Appendix 1

Here we summarize key characteristics of the Ecopath with Ecosim (EwE) food web modelling approach, and relevant mechanisms of EwE for the Maritime Spatial Planning Challenge platform dynamics.

Ecopath

The foundation of the Ecopath with Ecosim (EwE) modelling approach, Ecopath, is a mass-balanced model that represents the energy flow in a food web (Polovina 1984, Christensen and Pauly 1992). Living components in the food web are represented as functional groups, which can be a single species, a combination of species with similar roles in the ecosystem, or discrete life stages of a single species.

Ecopath uses a system of linear equations to describe the average flows of mass and energy between functional groups over a period of time, typically a year, which can be summarized as follows:

$$B_i \cdot \left(\frac{P}{B}\right)_j = \sum B_j \cdot \left(\frac{Q}{B}\right)_j \cdot DC_{ji} + BA_i + E_i + Y_i + B_i \cdot \left(\frac{P}{B}\right)_i \cdot (1 - EE_i) \qquad \textit{Eq.1}$$

where, for functional groups *i* and *j*, *B* is biomass; *P/B* is production per unit of biomass; *BA* is biomass accumulation rate; *E* is net migration rate (emigration − immigration); *Y* is total fishery catch rate; *EE* is ‘ecotrophic efficiency’, defined as the proportion of the production that is utilized in the system; *Q/B* is consumption per unit of biomass; and DC_{ji} the fraction of prey *i* in the diet of predator *j*.

For each group, Ecopath requires values for *B*, *Q/B*, *P/B*, *DC*, *Y*, and other values are optional. Of *B*, *P/B*, *Q/B*, and *EE*, three values must be entered while the fourth will be estimated by the model (Christensen and Pauly 1992 p. 1, Christensen and Walters 2004).

Ecosim

The temporal module of EwE, Ecosim, applies the mass-balanced Ecopath parameters, augmented with a few extra parameters related to behavior and temporal dynamics, to a series of time-dependent differential equations, expressing the biomass growth rate as:

$$\frac{dB_i}{dt} = g_i \cdot \sum Q_{ji} - \sum Q_{ij} + I_{ji} - (M_i + F_i + e_i)_i \cdot B_i \qquad \textit{Eq.2}$$

where, for functional groups *i* and *j*, *dB/dt* represents growth rate during time interval *dt*; *g* is net growth efficiency (*P/Q*); *I* is immigration rate; *M* is natural mortality rate; *F* is fishing mortality rate; *e* is emigration rate.

Ecosim stabilizes its food web dynamics through the concept of the foraging arena, which expresses that through predator avoidance behavior, at any given moment in time, only a fraction of a total prey biomass is vulnerable to predation by a predator (Ahrens et al. 2012).

In its simplest form, the consumption rate is defined as:

$$Q_{ij}\left(B_i, B_j\right) = \frac{v_{ij} \cdot a_{ij} \cdot B_i \cdot B_j}{v'_{ij} + v_{ij} + a_{ij} \cdot B_j} \qquad \textit{Eq.3}$$

where, for prey group *i* and predator *j*, *Q* is consumption; *B* is biomass; *a* is effective search rate; *v* is vulnerability to predation exchange rate; and *v'* is invulnerable to predation exchange rate.

The foraging area concept implies that predators, over time, may greatly vary the composition their diets with fluctuations of available prey.

Ecospace

The spatial-temporal module of EwE, Ecospace, extends the Ecosim parameter set with extra parameters related to spatial preferences and movement. Ecospace executes the Ecosim equations across a two-dimensional grid of equally sized cells, where functional groups and fishing effort gravitate towards better conditions (Walters et al. 1999, Christensen et al. 2014). Cells can be blocked out from having ecosystem dynamics to represent land (for marine ecosystems) or cells that fall beyond the modelled area of interest.

Species dynamics

Ecospace contains a highly configure niche model that defines cell suitability for functional groups. Central to this concept is the term of 'capacity', or 'habitat foraging capacity' in full, which defines the suitability of functional groups to forage across the spatial grid (Christensen et al. 2014). Ecospace affects the capacity of a predator to forage as follows:

$$V = \frac{vB}{v + v' + {}^{aP}\!/_{A}} \qquad \textit{Eq.3}$$

where, for a given predator, *V* is vulnerable prey density; *B* is prey biomass, *P* is predator abundance; *v* and *v'* are vulnerability exchange rates to and from the feeding arena; *a* is search rate; and *A* is the foraging arena size.

The niche model can derive its capacity, per cell, per group, per time step, from three different pathways:

1. Through habitats (spatial distributions of relevant spatial features) and habitat preferences (the ability to use each habitat for a given group)
2. Through environmental drivers (spatial distributions of relevant environmental parameters) and environmental responses (functional response curves that quantify the tolerance or preference of a given group to a specific environmental driver)
3. Through external forcing, in case an external species distribution model is used.

Habitat capacity *Ch* is defined as the total suitability of a cell for a species to feed due to the presence of preferred habitats:

$$Ch_i = \sum_{h=1}^{n} r_h \cdot p_{i,h}\,; \quad Ch_i \in [0,1]; r_h \in [0,1]; p_{i,h} \in [0,1] \qquad \textit{Eq. 4}$$

where, for functional group *i* and habitat *h*, *Ch* is habitat capacity; *n* is the number of habitats; *r* is the ratio of the cell area covered by a habitat; *p* is habitat preference of a group to a specific habitat.

Environmental capacity *Ce*, on the other hand, is defined as the multiplicative assessment of environmental preferences:

$$Ce_i = \prod_{e=1}^{m} Y_{i,e}\,; \qquad Ce_i \in [0,1] \qquad \textit{Eq. 5}$$

where, for functional group *i* and environmental driver *e*, *Ce* is environmental capacity; *m* is the number of environmental drivers, and *Y* is the environmental preference of group *i* to environmental condition *e* as dynamically evaluated across the spatial grid (Fig. 1).

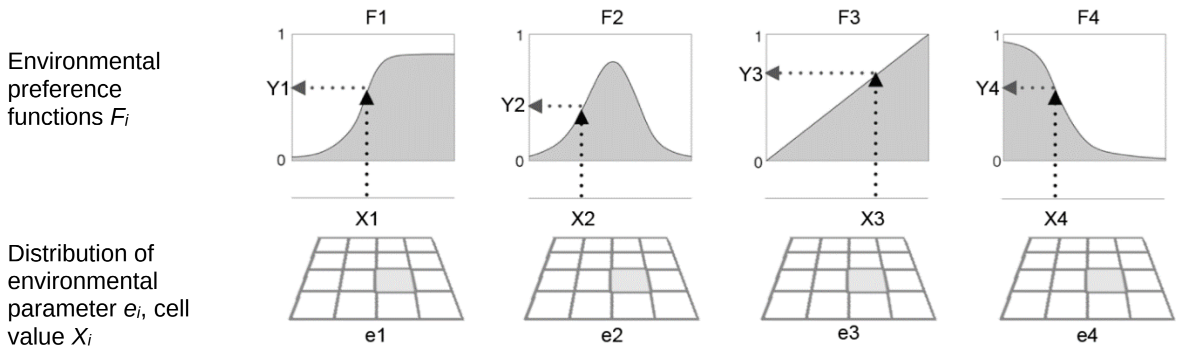

Fig. 1. Schematic diagram of the environmental capacity calculations with 4 hypothetical environmental preference functions. Environmental suitability *Y* for environmental driver e is obtained by looking up cell value *X* along environmental preference function *F*. The total environmental suitability for a cell is then defined as $Y_1 \cdot Y_2 \cdot Y_3 \cdot Y_4$ (adapted from Christensen et al. 2014)

The total capacity C_i in a cell for a functional group is then simply defined as:

$$C_i = Ch_i \cdot Ce_i; \qquad Ce_i \in [0,1] \qquad \textit{Eq. 6}$$

Note that EwE release 6.5 introduces the flexibility to derive capacity from habitats alone (Eq. 4), from environmental responses alone (Eq. 5), or from both (Eq. 6). This is a per-group setting.

Functional groups in Ecospace will gravitate towards better nearby conditions, with better feeding opportunities are lower risk to predation. A set of specific parameters controls functional group movement: dispersal (average distance a group moves, during the Ecopath period, while searching for food), advection (current-induced movement), and migration (directed behavioral movement patterns). Groups can also be coaxed to stay out of 'bad' habitat, where risk to predation can be higher, and increased movement rates serve to return to more suitable habitat. Ecospace considers a cell as bad habitat for a given group when the available foraging arena size drops to 10% or below (Christensen et al. 2015).

Fleet dynamics

Fishing intensity in Ecospace is inherited from the base intensity specified in Ecopath, and its temporal fluctuations in Ecosim, and is expressed as a spatial distribution of effort for each fishing fleet in the model. Fishing effort is distributed across the Ecospace grid based on a simple economic evaluation, which balances the financial returns of catching target groups and their market value, against combined fixed fishing costs and catch per unit of effort (CPUE).

Ecospace offers four mechanisms to control fishing effort, per fleet, and its spatial distribution:

1. The total amount of Ecospace fishing effort can be increased or decreased through a fishing effort multiplier;
2. Habitats can be used to prohibit fishing for specific fishing gear types over unsuitable bottom types;
3. No-fishing zones (generally referred to a Marine Protected Area or MPA) can be established to close specific cells to specific fishing gear types, too (Walters et al. 2000);
4. The CPUE component of the economic evaluation can be affected by entering a distribution of relative fishing costs across the spatial grid, making specific map areas more expensive for fishing than others (Walters et al. 1999, Bauer et al. 2018). Although typically used to incorporate distance from port as an economic evaluation factor, this mechanism can also receive inverted historical fishing effort distributions to coax Ecospace to mimic observed fishing patterns.

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