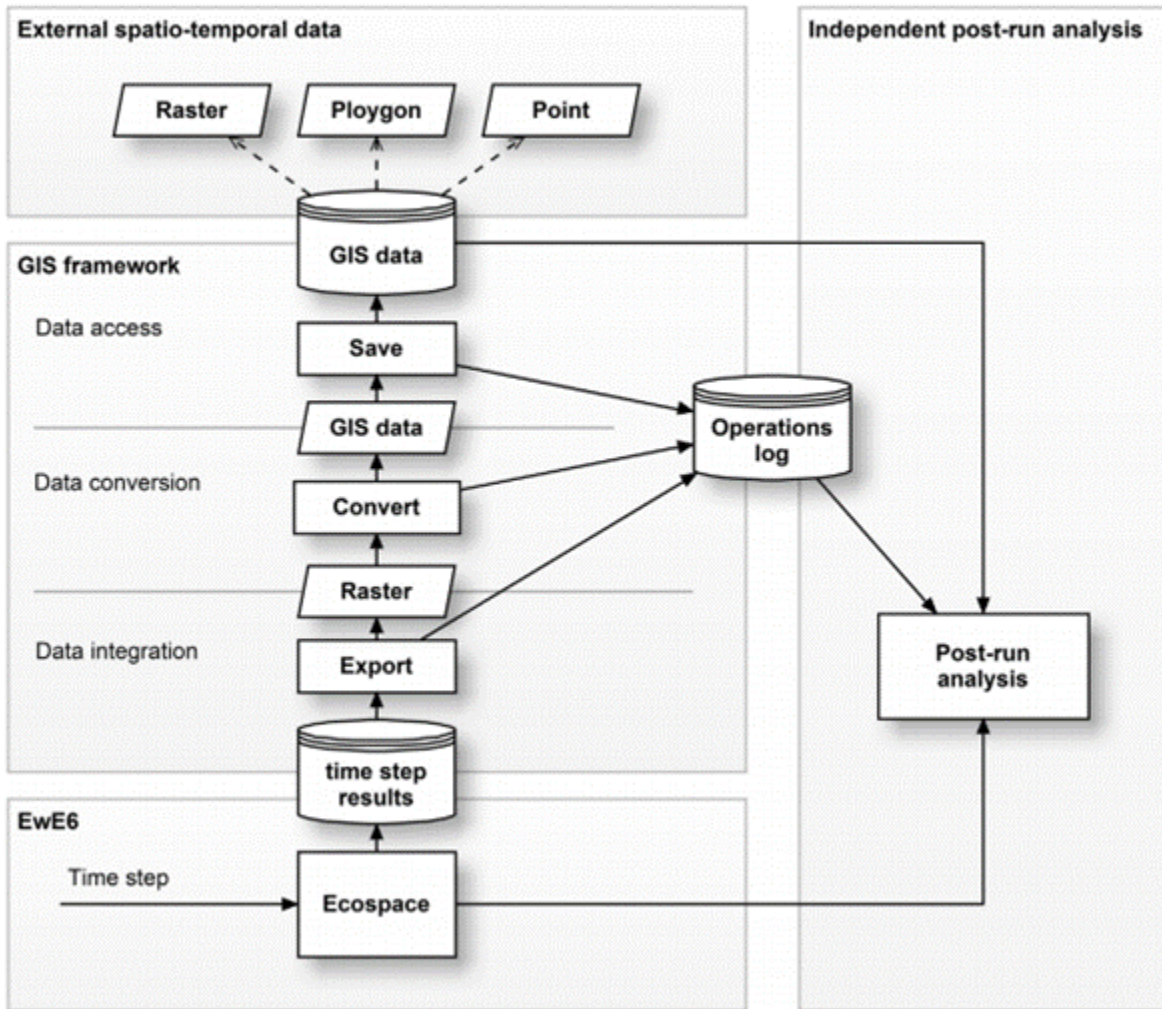
# Spatial-Temporal Data

A spatial-temporal data framework (STDF) has been added to Ecospace to facilitate dynamic data exchange into the running model (Steenbeek et al., 2013). Development of this framework was greatly facilitated by the modular design of EwE version 6 (Steenbeek et al., 2016). In the framework, external data integration into the model is divided into three layers: data access, data conversion and data integration (Fig. 2).

To obtain output of Ecospace in GIS formats, the pathway for data integration is effectively reversed. Once the output data are passed through a conversion process, data are made available to the user and can then be saved to an external location (Fig. 3).

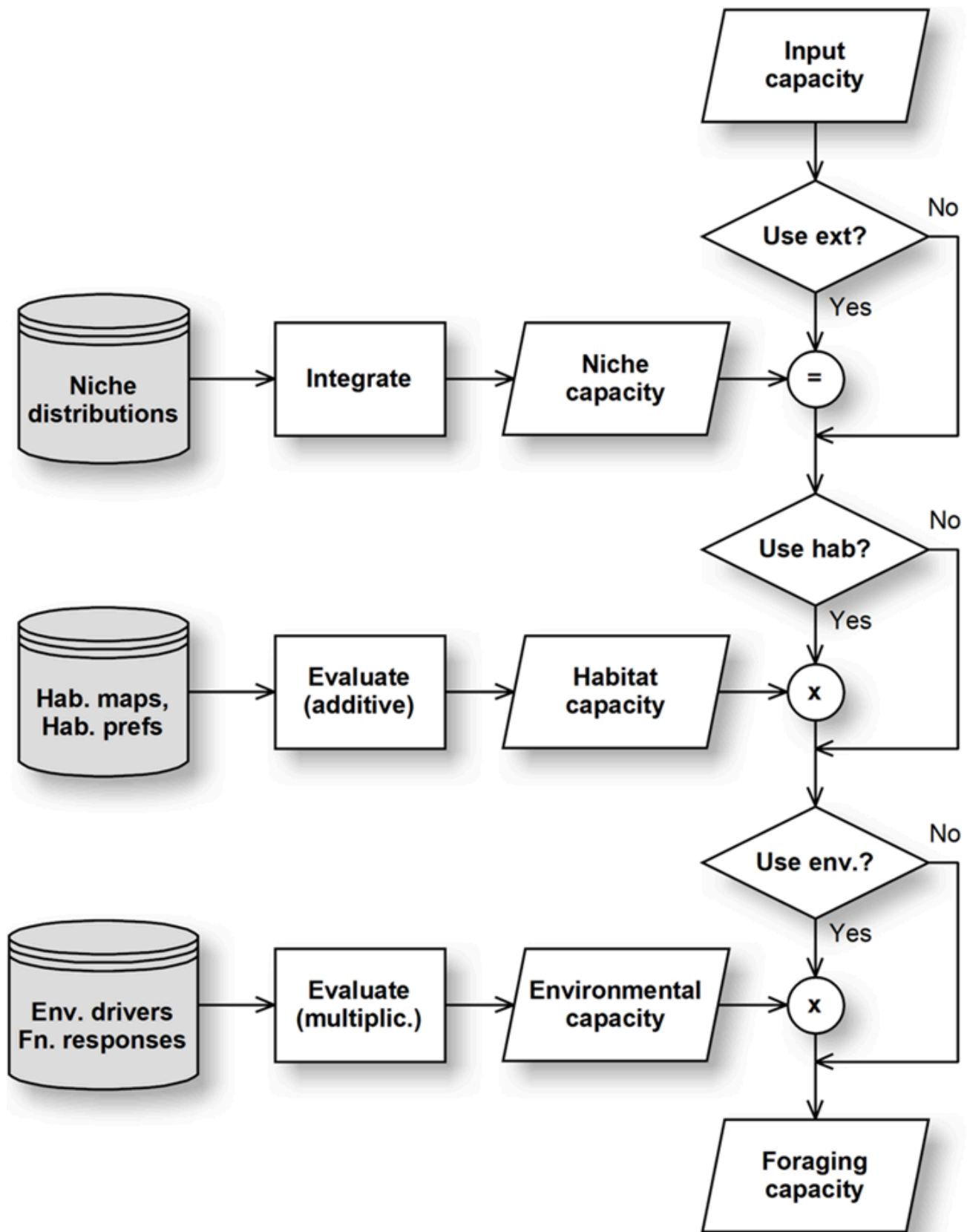


**Figure 2** – The modular design of the spatial-temporal framework in Ecospace, depicting how external GIS data are integrated into EwE (reproduced with permission from Steenbeek et al., 2013)



**Figure 3** – The modular design of the spatial-temporal framework in Ecospace, depicting how external data is output (reproduced with permission from Steenbeek et al., 2013)

The new capabilities added to Ecospace allow the user to fully develop spatial-temporal dynamic modeling simulations, considering spatial food-web dynamics and changes in environmental conditions and human activities over time and space. The current configuration of the HFC model of Ecospace has a flexible structural design, which allows the inclusion of spatial-temporal data in different steps of the HFC model according to data availability and ecological hypothesis and management scenarios (Fig. 4).



**Figure 4** – Modularity of the Habitat Foraging Capacity model (HFC). Every functional group has a base input capacity layer that can be overridden by external niche distributions. In addition, habitat affinities and

*preferences for environmental functions can be applied to redefine habitat foraging capacity within a species niche. This configuration is a per-group setting (modified from Coll et al., 2020)*

## Adaption

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# Spatial-Temporal Data Framework

JEROEN STEENBEEK

## Purpose

This chapter provides guidelines for configuring, and running external time series of maps in Ecospace, the spatial-temporal module of the Ecopath with Ecosim (EwE) food web modelling approach.

## Availability

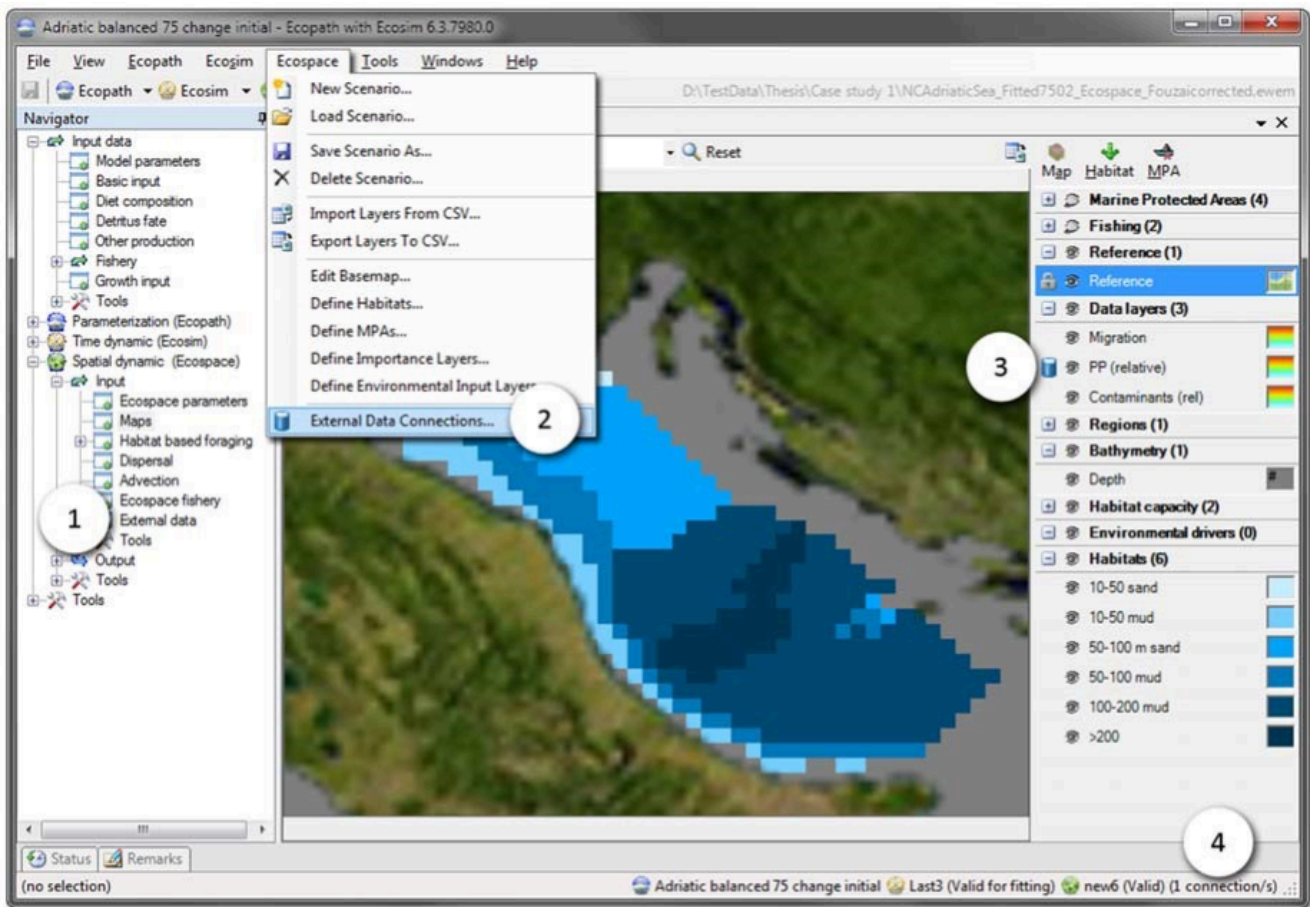
The spatial temporal data framework is under continuous development, and currently is only available under an EwE professional license, both to support the ongoing development and because setup of the framework is a requiring undertaking often requiring support. We do, however, seek to lower the learning curve through this chapter.

For more information about licensing, please see <https://ecopath.org/go-pro/>

## Using the Spatial Temporal Framework

The spatial temporal framework is a plug-in to the Ecopath with Ecosim food web modelling approach<sup>1 2 3</sup>, built with the sole purpose to dynamically insert (time varying) spatial data that is external to the EwE model into Ecospace map layers<sup>4</sup>.

The framework integrates with the EwE6 user interface in several locations as shown in Figure 1.



**Figure 1** – EwE6 user interface with indications of the presence of the external spatial data facilities: (1) an item in the EwE navigation tree, (2) a configuration option in the Ecospace menu, (3) a blue database icon beside each map layer in the Ecospace map interface to indicate this layer is connected to external data, and (4) a the number of external data connections summarized in the EwE status bar. Type your text box content here.

## Defining Connections

A ‘connection’ is the link between an Ecospace map layer and a repository of maps (or time series of maps) that are not stored within the EwE model. Connections are defined by the EwE user, and can be shared across computer systems.

Connections are managed from the central Define external spatial temporal connections screen (Figure 2), which is accessible from several locations throughout Ecospace. Here, one can create and delete connections of different types, manage in which file the connections are stored on the local machine, export connections and their data for reuse or sharing with others, and control whether the framework is allowed to dedicate background processing time to index the spatial and temporal overlap of external data with the current Ecospace scenario.

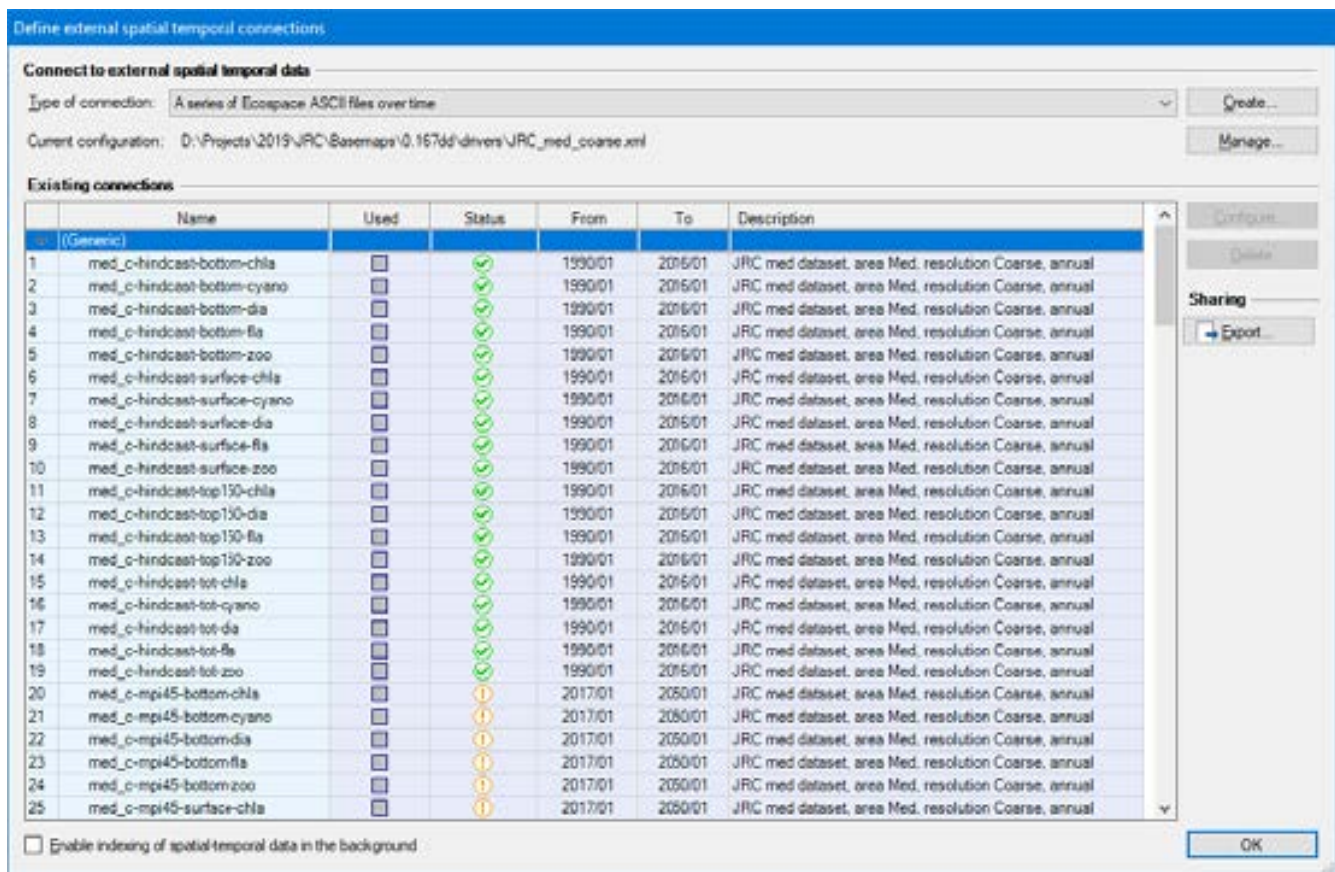


Figure 2 – Define external spatial temporal connections screen

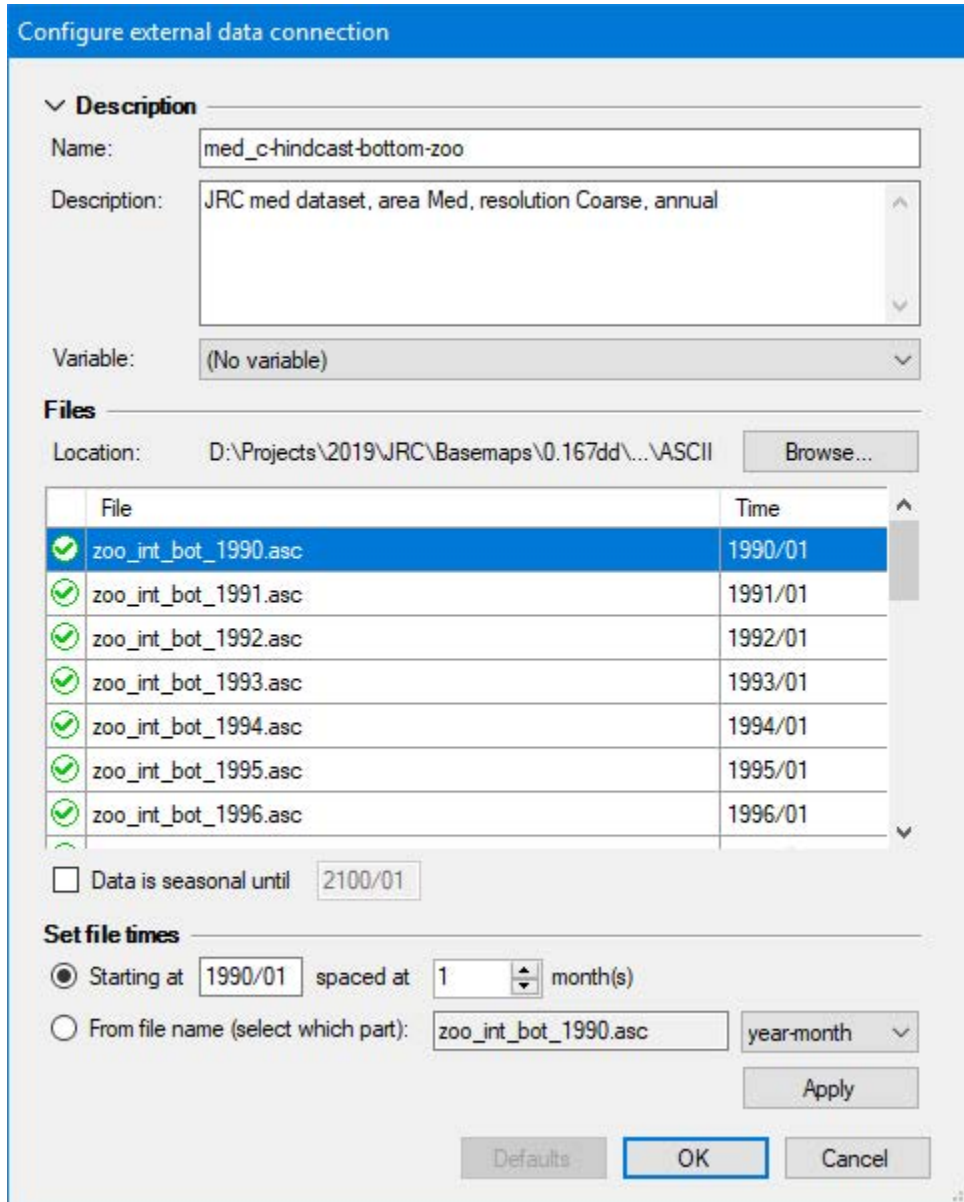
Existing connections are briefly summarized. The Used column states if the connection is actually applied to one or more Ecospace layers. The Status column uses icons to explain whether the connection has errors (Red X), has only partial spatial overlap with the modelled area (Orange !), or entirely covers the modelled area (Green checkmark). The warning icon is also used to notify that data compatibility has not been assessed yet, which can be done by enabling indexing or by running Ecospace, in case each used connection is automatically validated.

To define a new connection:

- Go to Menu > Ecospace > Define external data connections...
- Select the type of connection to create. Presently, four file-based connection types are supported,
  - (1) a time series of ASCII files that must be prepared to match the spatial extent and cell size of a dedicated Ecospace scenario;
  - (2) a time series of spatial files that will be made fit for inclusion in Ecospace by the DotSpatial / GDAL GIS engine encapsulated in the spatial temporal data framework;
  - (3) a file with X,Y,Z,T time series values provided in CSV file format, where (X,Y) coordinates

can either indicate (column, row) or (longitude, latitude); and  
(4) a single spatial file.

- Press Create.... A new connection is defined, and the Configure external data connection view opens up (Figure 3) to allow its content to be modified.



**Figure 3** – Configure external data connection screen, where users configure a time series of external maps

The configuration process of file-based connections is straightforward:

- Enter a name that identifies its content, keeping in mind that you may have a large number of

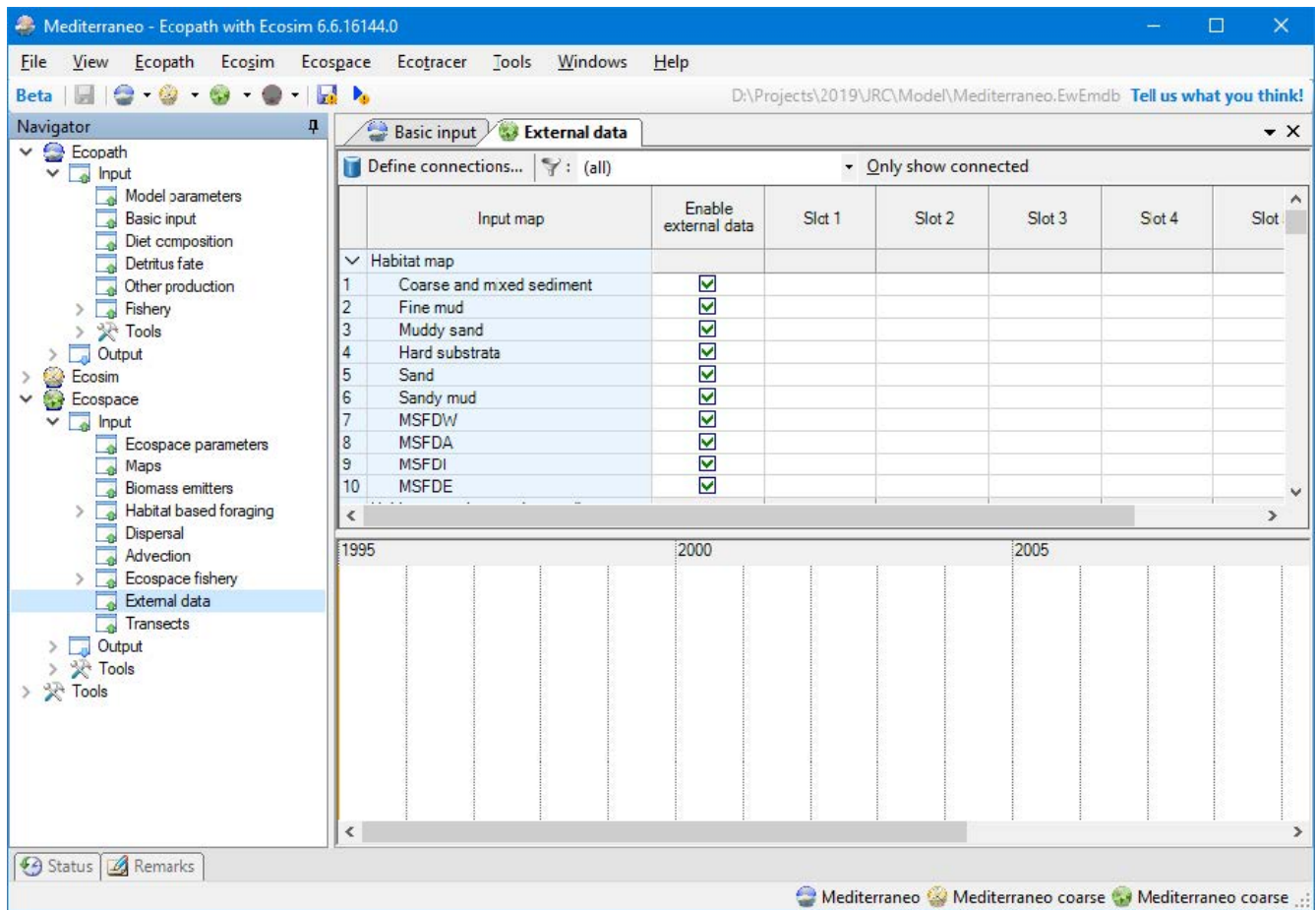
connections to sift through. To illustrate, the Mediterranean modelling exercise used for illustration in this chapter featured 150 different connections per scenario.

- Enter a description to state data source, spatial and temporal resolution, data pedigree, and other details, considering one may have many connections to manage.
- Optionally, select the Ecospace variable the connection is limited to. This does NOT assign the connection; it only limits where this connection is available in the EwE user interface.
- Press Browse to select which files belong to the connection browse to the folder where the files reside, and select and insert the desired files. The files list will populate in response. Note that each file represents a map in time. times can be entered by hand, or can be set automatically, either by entering a start date (year/month) and monthly interval, or by reading the time step from a fixed position in the file names. Seasonal data rotates the first year of data until the indicated end date.
- Press OK

## Assigning External Data to Ecospace

To make external connections operational in Ecospace, do the following:

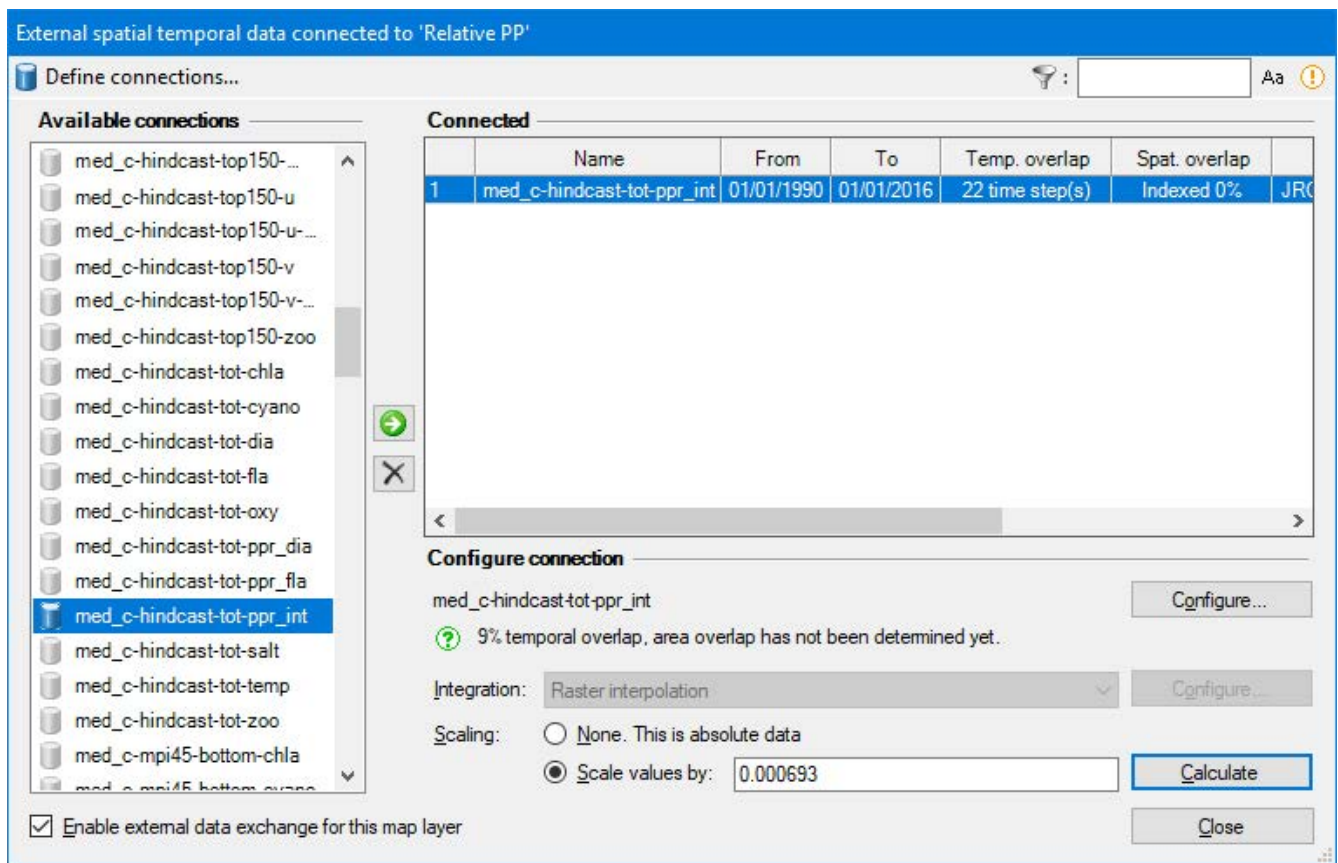
- Go to Navigator > Ecospace > Input > External data... The External data view opens up (Figure 4), and displays all Ecospace map layers that can receive external data. The toolbar offers options to limit the number of layers on display, with filters by layer type, and only viewing layers with active connections. The external data interface also shows a time line that reflects the temporal overlap of external data with the Ecospace scenario.



**Figure 4** – External data view, which provides an overview of which Ecospace layers have external data assigned to them.

Every map layer has up to six slots for assigning connections. To assign external data to a layer,

- Click the first available slot in the layer that you wish to drive with external data.



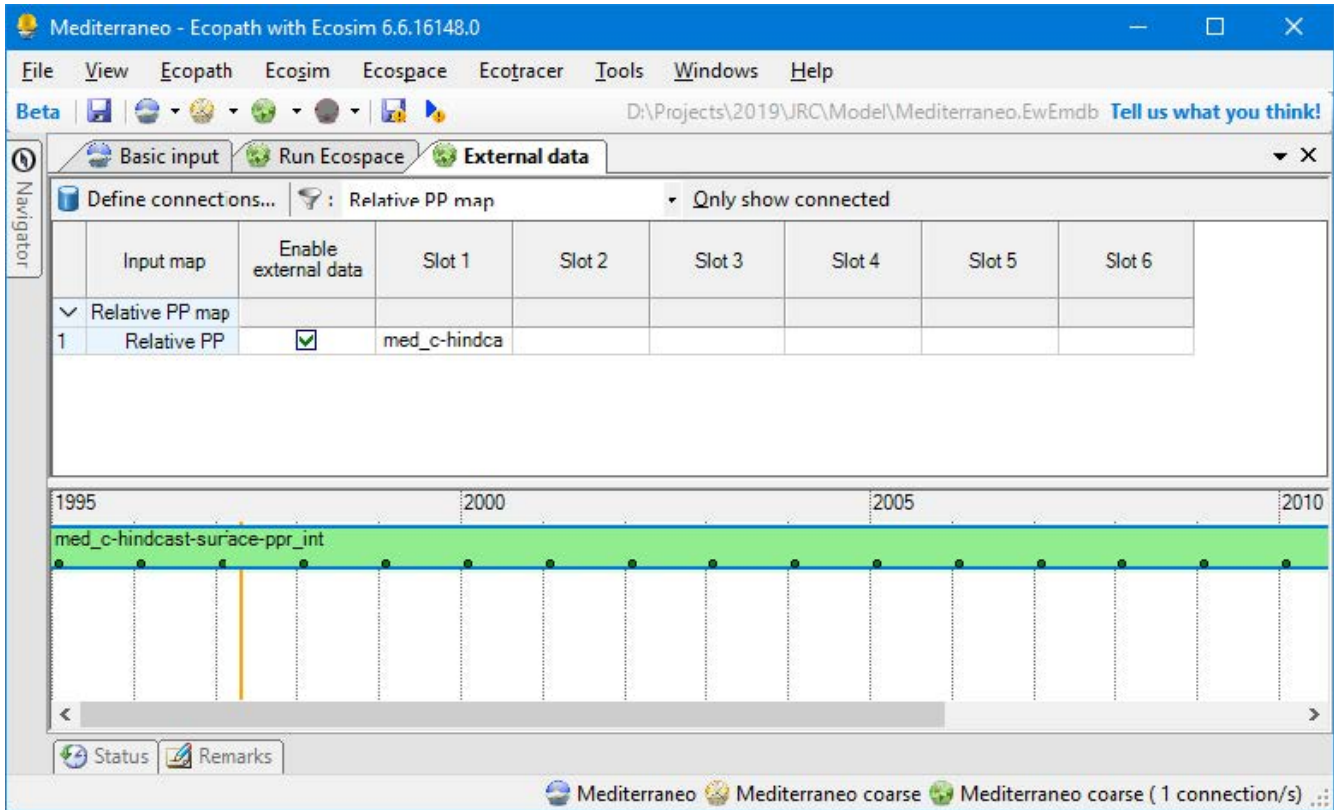
**Figure 5** – Define connections interface, where an external data connection is assigned to a single Ecospace map layer.

This opens up the interface Assign connections (Figure 5),

- Select a connection from the list of available connections
- Click the use button (Green arrow pointing right) to assign the connection. A configuration panel opens with additional options. Available options depend on the type of connection that was selected, and the type of Ecospace layer the connection is applied to. Some Ecospace layers may require data to be scaled, for instance, and for those layers you will need to provide a scalar. The configuration panel also summaries compatibility of assigned external data with the current Ecospace scenario.
- Click Configure to review or change the configuration of the connection (as explained above).
- Select an Integration method if applicable – these are geospatial macros that convert data to the desired Ecospace layer needs.
- Enter a scaling method if applicable
- Enter a scaling factor, which can be left at default 1 if data in the Ecospace scenario is the same as the first month of external data.
- Calculate the scaling factor to scale the first year of external data scales to an Ecopath base

value (this is highly recommended when driving the Relative PP layer, for instance).

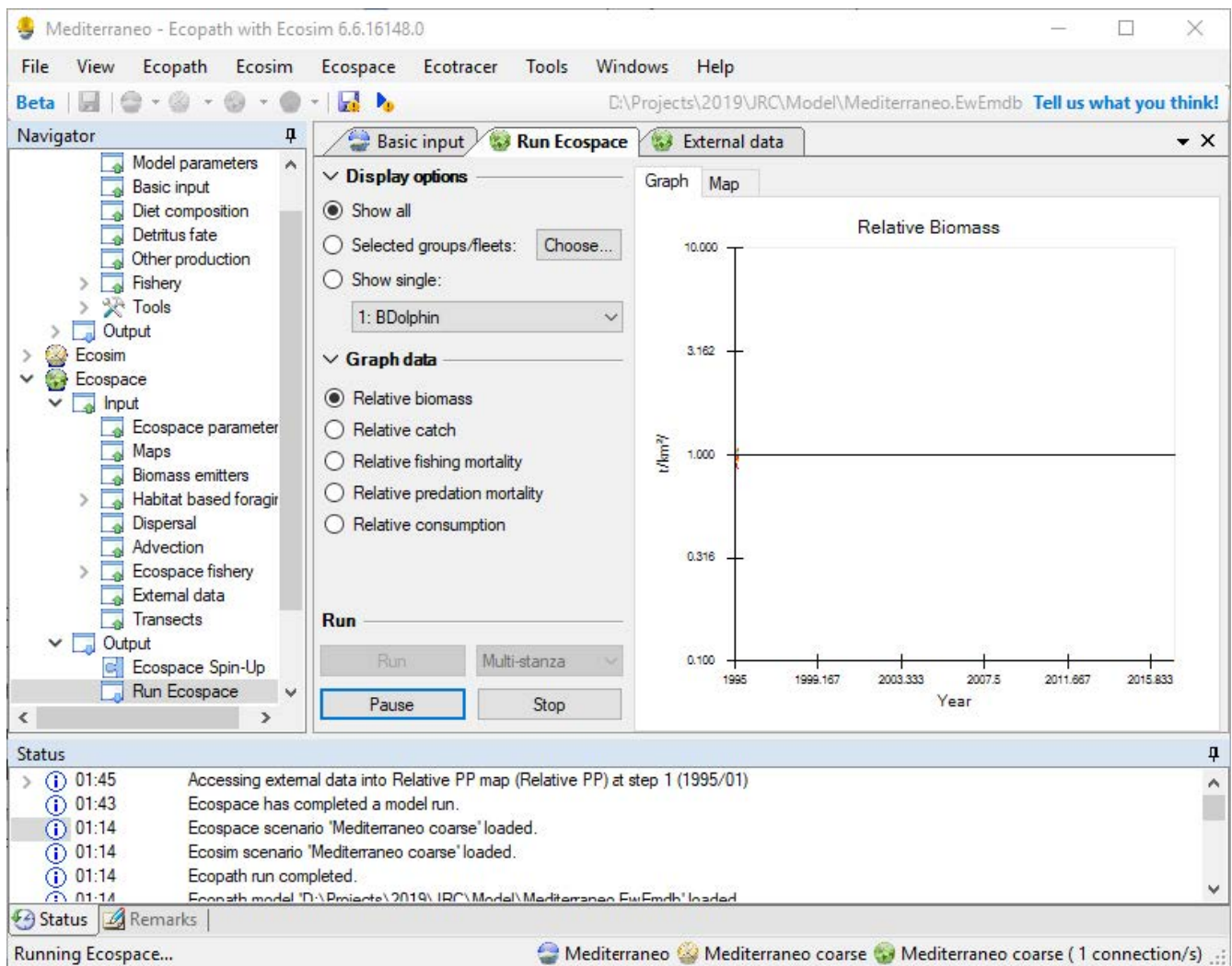
- Press Close to make the external data connection stick, and save the model.



**Figure 6** – The external data view with External data assigned to drive the content of the Ecospace Relative PP layer.

## Running Ecospace with External Data

When Ecospace is executed as normal, the EwE status panel will show a notification every time external data is accessed, and also whether integration into the intended Ecospace layer was successful. These notifications are also written to an extensive log file, which is saved in the directory where the EwE model is located. This file can be helpful for troubleshooting external data connection issues.



**Figure 7** – Run Ecospace interface and the EwE status panel. The status panel informs users when Ecospace has attempted to integrate external data into the running model.

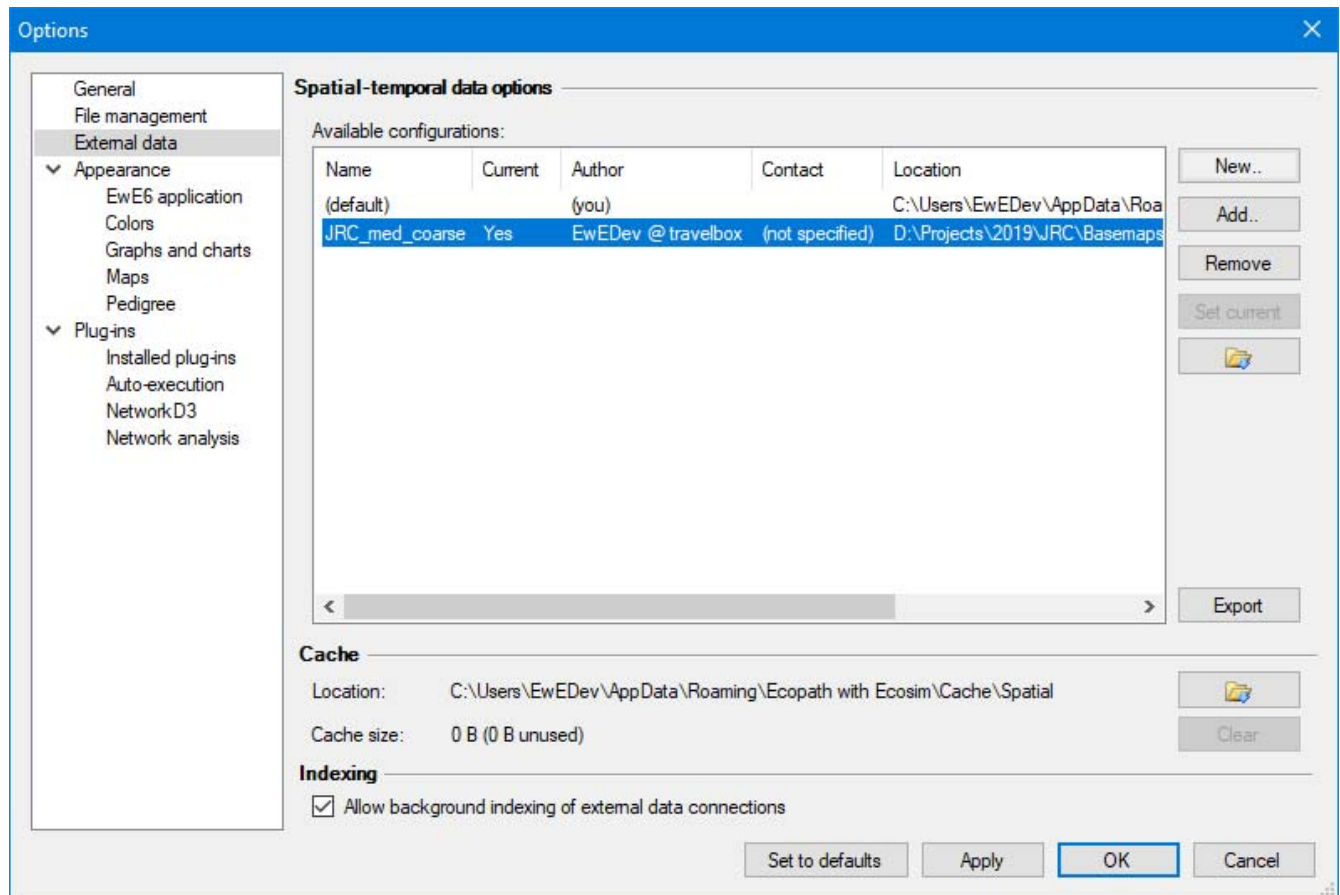
If Ecospace has encountered any issue with external data during a run, it will notify the user that issues were encountered. As the Ecospace run missed some needed external data it should not be trusted, and the status panel and/or spatial log file will provide clues as to why needed spatial data was not found.

## Configuration Files

All spatial temporal data connection definitions are stored in configuration files. At any given moment, EwE operates on only one configuration file that defines available external data

connections. This central storage allows external connections to be reused between Ecospace modelling exercises, and provides a means to organize how much data is visible to a specific modelling exercise.

Configuration files are managed in Menu > Tools > Options > External data... Here, one can create or delete configuration files (in .xml format), add an existing configuration file to EwE, and set the active configuration file.



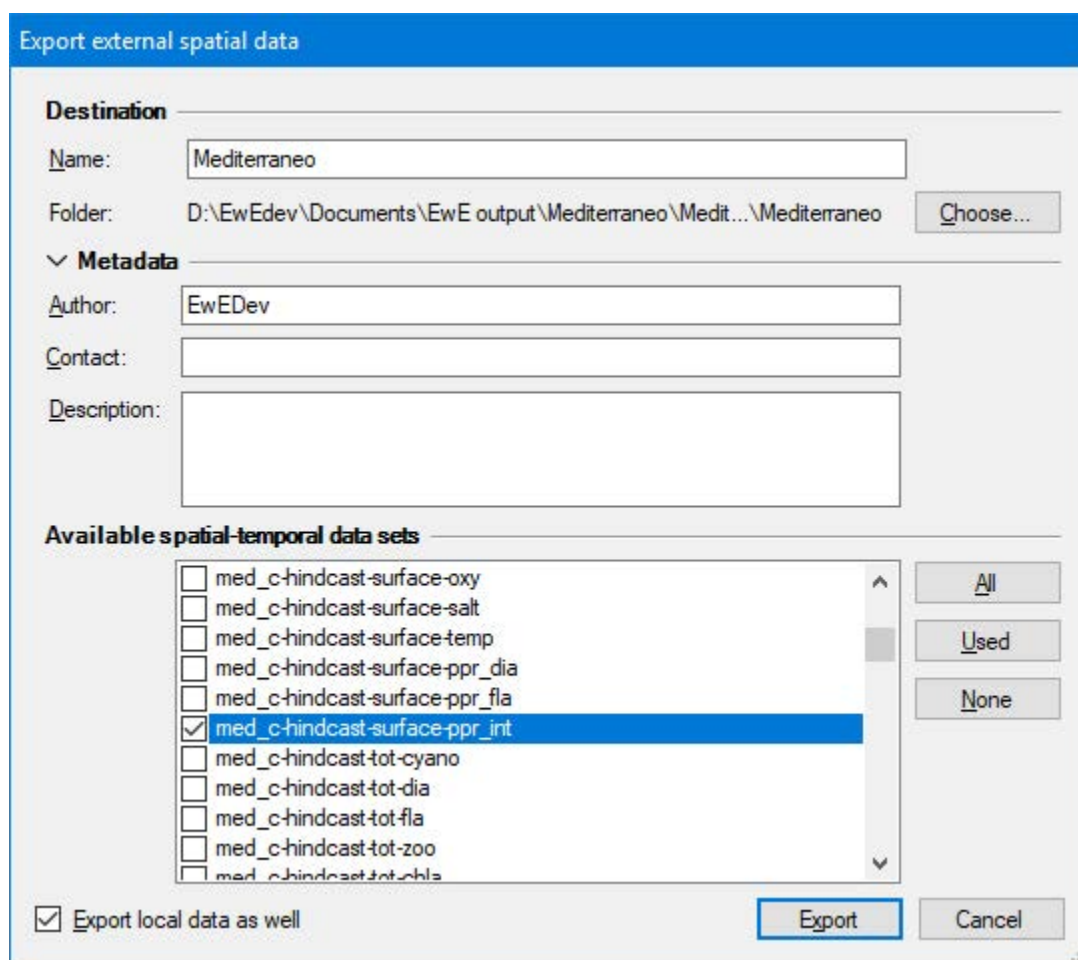
**Figure 8** – The form where you can switch external data configuration files. Use this only when you run multiple projects at the same time, each requiring numerous external data connections.

Once a connection is applied to an Ecospace layer, the definition of the connection is stored within Ecospace, while the data remains outside the model.

It is advisable to use separate configuration files for different models, as the number of external spatial temporal data connections can become overwhelming.

## Sharing External Data

The export external spatial data interface, which can be launched from all locations in the EwE user interface where external data connections are managed, creates new configuration files from selected external data connection definitions, and optionally their data. All exported data is placed in a user selected folder.



**Figure 9** – The Export external data interface

To share external data connected to your model with another computer or colleague,

- Open the export external spatial data view, for instance through Menu > Tools > Options > External data > Export
- Enter a descriptive file name (such as “External data Med 0.01667dd”)
- Select Choose to browse to the a location where the exported data can be placed
- Select which connections to export. The “Used” button selects all connections assigned in

Ecospace; the “All” button selects all available connections as defined the current configuration file.

- Check “Export local data as well”
- Click Export. Please be patient, this may take a while.

Once the export process is complete, share the data as follows,

- Copy the entire exported folder with your model to make it available or place the exported folder on a shared network drive.

To incorporate shared data into EwE,

- Go to Tools > Options > External data
- Click Add
- Browse to the shared configuration file
- Press Open and the configuration file will be added to EwE
- Press Set Current to make this the active configuration file
- Load Ecospace.

When an Ecospace scenario is loaded, the spatial temporal data framework automatically resolves conflicts in external data connections against the current configuration file.

## Notes

1. Christensen, V., Walters, C.J., 2004. Ecopath with Ecosim: methods, capabilities and limitations. *Ecological Modelling, Placing Fisheries in their Ecosystem Context* 172, 109–139. <https://doi.org/10.1016/j.ecolmodel.2003.09.003>
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# Sharing External Spatial Datasets

JEROEN STEENBEEK

The Ecospace module of EwE has gained capabilities to be driven by external spatial-temporal datasets. These external data sets cannot be embedded within a EwE model database because they tend to be model-derived datasets that frequently update, and that are of prohibitive file size. The process of connecting to these data is detailed in Steenbeek et al. <sup>1</sup>(2013), see [chapter](#).

To enable sharing of temporal spatial data by, e.g., scientists at different institutes in different locations, this system has been extended to offer support for shared use of the same model with accompanying external spatial data via cloud-based transfer media.

## Changes to EwE

The Ecospace model stores definitions of available spatial-temporal data series in a local configuration file <sup>2</sup>. Sharing this configuration file is impractical when a local system contains dataset definitions for a suite of Ecospace models: support was needed to only selectively share relevant data for a given modeling exercise. To enable this, the following changes have been made to the EwE6 software,

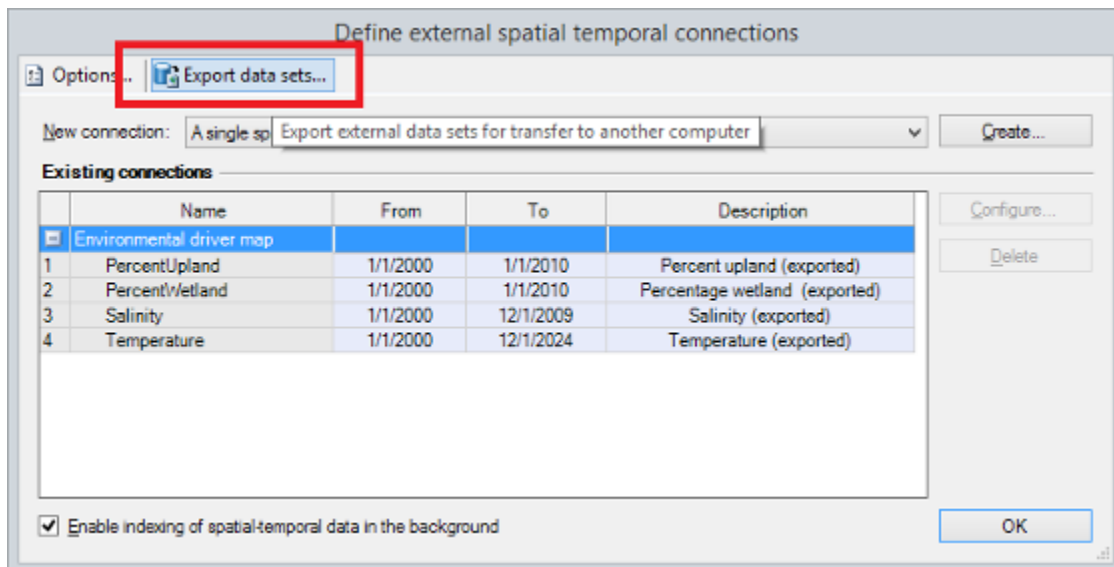
1. An export function was added to EwE6 that make it possible to copy a selection of dataset definitions to a local folder with a local configuration file. Whereas datasets on a local system are indicated by absolute file paths, the exported datasets refer to their files via local paths, making this export folder highly suitable for transfer to another computer.
2. An option has been added to allow for switching to a different configuration file – either locally created configuration files particular to a given modeling exercise, or shared configuration files obtained via a cloud-based file transfer system – which provides Ecospace with access to the external spatial-temporal data connections described in the configuration file.

EwE6 model databases already carried all information needed to connect an Ecospace layer to external data sets <sup>3</sup>. However, this information just contained technical details internal to the model, and was too sparse to assist troubleshooting when expected data sets could not be located. The following changes were therefore made to the EwE6 software:

1. EwE6 model databases now also store the configuration of data sets, but not the actual data due to its prohibitive size.
2. When Ecospace loads this information it tries to resolve these data sets. If a local computer does not know these data sets, the data sets are instantiated from the data stored in the model, and the user is warned that the data set may be incomplete. Having access to the complete configuration information, a user can figure out what external data is needed to reassemble the model configuration by requesting a data set export from the original model author, and then linking to these data.

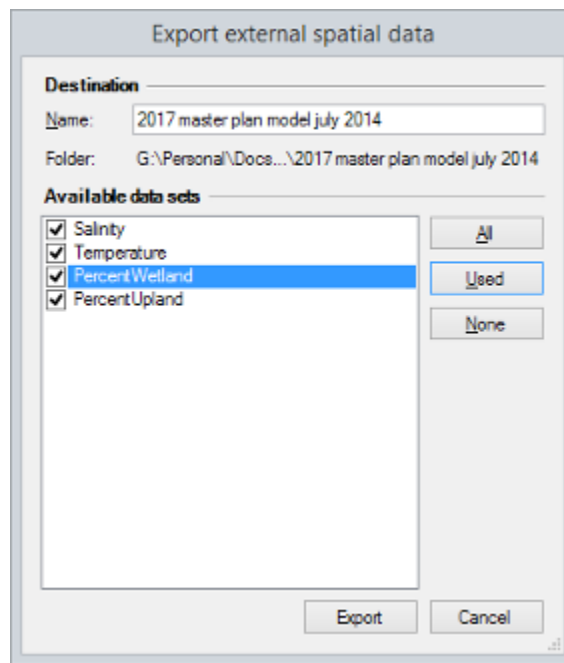
## Using these Developments

It is possible to export data sets from several locations in EwE, such as the main Ecospace menu and the interface where external datasets are defined (Figure 1).



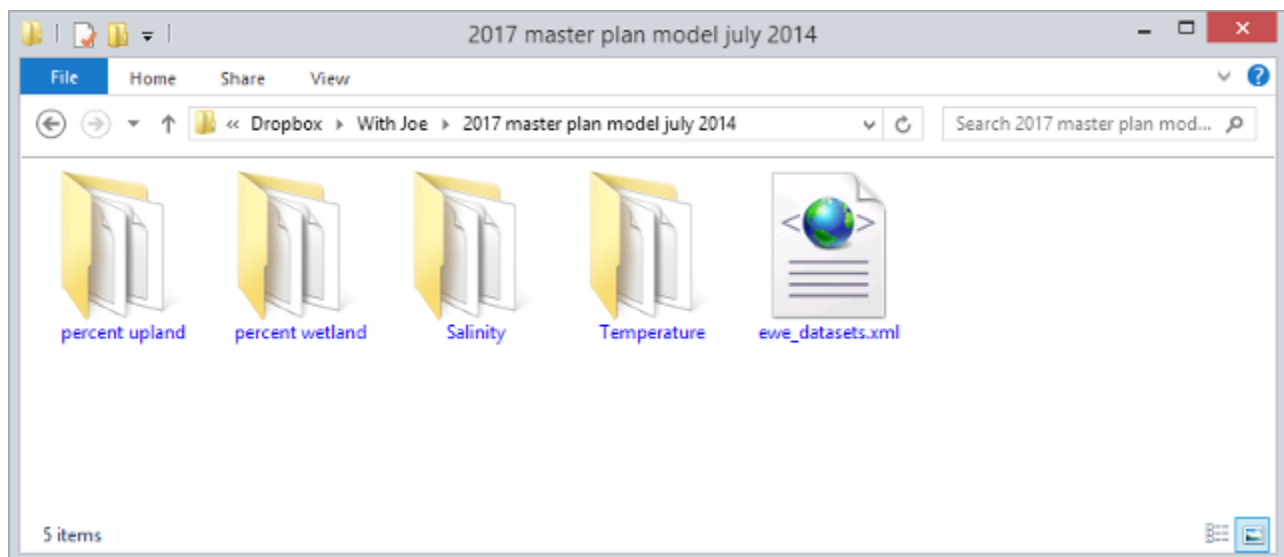
**Figure 1** – Where to find the Export data sets option.

When this option is selected a dedicated interface is displayed. Here users can decide which data sets to export for transfer to another computer, such as all data sets or only those used by the current model (Figure 2). Note that this interface is still in its infancy and may need further work to allow for selection of an export directory, to display export progress, and to display export result information.



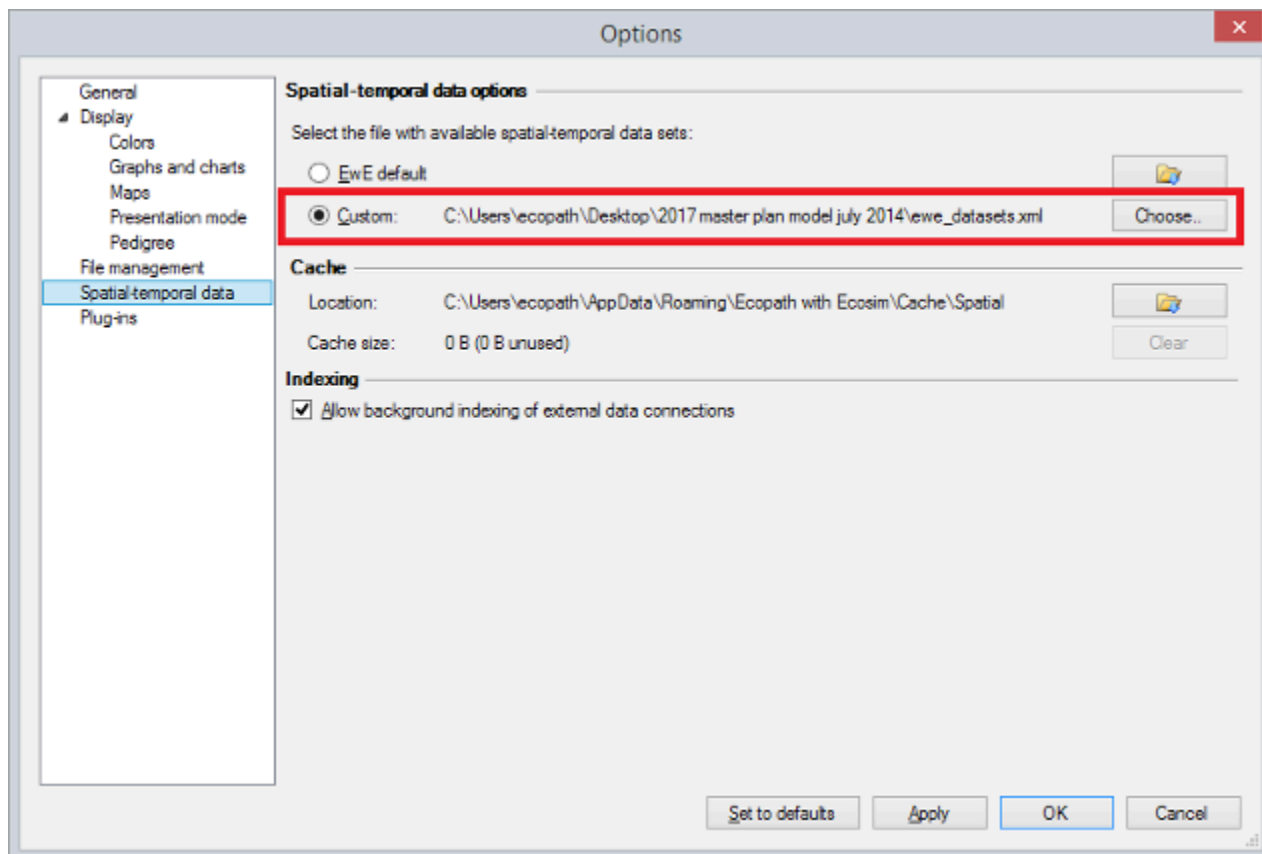
**Figure 2** – Data set export interface.

The EwE6 status panel notifies about where where the data sets have been exported to. When clicking this link, you are brought to the export directory, which in its entirety can be transferred to another computer, or can be shared via a cloud-based service such as Dropbox. The Export folder contains directories with file content for individual data sets where applicable, and a “ewe\_datasets.xml” configuration file for these files (Figure 3).

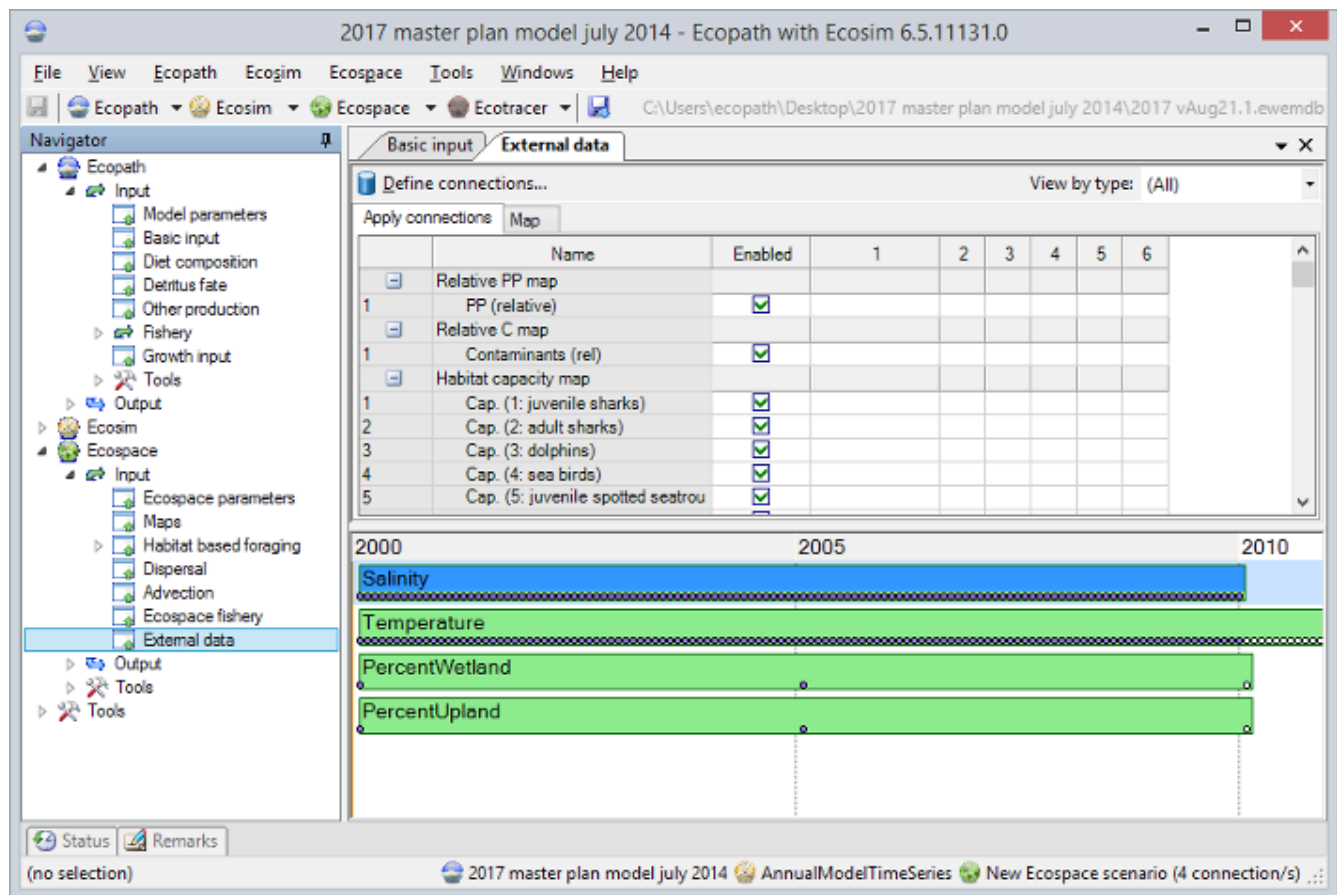


**Figure 3** – Example contents of a data set export folder.

Once the exported data sets are transferred to another computer they can be used by EwE. For this, a user switches the local configuration to the exported data sets via the spatial temporal data page in the main EwE options interface (Figure 4). Ecospace now shows the data sets as usable for the model (Figure 5).



**Figure 4** – Linking to a set of exported data sets that has been received from another user.



**Figure 5** – The imported data sets displayed in Ecospace, ready to be used.

## Notes

1. Steenbeek, J., Coll, M., Gurney, L., Mélin, F., Hoepffner, N., Buszowski, J., Christensen, V., 2013. Bridging the gap between ecosystem modeling tools and geographic information systems: Driving a food web model with external spatial-temporal data. *Ecological Modelling* 263, 139–151. <https://doi.org/10.1016/j.ecolmodel.2013.04.027>
2. Steenbeek et al. 2013, op. cit.
3. Steenbeek et al. 2013, op. cit.

# Spatial Model Skill Assessment

## Spatial Fitting

When fitting a model to data, two main processes are involved: the modification of parameters to better-fit observational data (called model calibration), and the comparison of predicted results with independent observations to validate results (or model validation). These processes are frequently done together to evaluate the performance of a model. With increasing spatial data available, the separation between calibration and validation should ideally become standard practice in Ecospace modeling.

## Advancing Towards Calibration of Ecospace

Contrary to the temporal model Ecosim, Ecospace model calibration is still rarely systematically executed due to the complexity of parameters involved, the need for large space-time datasets, and lack of computing power <sup>1</sup>[/footnote]. The majority of Ecospace users are manually tuning key parameters to obtain reliable distribution of species on the basis of visual inspection and confrontation with available spatial data. Some advances have been made by running Ecospace outside the user interface, using R or Python, to systematically evaluate parameter sensitivities and search for values that improve model fit <sup>2</sup>Vilas, D., 2022. Spatiotemporal Ecosystem Dynamics on the West Florida Shelf: Prediction, Validation, and Application to Red Tides and Stock Assessment. University of Florida. <https://doi.org/10.1038/s41598-023-29327-z>[/footnote]. In addition to tuning Ecospace parameters (as described in previous sections), also several Ecosim parameters could be changed during the tuning process. For example, vulnerability multipliers are calculated based on biomasses averaged over the entire spatial domain. When a fitted Ecosim model is migrated into Ecospace the calibrated vulnerability multipliers of some species might be too high for species that are confined to limited domains (restricted depth range, specific substrates, etc.) in Ecospace due to its spatial overlap with that of its predators and of the main target fishery. In cases such as these, Ecosim vulnerability multipliers (by predators or by predator-prey interactions) need to be manually tuned to reach the temporal-spatial stability of these species.

When dispersion rates are low, they might help to concentrate a species into stable hot spots or conversely, when high, dispersal rates might allow excessive dispersal of biomass in the domain. Consequently, higher dispersal rates tend to lead to models that better fit observational data but

that can become ecologically unrealistic. The dispersion rate also influences the resulting effects of MPAs, since high dispersal might predict large spill-over from areas of protection and hamper biomass rebuilding thus reducing the benefits for highly exploited species. Iterative testing the effects of the parameter values such as dispersal rates and vulnerabilities on spatial distribution of species (based on simple visual inspection) under e.g. MPAs setting can be done manually as part of the calibration process <sup>3</sup>.

Another component of spatial calibration is adjusting the response curves to environmental drivers (e.g., temperature, depth, dissolved oxygen) to better represent the aggregation of species, i.e., to resemble the aggregation in favorable areas in terms of environmental conditions <sup>4</sup>. Species distributions obtained from species distribution models or SDMs <sup>5</sup> can be used to either force the habitat capacity of a species <sup>6</sup> or can be used to compare with Ecospace model outputs for validation purposes: this is often done off-line, which allows for testing of the efficacy of tuning done manually, while not using optimization routines to create a better fit <sup>7</sup>.

To tune the cost of fishing and the distribution of fishing effort in Ecospace, distance from ports can be compared with, for example, analysis of Vessel Monitoring Systems (VMS) or Automatic Information System (AIS; <sup>8</sup>). Furthermore, administrative boundaries (EEZ boundaries), gear specific costs and habitat preferred for fishing (e.g., trawling avoiding rocky areas) are additional parameters that can improve accuracy of fisheries distribution over space. However, some specific spatial behavior of fishermen not directly related to the abundance and value of target species (e.g., fishery ground fidelity) might be quite difficult to represent. Overall, lacking better features to reproduce fishers' behavior, Ecospace assumes that all fleet elements have complete knowledge of distribution of the target species. Connecting Ecospace to an explicit fisheries behavior model is a development of interest for the future.

## Spatial Validation

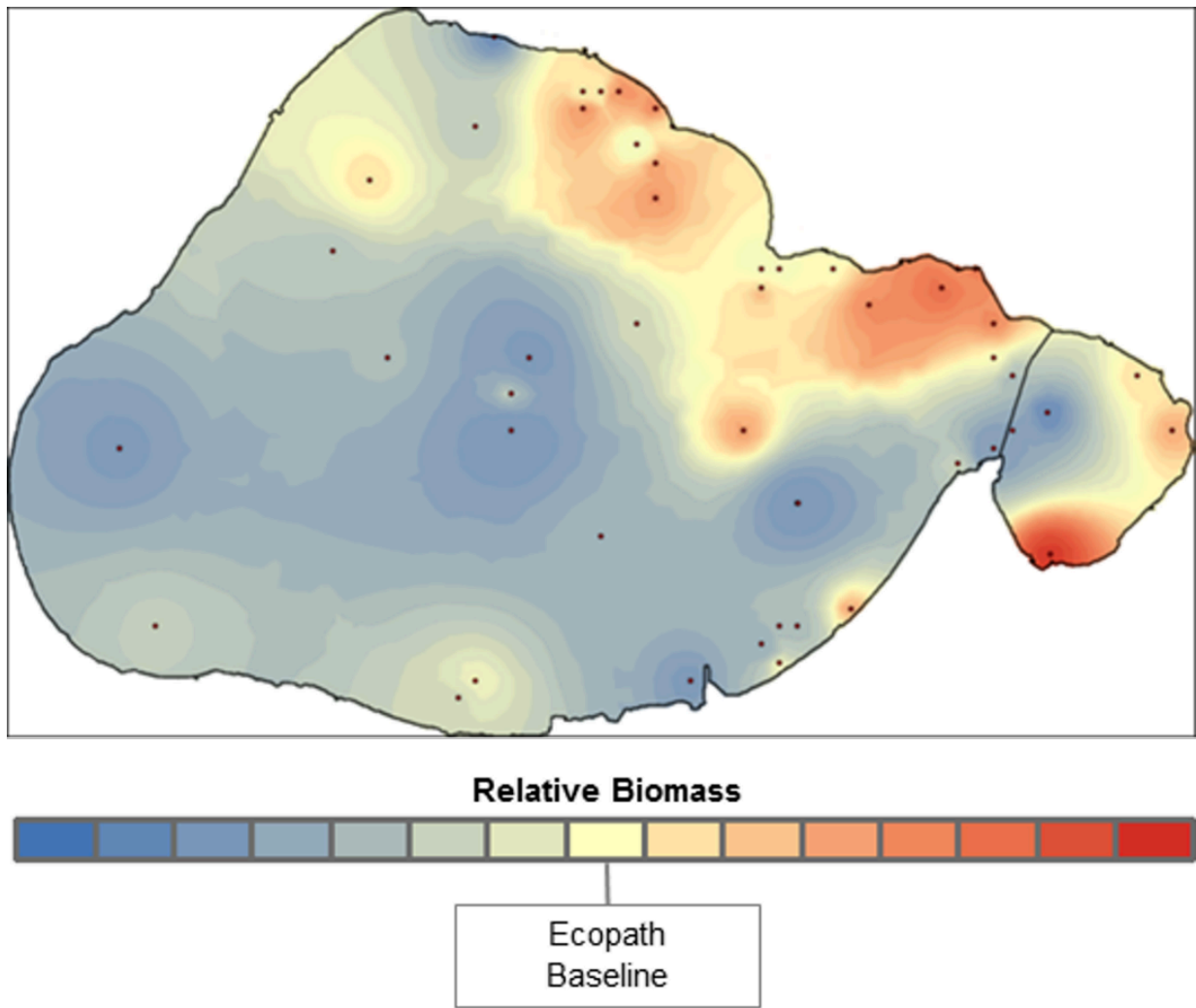
Validation is the process of assessing whether a parameterized and calibrated model effectively performs as it should. In other modelling context, traditionally the data pool is split in a set only used for calibration, and another set only used to finally validate the model with a proportion that can range from 50-50 to 80-20. Alternatively, completely different sets of data can be used for the validation. The validation serves as a proof of model skills. Such formal exercise is not often performed in Ecospace, while in the context of progressive application of EwE and Ecospace in operational context it is ideal to deliver a systematic validation of the models, and some examples of how this has been done are provided below.

## Hotspot Analysis

The use of existing telemetry data on particular species of interest is one data source that has been under-utilized in developing validation methods for spatial-temporal models. Ecospace includes a plug-in called the XY Hotspot Tool, which allows the user to include the frequency of detection of species from telemetry data and calculates the error between predicted and observed between telemetry data and Ecospace output maps. One unpublished example of this approach, called the XY Hotspot Analysis, was tested on Spotted Seatrout (*Cynoscion nebulosus*) in Lake Pontchartrain, Louisiana, USA. From 2012 to 2014, the movements of 211 Spotted Seatrout were monitored using an acoustic array composed of 90 autonomous receivers. The “pings” recorded on the receivers were converted to biomass using a novel methodology and then using various GIS interpolation techniques, species distribution maps were created at monthly time steps. Then, using the XY Hotspot tool, the prediction error between the maps output by the Ecospace model and the maps developed using the telemetry data were calculated (Figure 1).

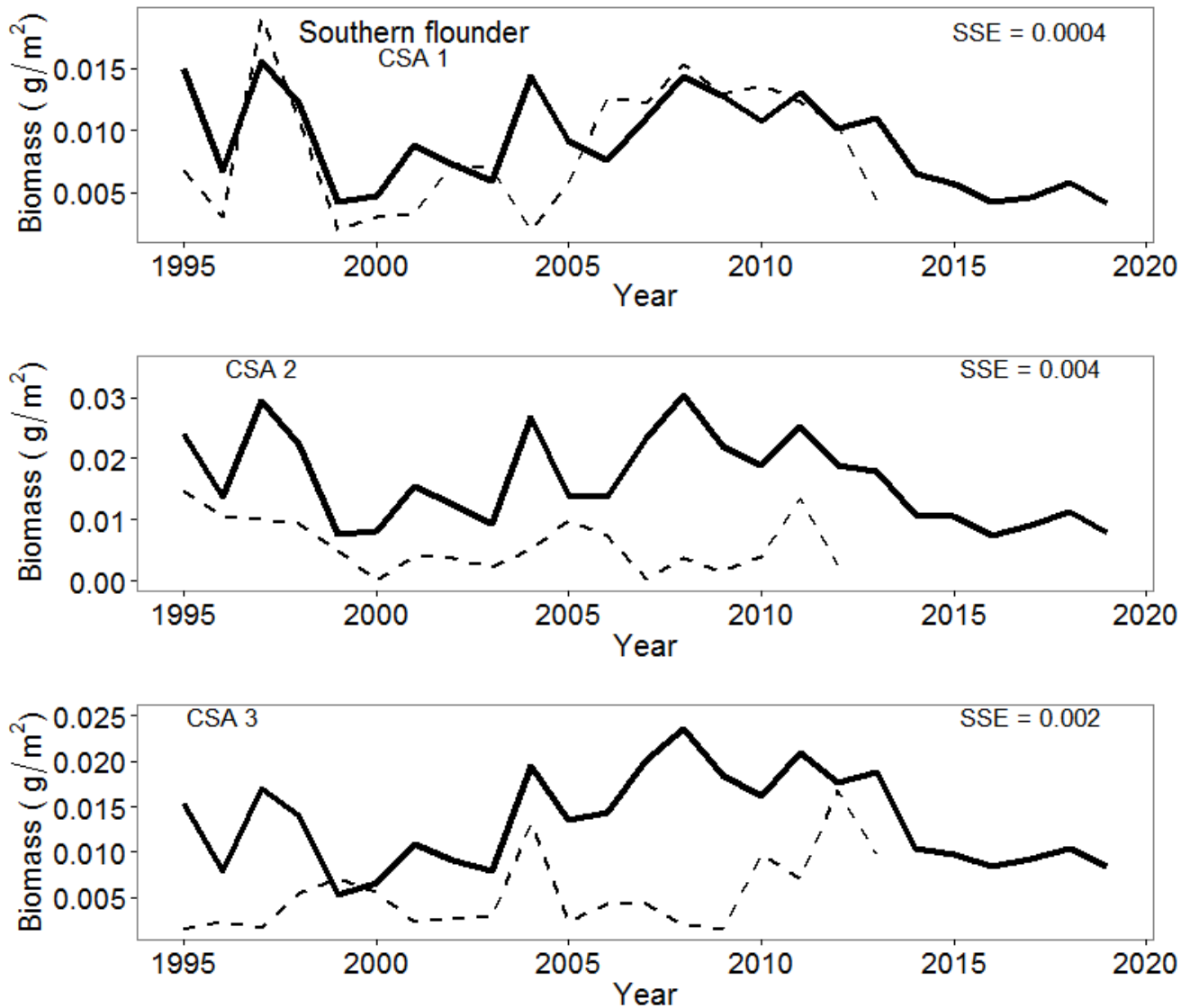


image



**Figure 1** – Lake Pontchartrain, Louisiana, USA. Resulting predictive error raster map, which indicates the degree of agreement between modeled output of Spotted Seatrout (*Cynoscion nebulosus*) and GIS rasters developed from in situ telemetry data. The black dots indicate the telemetry receiver distribution in the lake. The blue colors indicate negative predictive errors (the model underestimated biomass, red colors indicate positive predictive errors (the model overestimated biomass), and the yellow or beige colors indicate predictive zeros close to or at zero, indicating agreement between the two datasets.

## Using Regional Observations to Validate Distribution Patterns



**Figure 2** – Comparison of predicted absolute southern flounder biomass (solid lines) distributed into regions (coastal study area or CSA 1, 2, and 3) of the total model area over time to observed southern flounder biomass (dotted lines) in those same regions during the same time. The sum of squares error (SSE) provides a metric of fit between the two.

Validation often requires two datasets covering the same area (one for model creation, one for model validation), which is rare to have, e.g., two monitoring programs covering the same area. However, when a dataset has not been initially used to determine the spatial distribution of species, it can be used to validate distribution patterns. This is often the case with EwE models. Survey data that cover the whole model area can be used to create a representative snapshot of

the ecosystem (the Ecopath model). By creating regions within the Ecospace model area, averaged output of subsections can be generated. Time series of this output can be compared with survey data time series from field sites within that same subsection (see De Mutsert et al.<sup>9 10</sup> for examples). Goodness-of-fit metrics can be applied outside of the model interface. This is an easy non-spatial solution to validate how the habitat capacity framework distributes species based on habitat affinity and environmental preferences when spatial features are included in the model with response curves (Figure 2).

image

## Multi-Model Comparisons

Statistical analysis of species occurrences and their relationships with associated environmental factors is used to predict how likely a species is to occur in unsampled locations as well as future conditions. However, environmental factors alone may not be sufficient to account for species distribution. Other ecological processes including species interactions (such as competition and predation) and the impact of human activities, may affect the spatial distribution of a species. Novel techniques have been developed to take a more holistic approach to estimating species distributions, such as Bayesian Hierarchical Species Distribution model (B-HSD model) and mechanistic food-web models using the HFC model. Coll et al. (2019) used both species distribution and spatial food-web models to predict the distribution of European hake (*Merluccius merluccius*), anglerfishes (*Lophius piscatorius* and *L. budegassa*) and red mullets (*Mullus barbatus* and *M. surmuletus*) in an exploited marine ecosystem of the Northwestern Mediterranean Sea. They explored the complementarity of both approaches, comparing results of food web models previously informed with species distribution model results, aside from their applicability as independent techniques. The study showed that both B-HSD and E-HFC model results were positively and significantly correlated with observational data. Predicted spatial patterns of biomasses showed positive and significant correlations between modeling approaches and were more similar when using both methodologies in a complementary way: when using the E-HFC model previously informed with the environmental envelopes obtained from the B-HSD model outputs, or directly using niche calculations from B-HSD models to drive the niche priors of the Ecospace HFC<sup>11</sup>.

## Adaption

The chapter is adapted, with permission, from:

De Mutsert K, Marta Coll, Jeroen Steenbeek, Cameron Ainsworth, Joe Buszowski, David Chagaris, Villy Christensen, Sheila J.J. Heymans, Kristy A. Lewis, Simone Libralato, Greig Oldford, Chiara Piroddi, Giovanni Romagnoni, Natalia Serpetti, Michael Spence, Carl Walters. 2023. [Advances in spatial-temporal coastal and marine ecosystem modeling using Ecopath with Ecosim and Ecospace](#). Treatise on Estuarine and Coastal Science, 2nd Edition. Elsevier.

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2. [footnote]Vilas, D., Buszowski, J., Sagarese, S., Steenbeek, J., Siders, Z., Chagaris, D., 2023. Evaluating red tide effects on the West Florida Shelf using a spatiotemporal ecosystem modeling framework. *Scientific Reports* 13, 2541.
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11. Coll et al., 2019, op. cit

# ECOTRACER

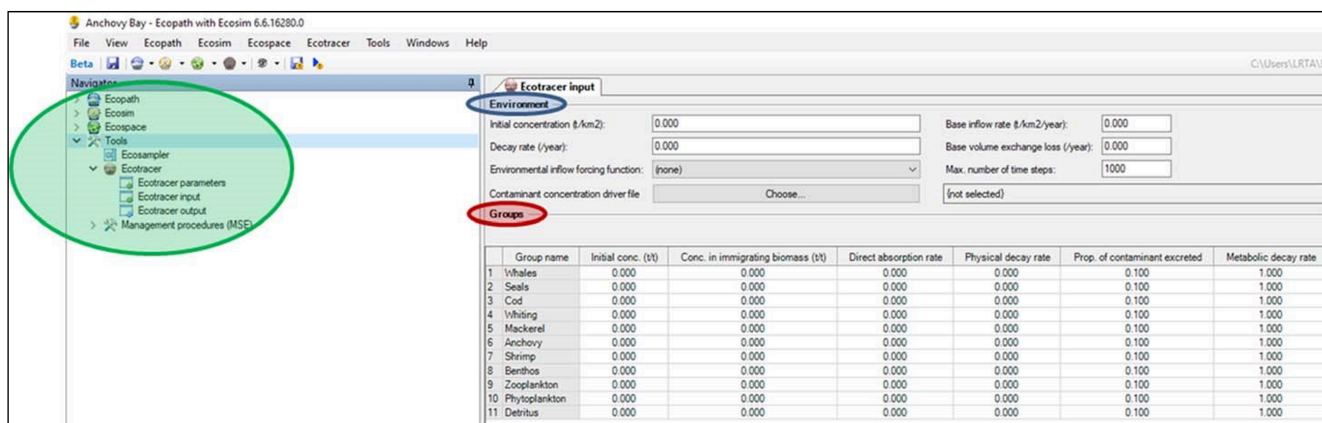
# Input and Data

SHAWN BOOTH; JEROEN STEENBEEK; AND SABINE CHARMASSON

Ecotracer is a useful tool within the Ecopath and Ecosim (EwE) modelling approach to track radioisotopes, contaminants, persistent pollutants, or stable isotopes through a food web model. After achieving a mass-balanced Ecopath model, Ecotracer can be used with the Ecosim (time dynamic) or Ecospace (spatial-temporal dynamic) to track the flow of the pollutant through the modelled ecosystem.

EwE uses a mass-balance approach, and the flows of a contaminant due to predator/prey interactions are tracked within the underlying Ecopath model. However, Ecotracer also needs parameters for groups based on a kinetic toxicology approach to estimate initial conditions. However, similar to Ecopath, Ecotracer can become dynamic through either the use of Ecosim or Ecospace to follow the changes of a contaminant that has different temporal inputs or to variations in temporal spatial concentrations in the water column.

The Ecotracer interface involves a number of input parameters (e.g., BI) and some that are calculated internally by the program, (e.g., gains from diet). Ecotracer's interface can be loaded from the task bar or from the side-menu. The interface is divided into three parts: the side panel (navigator) to choose Ecotracer or one of the other components of EwE; the interface for input for the environment; and input data for the functional groups based on the Ecopath model (Figure 1). The fields for the environment and the functional groups, their description and units are described below.



**Figure 1** – Screen capture of the Ecotracer routine showing the access to the user interface on the side panel (green), the areas for environmental data (blue) and functional group (red) inputs. The input data user interface can also be accessed through the toolbar at the top of the interface.

# Navigator

The side panel allows easy access to the different routines within the EwE modelling framework. After creating a balanced Ecopath model, the Ecotracer routine can be selected in this area. Ecotracer parameters must be selected and a name can be given to the scenario. Also, it is necessary to select either 'enable contaminant tracing for Ecosim' if the model is only being run forward in time or 'enable contaminant tracing for Ecospace' if the model is spatialized using the Ecospace. The selection of which is dependent upon the underlying model and whether there are time or spatial-temporal dynamics that are of interest.

Troubleshooting: if you do not get a response in Ecotracer and you have entered a direct absorption rate for primary producers; ensure that Ecosim or Ecospace have the contaminant tracing box checked.

# Environment

The simplest case for the environment is if the model area has a near uniform concentration. If this is the case then one concentration can be used for the initial concentration of the environment. If there are differences in time, but the spatial area is treated as being homogenous in concentration, then the base inflow rate can be changed using a csv file that represents either absolute or relative changes to the initial environmental concentration. If there are spatial-temporal variations in environmental contaminants in the model area, then a professional license for EwE is needed. Through the Spatial Temporal Data Framework (STDF <sup>1</sup>, see chapter [Spatial-Temporal Data Framework](#)), monthly maps of contaminant concentrations can be inserted into Ecotracer, enabling modellers to incorporate historical and/or projected environmental contaminants into Ecotracer. **Brief instructions how to use the STDF with Ecotracer are provided as an annex at the end of this manual.**

Groups							
	Group name	Initial conc. (t/t)	Conc. in immigrating biomass (t/t)	Direct absorption rate	Physical decay rate	Prop. of contaminant excreted	Metabolic decay rate
1	Whales	0.000	0.000	0.000	0.000	0.100	1.000
2	Seals	0.000	0.000	0.000	0.000	0.100	1.000
3	Cod	0.000	0.000	0.000	0.000	0.100	1.000
4	Whiting	0.000	0.000	0.000	0.000	0.100	1.000
5	Mackerel	0.000	0.000	0.000	0.000	0.100	1.000
6	Anchovy	0.000	0.000	0.000	0.000	0.100	1.000
7	Shrimp	0.000	0.000	0.000	0.000	0.100	1.000
8	Benthos	0.000	0.000	0.000	0.000	0.100	1.000
9	Zooplankton	0.000	0.000	0.000	0.000	0.100	1.000
10	Phytoplankton	0.000	0.000	0.000	0.000	0.100	1.000
11	Detritus	0.000	0.000	0.000	0.000	0.100	1.000

**Figure 2** – Close-up view of the interface for environmental parameters for Ecotracer. Environmental inflow forcing function (highlighted in green) requires a csv file (see Table 1), whereas the contaminant concentration driver file (highlighted in red) uses a series of ASCII files for each grid cell used in Ecospace, and requires the EwE pro license for the spatial-temporal framework.

**Initial concentration:** concentration in the water. Currently, there is no explicit depth representation in Ecospace and to be consistent with the biomass units (i.e., t·km<sup>-2</sup>) in Ecopath the units are expressed per km<sup>2</sup> with the units commonly being mass for most contaminants (e.g., g·km<sup>-2</sup>) or becquerels for radioisotopes (i.e., Bq·km<sup>-2</sup>). Therefore, units expressed in terms of unit per volume (e.g., µg·L<sup>-1</sup>) must be converted to the spatial resolution used.

**Base inflow rate:** the amount entering the environment each year (e.g., g·km<sup>-2</sup>·year<sup>-1</sup>). Obviously a base inflow rate for a one time release of, for instance, a hazardous chemical would not need a base inflow rate. However, to maintain background levels under equilibrium conditions a base inflow rate is needed to account for uptake and/or physical decay rates of the contaminant.

**Base volume exchange loss:** the rate at which a contaminant is lost to the environment (year<sup>-1</sup>).

**File for Base Inflow Rate:** this is intended to be used when the environment receives a uniform increase. This is a .csv file that is arranged to implement changes to the environment on a relative or absolute scale through time (Table 1).

**Table 1: Environmental inflow forcing function file that changes the relative base inflow rate from 1 to 3.40 over ten years; pool indicates the environment; and type 2 signifies a relative rate to the original environmental concentrations.**

name	Environment
pool	4
type	2
0	1.00
1	1.24
2	1.48
3	1.72
4	1.96
5	2.20
6	2.44
7	2.68
8	2.92
9	3.16
10	3.40

**File for Point source Release:** the point source release is another way of implementing changes to the environment on a spatial-temporal scale in conjunction with Ecospace. It requires a series of ASCII files to implement the changes in a spatial cell through time and is a feature of the EwE pro license.

**Maximum number of time steps:** Ecotracer numerically solves the equations at a higher resolution (i.e., more time steps) than Ecopath, Ecosim and Ecospace, which all have monthly time steps in order to reach a stable solution using an explicit integration method. The number of time steps is important for some contaminants that have relatively high physical decay rates. Therefore, the time steps and the number of calculations are increased to accurately trace the contaminant within Ecotracer, but Ecotracer integrates itself with the monthly time steps of Ecopath, Ecosim and Ecospace.

## Biota

For ease of computation within the Ecotracer program, Ecotracer uses the amount of substance (e.g., Bq or g). However, for output (see [next chapter](#)) you can choose between the amount in a

group (e.g., Bq) or biomass concentration (e.g., g·t<sup>-1</sup>). When validating model output to field sample data, it is likely that you will be comparing the biomass concentrations. All functional groups do not need to have starting concentrations, but they should have estimates of direct uptake rates, otherwise the resulting biomass concentrations will only reflect dietary uptakes based on the diet compositions entered for the Ecopath model. While this may not be important for top piscivores due to the fact that their diets mostly determine their contaminant load, it may affect the lower trophic levels of the food web where direct uptake rates may be more important than diet, and are the only entry way for primary producers. Dietary uptake is not entered as part of the Ecotracer routine as it is determined from the diet matrix, the consumption rate, the unassimilated amount, and the proportion of contaminant excreted.

Groups							
	Group name	Initial conc. (t/t)	Conc. in immigrating biomass (t/t)	Direct absorption rate	Physical decay rate	Prop. of contaminant excreted	Metabolic decay rate
1	Whales	0.000	0.000	0.000	0.000	0.100	1.000
2	Seals	0.000	0.000	0.000	0.000	0.100	1.000
3	Cod	0.000	0.000	0.000	0.000	0.100	1.000
4	Whiting	0.000	0.000	0.000	0.000	0.100	1.000
5	Mackerel	0.000	0.000	0.000	0.000	0.100	1.000
6	Anchovy	0.000	0.000	0.000	0.000	0.100	1.000
7	Shrimp	0.000	0.000	0.000	0.000	0.100	1.000
8	Benthos	0.000	0.000	0.000	0.000	0.100	1.000
9	Zooplankton	0.000	0.000	0.000	0.000	0.100	1.000
10	Phytoplankton	0.000	0.000	0.000	0.000	0.100	1.000
11	Detritus	0.000	0.000	0.000	0.000	0.100	1.000

**Figure 3** – Close-up view of the interface for functional group parameters for Ecotracer. The direct absorption rate ( $u_i$ ; highlighted in red) indicates that primary producers are generally the first compartment that are involved in the transfer of a contaminant through the food web model. The amount taken up by predator/prey interactions are defined by parameters in the underlying Ecopath model and by the diet matrix, and are accounted for internally by EwE. Note that the Initial concentration is the total amount in the functional group (see text for details).

**Initial conc:** the amount (e.g., Bq) in a group at the start of the model period (i.e.,  $t = 0$ ). Groups with no data from sample surveys can have a starting amount of zero.

**Concentration in immigrating biomass:** the concentration of a contaminant (Bq·t<sup>-1</sup>) in a functional group that is entering the model area under consideration.

**Direct absorption rate:** represents the amount of a contaminant that a functional groups takes up from the environment (km<sup>2</sup>·t<sup>-1</sup>·year<sup>-1</sup>). It represents the proportionality coefficient between the direct uptake rates (e.g., Bq·year<sup>-1</sup>), and the biomass (t) and environmental concentration (e.g., Bq·km<sup>-2</sup>). Generally, the primary producers must have a direct absorption rate, and it is useful to determine the direct absorption rate for other groups otherwise the resulting concentrations will only be due to trophic interactions (i.e., dietary items). Also, direct absorption rates are important for simulating changes in environmental concentrations through time.

**Metabolism rate:** the rate (year<sup>-1</sup>) of losses due to the transformation of the contaminant of

concern into another form (e.g., methylmercury to ionic mercury). These represent losses to the system.

**Decay rate:** the instantaneous physical decay rate constant (i.e.,  $\lambda$ ; year<sup>-1</sup>) of radioisotopes and represents losses to the system.

**Proportion of contaminant excreted:** this is the proportion (0-1) of the contaminant that is excreted back into the environment and stays in the system. It is equivalent to 1 – assimilation efficiency.

**Excretion rates:** excretion rates (year<sup>-1</sup>) are also described in Walters and Christensen <sup>2</sup>, but at this time are not represented in the user interface. If they are small relative to the surrounding environment they may not be important. However, in comparison to the metabolism rate there is an important difference. Excretory products stay within the system (i.e., they are available to be taken up again by biota), whereas the metabolism of contaminants are lost to the system because they are changed into something else.

## Attribution

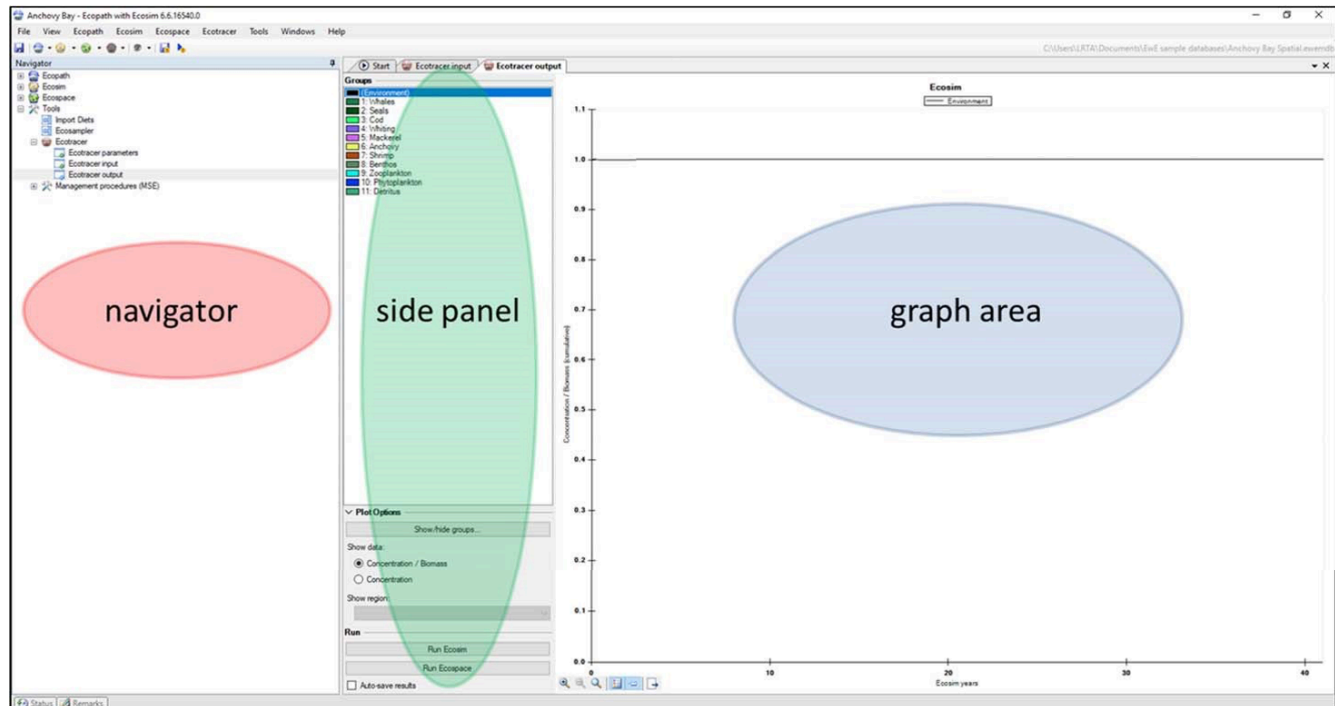
This work has been funded by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) and the French program Investissement d'Avenir run by the National Research Agency (AMORAD project, grant ANR-11-RSNR-0002, 2013-2022).

## Notes

1. Steenbeek, J., Coll, M., Gurney, L., Mélin, F., Hoepffner, N., Buszowski, J., Christensen, V., 2013. Bridging the gap between ecosystem modeling tools and geographic information systems: Driving a food web model with external spatial-temporal data. *Ecological Modelling* 263, 139–151. <https://doi.org/10.1016/j.ecolmodel.2013.04.027>
2. Walters & Christensen. 2018, op. cit.

# Output and Data Management

SHAWN BOOTH; JEROEN STEENBEEK; AND SABINE CHARMASSON



**Figure 1** – Full view of the Ecotracer output interface composed of the navigator, side panel and graphing area. The graph area, in this example shows that the amount of contaminant in the environment is generally constant through time. It is also possible to select more than one group by using the control or alt key. The Navigator pane has a Status and Remarks area at the lower left, which allows you to determine what changes have been made and to find the directory path for output files generated after a simulation. The Side panel has details for the environment and functional groups, plotting data type, and a for auto-saving results after each simulation run. In the show data section, the label concentration is the amount of contaminant and the concentration/biomass is the concentration.

The interface for the output of the data involves the navigator, a side panel and a graph area (Figure 1). Ecotracer output is selected from the navigator to display the side panel and the graph area. Data on the side panel involves choosing the data that is to be displayed on the graph area, the type of contaminant data displayed, the data displayed on the graphing area, the specific routine run button, and whether or not the data is automatically saved. Once data has been entered into the input interface, the simulation is initiated from the output interface either through the Run Ecosim or Run Ecospace buttons on the side panel to the graphing interface.

The graphical interface displays how the contaminant in the environment and in each functional group changes through time. There is a choice between having the functional groups trace the

contaminant by the amount (e.g., Bq) in the group or by the biomass concentration (e.g. Bq·t<sup>-1</sup>). The environmental concentration is essentially an area density (e.g., Bq·km<sup>-2</sup>). Under an assumption of environmental equilibrium, the environmental concentration on the graph should show a flat line. Under no changes to the functional groups underlying parameters (e.g., fishing mortality), the concentration in each group (e.g., Bq·t<sup>-1</sup>) should also be represented by a flat line.

For radioisotopes under assumed equilibrium conditions, the amount lost by radioactive decay would have to be added in as a base inflow rate to maintain equilibrium. Although equilibrium conditions may not be realistic, it is definitely a good way to see if the model is behaving properly, and may be a good assumption if the environmental concentrations do not change much due to a radioisotope having a long half-life, or when long-lived animals (e.g., whales) are not represented in the model as they would not be affected by historical environmental concentrations. The inverse of the P/B (unit: year<sup>-1</sup>) ratio is an indication of the average longevity of the groups in the model (B/P, unit: year).

Output files in Ecosim can be saved to a directory by selecting auto-save results. In Ecospace, it is necessary to open Ecospace parameters on the navigator panel and then select the files under the auto-save dialogue box. In most cases, the biomass maps and the contaminant concentration map need to be selected. This is because the concentration map is for the amount and therefore it is necessary to compute the concentration (e.g., Bq·t<sup>-1</sup>) from the two sets of data. The path directory for output files can be found in the status window. However, usually for the first run of a scenario it is useful to not save the data and examine the output by hovering over the concentration data on the graph; point-values can be shown by right clicking on a line on the graph and selecting Show point values. After adjustments have been made to basic input parameters (Ecopath or Ecotracer) if required, and the point values are in the desired range of expected output values, it is then worthwhile to save the output files.

Currently post-processing of the output files must be done in another program such as Microsoft Excel or R. Models that only use Ecosim for time dynamics will have a single output file containing a single column of output for each functional group, and 12 rows of data for each year with the cells containing the amount in the group. Models using Ecospace have CSV output files for each species that cover one time step for one species with the columns representing the longitudinal grid of the map and the rows the latitudinal grid working from the top left cell to the bottom right cell.

Changes in concentration for the environment and functional groups other than those resulting from changes in environmental concentrations result from the kinetic interactions as described earlier. Functional groups with no starting concentrations will have increasing concentrations, and groups with starting concentrations may have changes through time as a result of their losses and gains at each time step. However, differences between a functional group's model output and those with a starting amount based on field collected samples can also be affected by biases in

sampling (i.e., sampling not being representative of the population concerned) or by incorrect Ecopath or Ecotracer parameters. The biomass of a group may also change through time most commonly due to trophic interactions or changes in fishing mortalities if these are represented in the model. Thus, the resulting biomass concentrations can be a function of changes in the amount of contaminant in the functional groups and changes in the underlying state variables (biomass) through time.

Ecotracer is a useful computer simulation tool to gain knowledge on the transfer of pollutants in an ecosystem. We have attempted to give a practical guide to colleagues who are interested in the use of the EwE ecosystem modelling framework a better understanding on the technical use of the routine, and the interfaces used. We hope this inspires people from various backgrounds to engage and gain a better understanding of how contaminants behave in an ecosystem.

## Attribution

This work has been funded by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) and the French program Investissement d'Avenir run by the National Research Agency (AMORAD project, grant ANR-11-RSNR-0002, 2013-2022).

# Driving Ecotracer with Spatial-Temporal Data

SHAWN BOOTH; JEROEN STEENBEEK; AND SABINE CHARMASSON

Environmental distributions of contaminants can be made time-varying through the spatial temporal framework (STDF). Incorporating monthly changing patterns of contaminant concentrations into Ecotracer is a three-step process: 1) Prepare maps in a GIS; 2) define external data connections in EwE; and 3) connect an external data connection to drive the contents of the Ecospace contaminants layer.

## Prepare Maps in a GIS

Although the [STDF](#) contains a GIS engine that converts GIS data to the Ecospace grid (Steenbeek et al. <sup>1</sup>), it is highly recommended that ecosystem modellers perform this step in a dedicated GIS software to minimize GIS processing artifacts.

The step to prepare maps in a GIS entails the necessary steps to convert contaminant distributions over time into discrete, monthly ESRI ASCII maps that match the exact dimensions, cell size, spatial extent, and geospatial projection of the base map in an Ecospace scenario.

The Ecospace base map can be extracted from a loaded Ecospace scenario as follows:

- Click Navigator > Ecospace > Input > Maps
- Double-click the Depth layer at the right-most panel
- In the Edit layer interface that appears, select the Data tab. In the Data tab, select Export > To ASCII...

The actual steps to convert contaminant distributions to monthly Ecospace maps can require a number of GIS operations, depending on the format and content of the original contaminant data. Operations may require:

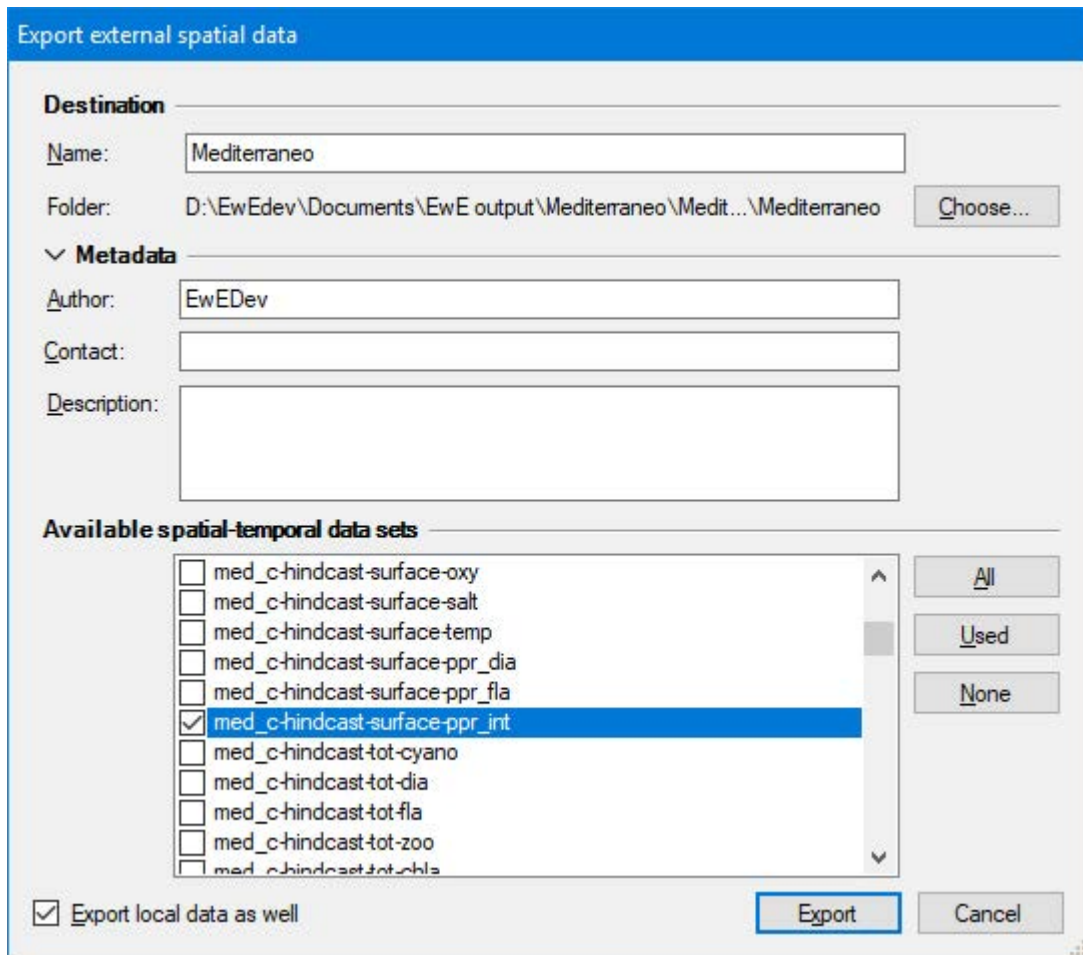
- Reprojecting to the Ecospace base map (most likely WGS84 / epsg:4326)
- Temporal clustering
- Clipping
- Kriging (point data) and/or resampling (vector data)

- Exporting to the ESRI ASCII format.

## Define External Data Connections in EwE

Once one or more time series of monthly ASCII maps have been prepared, Ecospace needs to know where to find these time series on the local machine. Do the following,

- Click Menu > Ecospace > Define external data connections...



**Figure 1** – To define a new spatial-temporal data connection, select the type of the connection and click . From this interface one can also reconfigure external data connections that were previously created.

- In the Define external data connections interface, select connection type A series of Ecospace ASCII maps over time and click Create (Figure 1). This will define the time series, and will bring up the Configure external data interface to configure the new time series

(Figure 2).

**Configure external data connection**

**Description**  
Name: Fukushima\_05km\_Cs137  
Description: Cesium 137 concentrations (Bq/m3) converted from Japanese model at 5km resolution  
Variable: (No variable)

**Files**  
 Location: D:\Projects\2019\ShawnBooth\Basemaps\...\cs137 Browse...

File	Time
✓ 137Cs_2011-03.asc	2011/03
✓ 137Cs_2011-04.asc	2011/04
✓ 137Cs_2011-05.asc	2011/05
✓ 137Cs_2011-06.asc	2011/06
✓ 137Cs_2011-07.asc	2011/07
✓ 137Cs_2011-08.asc	2011/08
✓ 137Cs_2011-09.asc	2011/09

Data is seasonal until 2100/01

**Set file times**  
 Starting at 2011/03 spaced at 1 month(s)  
 From file name (select which part): 137Cs\_2011-03.asc year-month

Apply Defaults OK Cancel

**Figure 2** – The interface to configure a specific external data connection (e.g, a time series of maps). Each time series has a name to uniquely define the series in the Ecopath with Ecosim user interface, an optional description, a variable that only serves to limit where the external data connection appears in the Ecopath with Ecosim user interface, and a series of timetagged maps that, in this particular figure, reflects historical concentrations of 137Cs in the water off of Fukushima, at monthly time steps, since March 2011.

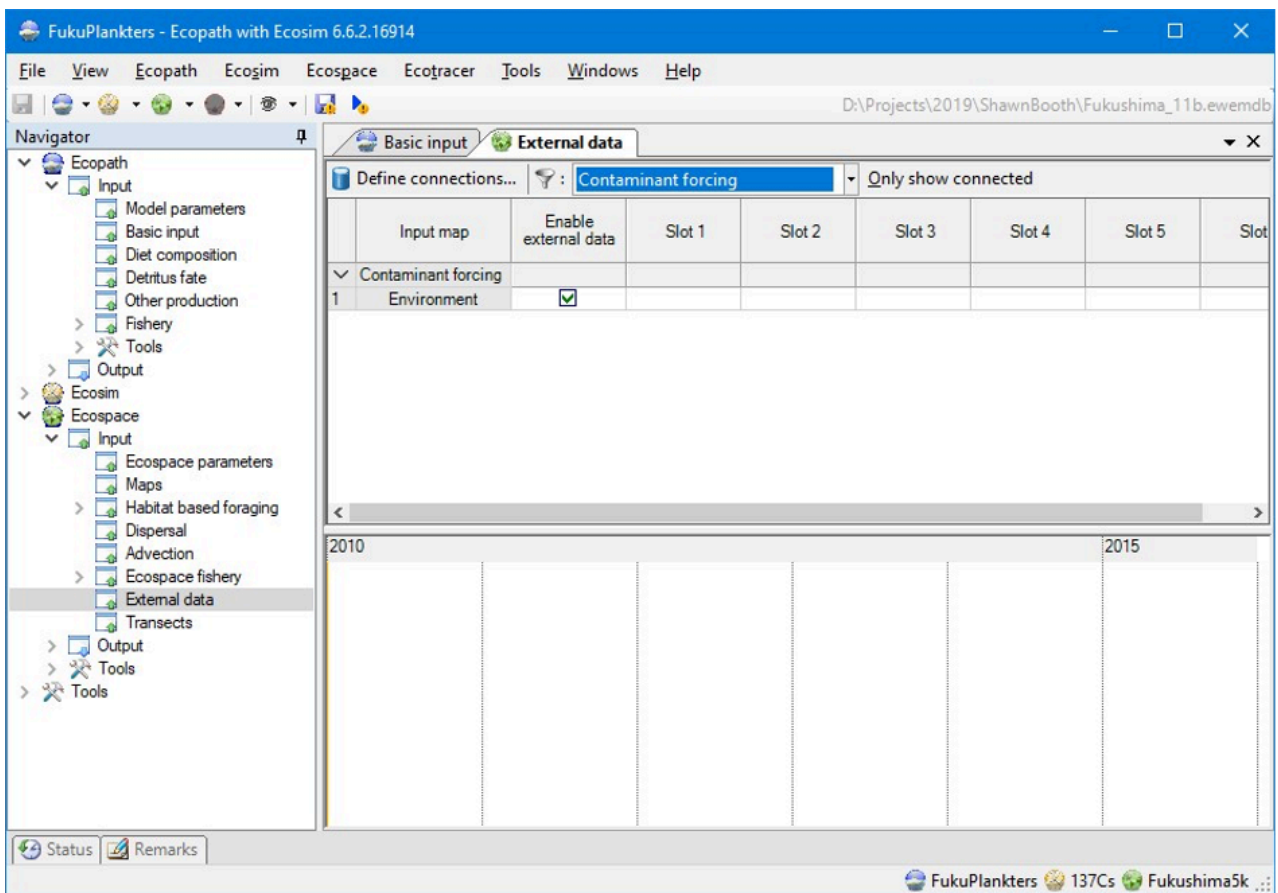
- In the Configure external data interface, enter a unique name to identify the time series in the Ecopath with Ecosim user interface.
- It is advisable to use the description to describe where the maps time series came from.
- The variable field serves to limit where the external data connection appears in the EwE user interface. For contaminants, leave this field at its default value (No variable).
- Now add the actual maps to the external data connection. Click Browse and navigate the folder that contains the maps. Select all the maps, and click Open. The maps will appear in the Configure external data interface.
- This interface has limited abilities to parse the date from map file names. Please check the Time column and ensure that each map has a correct time tag. You can modify time tags by hand, or with the tools provided in the Set file times section.
- Once all maps are correctly time-tagged, close the Configure external data. The newly configured time series of external maps will appear in the Define external data connections interface.
- Close this interface too.

Ecospace now has the information to locate and integrate time series of external ASCII contaminant maps into the running model.

## Connect the External Data to the Contaminants Layer

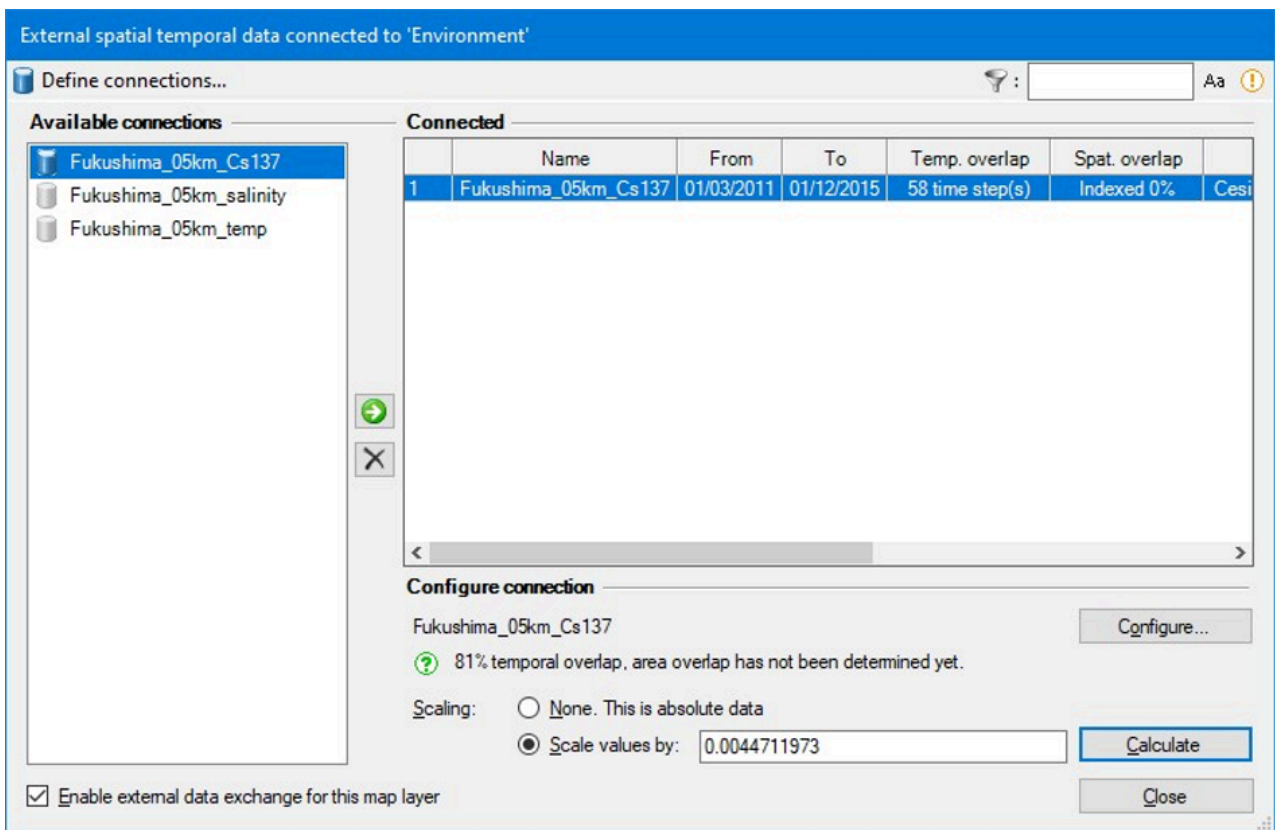
Now at least one time series of contaminants in seawater has been defined, this time series needs to be connected to drive the contents of the Ecospace contaminants map layer. Do the following,

- In the Navigator, open Ecospace > Input > External data (Figure 3)



**Figure 3** – The External data interface where previously defined external data connections are applied to Ecospace layers.

- Under input maps, locate the environmental contaminants map. One can also use the on-screen filter options to reduce the number of visible input maps
- In the row for the environmental contaminants map, click the cell Slot 1 to assign an external connection here. This brings up an interface dedicated to configuring how external data is integrated into Ecospace (Figure 4)



**Figure 4** – Configuring the integration of an external time series of maps into Ecospace, in this case to the environmental contaminants layer. Applied external time series are shown as “Connected”. The selected connection can be configured, which includes entering a scaling factor to ensure that external data matches the magnitude of data currently in the Ecospace environmental contaminants layer. As described in Steenbeek et al., the Calculate option scales the average map mean for the first full year of external data to the map data loaded in Ecospace.

- Here, from the list of available connections, select the connection that you wish to apply, and click the Apply (green arrow pointing right) button. The connection now appears under the list of Connected external data connections.
- An important aspect is to set a proper scale to ensure that the tracer (e.g., 137Cs) concentrations as obtained from external data is properly scaled to the units expected by Ecospace.
- Click Close.
- Run Ecospace.

## Attribution

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and the French program Investissement d'Avenir run by the National Research Agency (AMORAD project, grant ANR-11-RSNR-0002, 2013-2022).

## Notes

1. Steenbeek, J., Coll, M., Gurney, L., Mélin, F., Hoepffner, N., Buszowski, J., Christensen, V., 2013. Bridging the gap between ecosystem modeling tools and geographic information systems: Driving a food web model with external spatial-temporal data. *Ecological Modelling* 263, 139-151. <https://doi.org/10.1016/j.ecolmodel.2013.04.027>

# PLUG-INS

# Overview of EWE Plug-ins

<b>Plugin name</b>	<b>Concept</b>	<b>Developer</b>	<b>Status</b>	<b>Category</b>
Apply Environmental Responses Plugin	EII	EII	Prototype	UI Extension
Aquamaps Importer Plugin	JRC	EII	Released	Data integration
Ecological Indicators (EcoIND)	EII	EII	Released	Derived computations
Ecosampler Plugin	EII	EII	Released	Automation
Ecotroph plugin	Agrocampus Ouest	Agrocampus Ouest	Released	Derived computations
Ecosim Flow Diagram Plugin	NOAA	NOAA	Released	Derived computations
Import Export Layers Plugin	EII	EII	Released	Data import and export
Merge Split Groups Plugin	GEOMAR	EII	Released	Data integration
Model From Ecosim Plugin	UBC	UBC	Released	Data export
MPA Dynamics Plugin	UBC	EII	Released	Automation
MSE Plugin	CEFAS	CEFAS	Released	Automation
Multi-Sim Plugin	DFO		Released	Automation
Network Analysis	SAMS	UBC	Released	Derived computations
Prebal Plugin	UBC	UBC	Released	Derived computations
Remarks Plugin	EII	EII	Released	UI Extension
Results Extractor Plugin	CEFAS	CEFAS	Released	Data export
ShapeGrid Plugin	UBC	UBC	Released	UI Extension
Stepwise Fitting Plugin	SAMS	SAMS+ EII	Released	Automation
Transect Extraction Plugin	CEFAS	EII	Released	Data export
Value Chain	UBC	UBC	Released	Derived computations
WoRMS Plugin	UBC	EII	Released	Taxonomy search
FLEM File Reader Plugin	UBC	UBC	Released	Data import
CouplerLib Plugin	CEFAS	CEFAS + UBC	Prototype	Model interoperability

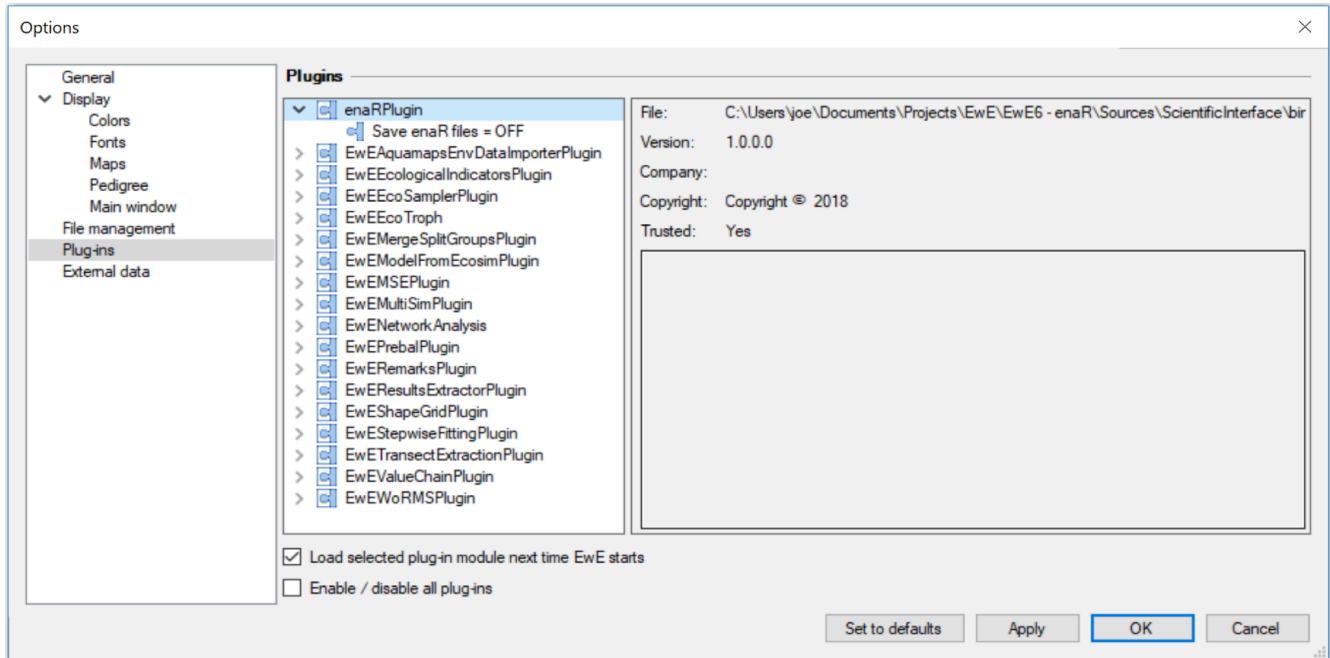
<b>Plugin name</b>	<b>Concept</b>	<b>Developer</b>	<b>Status</b>	<b>Category</b>
Depth Adapter Plugin	UBC	UBC	Internal	Data import
EcoEngineers Plugin	UCT	EII	Project deliverable	Derived computations
Ecospace MonteCarlo Plugin	UBC	UBC	Prototype	Automation
Ecospace NGOMEX Results Writer Plugin	George Mason	UBC	Project deliverable	Data export
Ecospace ICM Results Writer Plugin	CSIC	EII	Project deliverable	Data export
Ecospace Sensitivity Analysis Plugin	UBC	UBC	Prototype	Derived computations
enaR Plugin	CNRS	EII	Prototype	Automation
CSV Map Reader Plugin	UBC	EII	Prototype	Data import
Depletion Recovery Plugin	CSIC	UBC	Project deliverable	Automation
Ecospace Fit Plugin	UBC	UBC	Prototype	Derived computations
Ecospace Spinup Plugin	UBC	EII	EwE Pro	Automation
FishBase Search Plugin	FishBase	EII	Prototype	Taxonomy search
Import Diets Plugin	CSIC	EII	Prototype	Data import
Key Run Comparison	CEFAS	UBC	Prototype	Data import
Network Analysis R	SAMS	EII	Discontinued	Data import
OBIS Search Plugin	JRC	EII	Prototype	Taxonomy search
Resilience Plugin	IPMAR	EII	Discontinued	Derived computations
SAUP Taxon Search Plugin	SAUP	UBC	Prototype	Taxonomy search
Spatial Temporal Data Framework Plugin	UBC	UBC + EII	EwE Pro	Data import and export
FishMIP2	EII	EII	Project deliverable	Data import and export
SailCost Plugin	UBC	UBC	Project deliverable	Derived computations
Habitat Capacity Paper Plugin	UBC	UBC	Project deliverable	Various

<b>Plugin name</b>	<b>Concept</b>	<b>Developer</b>	<b>Status</b>	<b>Category</b>
Mejs Hasan Extensions Plugin	NOAA	EII	Project deliverable	Various
MSE Batch Plugin	UBC	UBC	Project deliverable	Automation
Roberts Bank Plugin	UBC	UBC	Project deliverable	Data import and export
Spatial SS Plugin	UBC	UBC	Prototype	Derived computations
MSP Tools Plugin	EII	EII + BUAS	Released	UI Extension

**Last Updated in 27 September 2022**

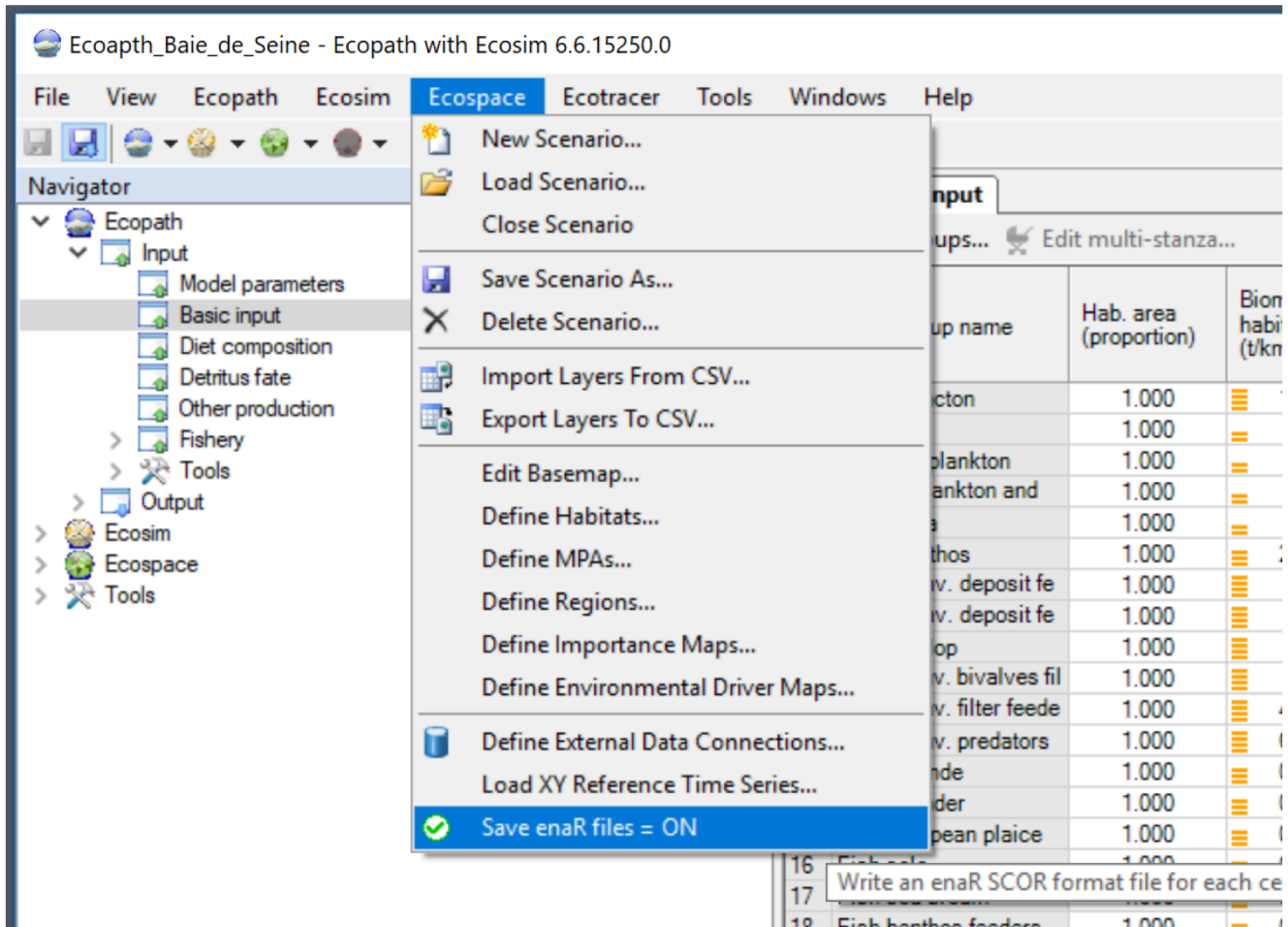
# enaR SCOR Files from Ecospace

The enaR SCOR file writer can be activated via by making sure the enaRPlugin is included in your version of EwE. You can see your loaded Plugins via the EwE's main menu Tools/Options and selecting the Plugins.



**Figure 1** – EwE Plug-ins manager.

The enaRPlugin will add a menu item to the EwE main menu to toggle file saving on or off  
**Ecospace/Save enaR file = On or Off**



**Figure** – 2enaR file save menu option.

The SCOR files will be written to your default output directory, which can be set via the Tools/Options/File management then setting the Output location. When the plugin is run it will create a new directory structure under the default output with the... /{Ecospace scenario name}/ena\_data/Timestep=000x. Each time step the model is run for will get its own directory. Within the timestep directories there will be a file for each Ecospace cell. The naming convention for the cell files is ‘nnn{row number}-nnn{column number}-{Ecopath Model Name} –{Ecospace Scenario Name}.txt’

i.e. “0001-0001-Ecopath\_Baie\_de\_Seine\_enaR-Test-1.txt” For the first row and column of an Ecopath model call “Ecopath\_Baie\_de\_Seine” with the Ecospace scenario “enaR-Test-1”. Rows and columns are one base from the upper left hand corner.

# Glossary

## **Anchovy Bay**

Anchovy Bay is a popular tourist attraction due to its century-old fishing port and its newer whale-watching industry. The fisheries have declined over the last decades, and have shifted from a focus on groundfish to being dominated by shrimp and pelagic fisheries.

## **EwE**

The Ecopath with Ecosim (EwE) approach and modeling framework

## **Foraging Arena Theory**

Foraging arena theory assumes that predator-prey interactions occur at the scale of hours and metres through various behavioural and physical mechanisms potentially restricting prey exposure to predation and intensify competition between predators

## **Instantaneous rate**

Instantaneous rate is the rate of change of a quantity at an exact moment in time, or at an instant. It is the limit of the average rate of change over an infinitesimally small time interval, as the time interval approaches zero. The instantaneous rate can be thought of as the slope of the tangent line to the curve representing the quantity being measured at a specific point in time. In calculus, the instantaneous rate is represented by the derivative of the function with respect to time.

## **Zero order cycles**

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# Versioning history

We are continuously seeking to improve this open textbook. Please submit your suggestions, recommendations, and/or corrections to EII.

This page lists major changes to this book with major changes marked with a 1.0 increase in the version number and minor changes marked with a 0.1 (or lower) increase.

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<b>Version</b>	<b>Date</b>	<b>Change</b>
0.1	2023/09/26	<ul style="list-style-type: none"><li>Imported the 2008 EwE6 User's Guide as a foundation/placeholder for this updated User's Guide</li></ul>
1.0	2023/x/x	<ul style="list-style-type: none"><li>First version of this User's Guide was published through <a href="http://pressbooks.bccampus.ca">pressbooks.bccampus.ca</a></li></ul>

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