Supplementary Material:

*2.2 Ecosystem Modelling*

An Ecopath model uses trophically-linked biomass pools to create a mass-balanced snapshot of the resources and interactions in an ecosystem (Christensen and Pauly, 1992; Pauly *et al.*, 2000; Christensen and Walters, 2004). The biomass pools typically represent either a single species or a group of species that comprise an ecological guild. These pools may be split into ontogenetic age categories (juvenile, subadult, adult, *etc.*), commonly called ‘stanzas,’ and a detailed accounting of growth and survival for monthly cohorts is conducted for such groups. Biomass pools are created for all major components of the ecosystem, regardless of trophic level. The parameterization of an Ecopath model is based on satisfying two ‘master’ equations. The first equation describes how the production term for each group can be divided for an arbitrary time period:

Production = catch + predation + net migration + biomass accumulation + other mortality (Eq.1)

More formally, equation (1) can be expressed as:

Bi = (P/B)iEEi = Yi + Ei + BAi + ∑ nj=1 Bj(Q/B)jDCji (Eq. 2)

where for biomass pool *i* = 1, …, *n*:

· *Bi* is total biomass during the period of question

· (*P*/*B*)*i* is the production to biomass ratio

· *EEi* is the ecotrophic efficiency, defined as the fraction of the production that is consumed within or harvested from the system

· *Yi* is the yield or catch in weight (note that *Yi* = *FiBi* where *F* is the fishing mortality rate)

· *Ei* is the net migration rate (emigration – immigration)

· *BAi* is the biomass accumulation rate for (*i*)

· *Bj* is the biomass of the consumers or predators of (*i*);

· (*Q*/*B*)*j* is the food consumption per unit biomass for consumer *j*

· *DCji* is the average fraction of *i* in the diet of *j* (note that *DCji* = 0 when *j* does not eat *i*)

At a minimum, Ecopath requires input of *DCji*, *Yi*, and three of the following four parameters for each species or biomass pool in the model: *Bi*, (*P*/*B*)*i*, (*Q*/*B*)*i*, and *EEi* (mass balance principles are used to estimate the fourth parameter). If all four parameters are known, then Ecopath can be used to estimate either *BAi* or *Ei*. Equation (2) implies that an ecosystem under study is described completely by an *n-*dimensional system of linear equations, the solutions of which can be easily calculated (Mackay, 1981); the resulting estimates of biomass, production, and consumption can be used to construct a quantitative network diagram of energy flow for the system (Ulanowicz, 1986). The second ‘master’ equation is based on the principle of conservation of matter within a group and is designed to balance the energy flows of a biomass pool:

 Consumption = production + respiration + unassimilated food (Eq. 3)

Winberg (1956) defined consumption as the sum of somatic and gonadal growth, metabolic costs, and waste products. Equation (3) generally follows this definition, but differs in the sense that it is used to estimate losses rather than to measure growth. Balance of the energy equation is achieved by estimating respiration from the difference between the consumption, production, and unassimilated food terms. For more details on Ecopath, see Christensen and Pauly (1992) and Christensen and Walters (2004).

Ecopath is used to describe the interactions among resources within an ecosystem. Additional modules are created to simulate the dynamics of the ecosystem resources and the effects of different putative management strategies on the structure and function of an ecosystem. The time-dynamic module, called Ecosim, provides a simulation capability that facilitates policy exploration at the ecosystem level, with initial parameters inherited from the base Ecopath model. To construct an Ecosim model, it is necessary to re-express the system of linear equations in (2) as a system of coupled differential equations. This transformation takes the following form (Walters *et al.*, 1997;Walters *et al.*, 2000; Christensen and Walters, 2004):

 $\frac{dBi}{dt}$ = gi ∑ nj=1 cji - ∑ nj=1 cij + ( Ii - Mi - Fi - ei ) Bi (Eq.4)

where:

· *gi* is growth efficiency

· *Fi* is the instantaneous rate of fishing mortality

· *ei* is the rate of emigration

· *Ii* is the rate of immigration

· *cij* (*cji*) is the consumption of biomass pool *i* (*j*) by biomass pool *j* (*i*)

This system of equations is used to represent the spatially aggregated dynamics of entire ecosystems and is combined with explicit age/size-structured delay-difference equations to represent populations that have complex life histories and selective harvesting of older animals. An important aspect of Ecosim is the expression of the consumption or ‘flow’ rates among linked species or biomass pools. Consumption of prey *i* by predator *j* is modeled as:

Qij(BiBj) = $\frac{aijvijBiBj}{(2vij + aijBj)}$ (Eq. 5)

where *aij* is the rate of effective search for prey *i* by predator *j*, and *vij* is the behavioral exchange rate between vulnerable and invulnerable prey pools. Equation (5) is based on the notion that

consumption is limited by ‘risk management’ behaviors of predators and prey at very small time scales. That is, predator-prey interactions are assumed to take place primarily in restricted ‘foraging arenas’ where prey only become vulnerable to predation through their own requirements for resource acquisition (Walters *et al.*, 1997; Walters *et al.*, 2000).

Relative to Ecopath, Ecosim introduces a number of new parameters, of which the simulations are especially sensitive to the vulnerability settings (Christensen and Walters, 2004). For this we use a vulnerability factor, (often referred to as ‘vulnerability’). The vulnerability factor expresses how much the predation mortality for a given prey can increase if the predator abundance is increased. When the predator is close to its carrying capacity with regard to the given prey, the predation mortality cannot be increased any further (v = 1), and an increase in predator abundance, (e.g., due to good recruitment) will be compensated for by a decrease in predator consumption rates. This in turn will result in lower predator production, and the predator abundance will move back toward its carrying capacity. In an opposite response, a decline in predator population size when it is close to its carrying capacity will be compensated for by a comparative increase in average consumption rates, which will bring the predator back toward its carrying capacity. A population at its carrying capacity is a stable population. On the other hand, if the predator is far from its carrying capacity for a given prey, the situation is very

different. An increase in predator biomass will lead to an increase in prey mortality rate. In Ecosim terminology, the vulnerability factor for the prey will be high. The consumption rate of the predator will remain relatively constant, and the increase in its biomass will manifest itself in population growth. There will be only limited compensatory effects. In general, it is not possible to estimate vulnerability factors from field or laboratory data. However, to assist with identifying appropriate settings, Ecosim includes several methods of estimation (see Christensen *et al.*, 2004 for details on these methods), and it is recommended that vulnerabilities be estimated based on time-series analyses, *i.e.*, by evaluating how groups in the ecosystem has reacted to changes in the past. Time-series data for model calibration are thus essential for developing and validating an Ecosim model. Therefore, time-series data depicting trends in relative and absolute biomass, fishing effort by gear type, fishing and total mortality rates, and catches for as long a period as possible should be viewed as additional data requirements.

Ecotacer uses three equations to control the uptake and flow of pollutants in biomass pools (Walters and Christensen, 2018).

Contaminant uptake (Bq/yr) into a biomass pool is regulated by direct uptake from the environment and uptake from food.

 Direct uptake = uiBiC0 (Eq. 6)

where C0 is the environmental concentration of the contaminant, Bi is the biomass of the trophic group i, and ui is the environmental uptake rate for group i.

Uptake from food is expressed as:

Food uptake = fi ∑ j=1 QjiCj /Bj (Eq. 7)

where Cj/Bj is the concentration/biomass of the prey items, Qji is the consumption rate of species j by species i, and fi is the assimilation efficiency of group I (calculated in Ecopath).

If a trophic group is divided into stanzas there is an age-flow in a trophic group:

Age inflow = $\frac{1}{∆ t}$ $\frac{Bi,k-1,t}{Bi,k-1}$ Ci  (Eq. 8)

Where B is biomass, i is trophic group, k is age class for groups with age structure, t is time, and C is the contaminant concentration.

Ecotracer uses similarly structured equations to account for contaminant loss in trophic groups as well as changes due to immmigration and emigration (see Walters and Christensen 2018).