Supplementary Material

# Description of the OSMOSE model and its parameterization for the Eastern English Channel

The individual element of the OSMOSE model is a super-individual of identical fish, i.e., of the same size, same trophic level (TL), same location and belonging to the same species. During each two week time step, the abundance and biomass of each super-individual changes according to the different modeled processes: spatial movement, local interactions and resulting mortalities, growth, reproduction.

**Spatial movement**: At each time step, super-individuals can move to adjacent cells following a random walk pattern (foraging), while always remaining within the limits of their presence map (provided as input for each species and possibly for different ages and/or seasons according to available knowledge, Travers-Trolet et al. 2019).

**Local interactions and resulting mortalities**: The predation process first assesses the food requirement for each super-individual, based on the maximum ingestion rate *r* of the predator *i*. This value is then compared to the amount of suitable food available locally, i.e., in the cell of the predator, defined by the suitability of prey size compared to predator size, the biomass *Bj* of each prey available and an accessibility coefficient *ai,j* representing vertical overlap and/or morphological constraints between the prey *j* and the predator *i*. The predated biomass *PBi,j* of a prey *j* by a predator *i* is expressed as follows:

$$PB\_{i,j}=min\left(rB\_{i}\frac{a\_{i,j }B\_{j}}{\sum\_{k}^{}a\_{i,k }B\_{k}} , a\_{i,j }B\_{j} \right)$$

The predation pressure is applied to all prey, proportional to their relative contribution to the total amount of edible food (i.e., no preference), by reducing prey abundance and biomass according to the realized predation pressure. According to the amount of food eaten compared to its maximum ingestion, the predation efficiency *ξ* is computed for each super-individual *i*. If *ξi* falls below the threshold corresponding to maintenance requirement *ξcrit*, the starvation mortality rate *Mξ* is positive and increases linearly with predation efficiency reduction:

$$M\_{ξ}=\frac{-M\_{ξmax}}{ξ\_{crit}}ξ\_{i}+M\_{ξmax}$$

The different mortality rates (starvation *Mξ*, fishing *F* and other sources *Moth*) are applied similarly to decrease the abundance of a super-individual *i* following the survival formula:

$N\_{i,t+Δt}=N\_{i,t}e^{-ΔtM\_{x}}$ with $M\_{x}\in \left\{M\_{ξ},F,M\_{oth}\right\}$

The fishing mortality rate is species-specific, but can vary temporally and/or spatially according to available knowledge. For the fishing process, knife-edge selectivity was used, affecting only recruited fish i.e., fish older than the species age at recruitment. Finally, mortality from other sources is also considered by taking into account predation by organisms non-explicitly represented in the model (e.g., other fish, birds, mammals) as well as diseases and senescence. A particularly high mortality term is applied to the first stages (eggs) to represent the bottleneck of survival due to non-fertilization of eggs, starvation of first-feeding larvae, advection, sinking and predation by non-explicitly modeled organisms.

**Growth**: growth can occur if the predation was successful enough, i.e., if the biomass eaten is higher than maintenance requirements. The length increment depends on the predation efficiency and averaged length increment (*∆L*) at the super-individual’s age derived from the von Bertalanffy growth curve. The weight *W* of an individual increases simultaneously with its length through an allometric relationship.

$$\left\{\begin{matrix}ΔL\_{i,t}=0&ifξ\_{i}<ξ\_{crit}\\ΔL\_{i,t}=\frac{2ΔL}{1-ξ\_{crit}}\left(ξ\_{i}-ξ\_{crit}\right)&ifξ\_{i}>ξ\_{crit}\end{matrix}\right.$$

**Reproduction**: new super-individuals of eggs are produced depending on the spawning stock biomass (computed from a sex ratio of 1:1 and from the biomass *B* of all fish older than age at maturity *Amat*, the species relative fecundity *φ* and the seasonality of spawning *st*.

$$N\_{0,t}=φs\_{t}\frac{1}{2}\sum\_{a>A\_{mat}}^{}B\_{a,t}$$

Parameters used for representing the 14 main species of the Eastern English Channel are reported in Table S1. Details about parameterization, calibration and validation can be found in Travers-Trolet 2019.

*Table S1: Input parameters of OSMOSE for the 14 fish species modelled explicitly. L∞, K, and t0 are the parameters of the von Bertalanffy growth model, with a linear growth before the threshold age ath and a growth following the von Bertalanffy model after ath; c is Fulton’s condition factor and b the exponent of the L-W allometric relationship; Lmat is length at maturity and φ is relative fecundity; amax is longevity; F is the annual fishing mortality rate and arec is age of recruitment; Moth is an additional mortality rate; Mξ max is the maximum starvation mortality rate, ML is the larval mortality rate applied to the first life stage; min and max size ratios define suitable prey size for a predator, ξcrit is the critical predation efficiency corresponding to maintenance requirements, r corresponds to the maximum amount of food edible per year relatively to the predator mass.*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | GROWTH AND CONDITION | REPRODUCTION | SURVIVAL | PREDATION |
| *Species* | L∞ | K | t0 | ath | c | b | Lmat | φ | amax | F | arec | Moth | Mξ max | ML | Min size ratio | Max size ratio | ξcrit  | r  |
|  | *cm* | *y-1* | *y* | *y* | *g.cm-3* |  | *cm* |  *eggs.g-1* | *y* | *y-1* | *y* | *y-1* | *y-1* | *month-1* |  |  |  | *g.g-1* |
| Lesser spotted dogfish | 87.4 | 0.118 | -1.09 | 0.5 | 0.00308 | 3.029 | 57 | 0.14 | 10 | 0.09 | 4 | 0.087 | 0.3 | 4.29 | 50 | 3 | 0.57 | 3.5 |
| Striped red mullet | 53.3 | 0.18 | -1.23 | 1 | 0.00716 | 3.178 | 16.7 | 500 | 11 | 0.194 | 0.4 | 0 | 0.3 | 13.01 | 125 | 10 | 0.57 | 3.5 |
| Pouting | 37.6 | 0.46 | -0.77 | 0.5 | 0.00657 | 3.202 | 23 | 620 | 4 | 0.106 | 1 | 0.12 | 0.3 | 6.69 | 50 | 3.5 | 0.57 | 3.5 |
| Whiting | 40.2 | 0.63 | -0.37 | 1 | 0.00621 | 3.103 | 20 | 797 | 20 | 0.122 | 1 | 0.405 | 0.3 | 17.03 | 30 | 1.5 | 0.57 | 3.5 |
| Poor cod | 22.2 | 0.462 | -0.679 | 0.5 | 0.0092 | 3.026 | 13 | 100 | 3 | 0 | 1 | 0.085 | 0.3 | 4.73 | 50 | 3.5 | 0.57 | 3.5 |
| North Sea cod | 103.9 | 0.19 | -0.1 | 0.5 | 0.00835 | 3.053 | 56 | 800 | 25 | 0.219 | 1 | 0 | 0.3 | 21.95 | 50 / 20\* | 2.3 / 1.8\* | 0.57 | 3.5 |
| Dragonet | 28.3 | 0.471 | -0.443 | 0.5 | 0.0262 | 2.442 | 17.4 | 255 | 6 | 0 | 1 | 0.148 | 0.3 | 2.58 | 125 | 10 | 0.57 | 3.5 |
| Sole | 37.3 | 0.35 | -1.61 | 0.5 | 0.00391 | 3.264 | 29 | 482 | 20 | 0.187 | 1.5 | 0 | 0.3 | 7.4 | 125 | 10 | 0.57 | 3.5 |
| Plaice | 71.7 | 0.23 | -0.83 | 0.5 | 0.0103 | 3.017 | 27 | 255 | 15 | 0.44 | 1 | 0 | 0.3 | 13.52 | 125 | 5 | 0.57 | 3.5 |
| Horse mackerel | 39.2 | 0.18 | -1.515 | 1 | 0.0054 | 3.114 | 22 | 1655 | 15 | 0.052 | 0.5 | 0 | 0.3 | 3.52 | 100 | 2.5 | 0.57 | 3.5 |
| Mackerel | 42 | 0.24 | -2.07 | 1 | 0.00338 | 3.241 | 29 | 1070 | 17 | 0.142 | 0.5 | 0 | 0.3 | 7.94 | 100 | 2.5 | 0.57 | 3.5 |
| Herring | 29.2 | 0.37 | -0.67 | 0.5 | 0.00503 | 3.1 | 25 | 458 | 11 | 0.156 | 1.5 | 0.008 | 0.3 | 1.24 | 1000 | 5 | 0.57 | 2 |
| Sardine | 24.6 | 0.79 | -0.22 | 0.5 | 0.00594 | 3.077 | 15 | 2228 | 15 | 0.03 | 0.5 | 0.216 | 0.3 | 14.07 | 1000 | 5 | 0.57 | 3.5 |
| Squids | 50 | 2 | 0.5 | 0.7 | 0.25 | 2.27 | 30 | 50 | 2 | 0.036 | 0.5 | 0.298 | 0.3 | 7.97 | 20 | 1.5 | 0.57 | 3.5 |

# Modelled impacts of climate change on OSMOSE processes

**Primary and secondary productions:** The effect of climate change on primary and secondary productions is projected via the biogeochemical model POLCOMS-ERSEM (Butenschön et al. 2016) available for the NorthEast Atlantic. The effects of climate change projections on plankton production in the EEC are very small, as the main phytoplankton group biomass decreases by 2.39% under RCP4.5 and by 6.72% under RCP8.5, while the main zooplankton group biomass decreases by 1.74% under RCP4.5 and by 3.16% under RCP8.5.

**Growth:** The effect of climate change on growth is modelled following Kielbassa et al. (2010)’s approach, in which the parameter K of the Von Bertalanffy growth model depends on temperature:



where Kopt is the optimal growth coefficient, Topt the temperature associated to the optimal growth coefficient, and Tmin and Tmax respectively the minimal and maximal temperature that a species can endure. For each species, values of Topt, Tmin and Tmax were collected based on global occurrence presence records of each species using the GBIF and OBIS databases (Table S2).

*Table S2: Values of Topt, Tmax and Tmin (in °C) for the 14 species of the model*

|  |  |  |  |
| --- | --- | --- | --- |
| **Common name** | **Tmin** | **Topt** | **Tmax** |
| Lesser Spotted Dogfish | 8,52 | 12,97 | 16,85 |
| Red mullet | 10,36 | 12,70 | 19,76 |
| Pouting | 5,70 | 15,74 | 18,13 |
| Whiting | 4,46 | 8,21 | 15,83 |
| Poor Cod | 5,79 | 12,01 | 16,51 |
| Cod | 2,64 | 6,63 | 14,65 |
| Dragonet | 6,32 | 14,86 | 17,77 |
| Sole | 6,73 | 16,34 | 18,76 |
| Plaice | 3,79 | 12,14 | 17,72 |
| Horse Mackerel | 7,77 | 13,31 | 17,92 |
| Mackerel | 7,13 | 12,41 | 17,65 |
| Herring | 2,99 | 7,13 | 15,07 |
| Sardine | 8,45 | 18,79 | 26,96 |
| Squids | 4,43 | 20,11 | 29,84 |

**Reproduction seasonality**: the effects of climate change on reproduction phenology are modelled by varying the seasonality parameter for each species. To do so, we used the results from Lange and Greve (1997) who indicate that for spring-spawning species 1630 degree\*day are needed to achieve gametogenesis during spring-spawning. Based on the historical spawning periods, we determined the beginning of gametogenesis by summing backwards the daily temperature until the 1630°C\*day threshold was reached. As no information was available for other spawning seasons, we applied this value to all species. Then, starting from the resulting day when gametogenesis begins, we sum 1630°C\*day forwards using the projected daily temperature under scenarios RCP 4.5 and RCP 8.5. Thus, the spawning period was earlier by 0 to 6 days according to species under RCP4.5 compared to historical conditions, and by 4 to 14 days according to species under RCP8.5.

**Spatial distribution**: the effects of climate change on species spatial distribution are only modelled for species close to their distribution tail. To identify these species, we used the occurrence record data and associated temperature and coordinates from GBIF and OBIS databases to evaluate if the EEC corresponds to their limit of distribution and if so, to determine the maximum temperature they can tolerate both in winter and summer. The maximum temperature they can tolerate is then used as isocline on the maps of future temperature under the two RCPs scenarios to define the future distribution for the species.

# Simulated species biomass

*Table S3: Species biomass (in tons) simulated with OSMOSE under historical conditions (mean over 2000-2009) and under climate change scenarios RCP 4.5 and RCP 8.5 (mean over 2050-2059). Biomass are averaged over 30 replicates.*

|  |  |  |  |
| --- | --- | --- | --- |
| **species** | **historical** | **RCP 4.5** | **RCP 8.5** |
| Lesser spotted dogfish | 21 235 | 35 381 | 31 368 |
| Striped red mullet | 4 671 | 8 103 | 8 578 |
| Pouting | 24 551 | 19 717 | 22 308 |
| Whiting | 41 975 | 9 132 | 0 |
| Poor cod | 8 434 | 7 997 | 5 221 |
| North Sea cod | 9 865 | 47 | 0 |
| Dragonet | 22 263 | 28 181 | 33 498 |
| Sole | 20 153 | 33 166 | 46 629 |
| Plaice | 7 443 | 6 931 | 3 535 |
| Horse Mackerel | 138 920 | 145 433 | 161 718 |
| Mackerel | 43 804 | 66 099 | 78 761 |
| Herring | 233 753 | 124 023 | 784 |
| Sardine | 329 787 | 375 151 | 367 036 |
| Squids | 66 117 | 44 589 | 62 056 |

# MSY reference points estimation

Estimation of MSY reference points involve exploring a wide range of fishing mortality rate (F) values. A first exploration was performed to identify the maximum F to use for each species, corresponding either to species collapse or the confirmation of the existence of a plateau in the yield to F curve. The final range of F explored for each species is reported in table S3 and was kept constant under historical conditions and for climate change scenarios.

*Table S4: Boundaries (min F and max F) and step (ΔF) used for the fishing mortality rate (F) of each species when exploring the relation between yield and fishing mortality, in order to estimate MSY reference points.*

|  |  |  |  |
| --- | --- | --- | --- |
| **species** | **Min F** | **Max F** | **ΔF** |
| Lesser spotted dogfish (SYC) | 0 | 0.8 | 0.01 |
| Striped red mullet (MUR) | 0 | 1 | 0.01 |
| Pouting (BIB) | 0 | 5 | 0.05 |
| Whiting (WHG) | 0 | 0.4 | 0.005 |
| Poor cod (POD) | 0 | 5 | 0.05 |
| North Sea cod (COD) | 0 | 0.4 | 0.005 |
| Dragonet (LYY) | 0 | 5 | 0.05 |
| Sole (SOL) | 0 | 5 | 0.05 |
| Plaice (PLE) | 0 | 1.2 | 0.01 |
| Horse mackerel (HOM) | 0 | 1 | 0.01 |
| Mackerel (MAC) | 0 | 0.8 | 0.01 |
| Herring (HER) | 0 | 2 | 0.02 |
| Sardine (PIL) | 0 | 1.5 | 0.02 |
| Squids (SQZ) | 0 | 3 | 0.025 |

*Table S5: Fishing reference points determined by stock assessment (ICES 2017) and used for advice, when available.*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **species** | **Corresponding stock** | **Average F (2000-2009)** | **FMSY** | FMSY lower | FMSY upper |
| Whiting | Whiting in Subarea 4 and Divisions 7.d | 0.076 | 0.15\* |  |  |
| North Sea cod | Cod in Subarea 4, Divisions 7.d and Subdivision 20  | 0.848  | 0.31 | 0.198 | 0.46 |
| Sole | Sole in 7d | 0.365 | 0.256 | 0.195 | 0.348 |
| Plaice | Plaice in 7d | 0.315 | 0.25 | 0.18 | 0.34 |

\* “Inestimable using standard equilibrium considerations and would need to be determined as part of a management strategy evaluation” (ICES 2017)

**References**

ICES. 2017. Report of the Working Group on Assessment of Demersal Stocks in the North Sea and Skagerrak (2017), 26 April–5 May 2017, ICES HQ. ICES CM 2017/ACOM:21. 1248 pp

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