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# Management Strategy Evaluation of the Eastern English Channel Common Sole: Management approach under uncertainty.

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# Résumé étendu en français

**Évaluation de stratégie de gestion pour la sole de Manche Est :
une approche de gestion sous-incertitude.**

## Introduction

La définition de la structure des populations est une étape fondamentale de l'évaluation et de la gestion des ressources marines (Kerr et al., 2016). Classiquement les stocks sont considérés comme des unités homogènes et isolées. Pour autant, ce cas de figure reste exceptionnel. Or, un décalage entre la structure des populations et les limites de gestion peut conduire à un biais dans la perception de la dynamique des populations, à la surexploitation d'un ou de plusieurs segments des stocks et à la diminution de leur productivité, de leur stabilité et de leur résilience. Cependant, l'incertitude sur la structure des stocks et la mauvaise compréhension des conséquences d'un décalage entre structure de stock et limites de gestion empêche généralement toute évolution de la gestion.

Dans ce contexte, l'évaluation de stratégie de gestion (MSE) est une approche de modélisation permettant d'évaluer l'effet de stratégie de gestion dans un contexte d'incertitude sur la structure spatiale des stocks (Punt, 2015; Punt et al., 2001; Smith, 1994). Cette approche a été appliquée au stock de sole de Manche Est (zone VIId), un stock historiquement surexploité pour lequel des indices suggèrent une forte structuration spatiale entre 3 subdivisions (UK, EastFR, WestFR - Du Pontavice et al., 2018; Lecomte et al., 2019; Randon et al., 2018 ; Rochette et al., 2012).

## Objectif

Cette étude cherche à évaluer la stratégie de gestion actuelle sur le court terme (10 ans) pour différentes hypothèses de connectivité reflétant l'incertitude sur la structure du stock.

Pour compléter cette étude, des projections sur le long terme ont permis de tracer des courbes de captures à l'équilibre pour chaque modèle. Ces courbes apportent des éléments complémentaires pour évaluer la stratégie de gestion actuelle.

Ces projections cherchent également à évaluer l'effet de la structure de stock sur la dynamique de la pêcherie. Dans le cas des projections à court terme, des scénarios alternatifs se focalisant sur quelques paramètres incertains visent à identifier les principales sources d'incertitudes liées aux performances de gestion.

## Méthode

Cette étude s'appuie sur le modèle spatialement explicite ISIS-Fish combinant un modèle de dynamique de populations, un modèle d'exploitation et un modèle de gestion (Mahévas and Pelletier, 2004a; Pelletier et al., 2009a). En comparaison à une approche MSE classique, le modèle de dynamique de population et le modèle de gestion constituent le modèle opératoire, c'est-à-dire le modèle qui reproduit au mieux la pêcherie de sole. Le modèle de gestion quant à lui reproduit le processus de gestion (i.e. l'évaluation de stock, le calcul du TAC et son implémentation dans la pêcherie).

### Modèle opératoire

#### *Dynamique de population*

Dans le cadre de ce travail, une équation de recrutement a été intégrée au modèle de population sur la base des travaux d'Archambault et al. (2016). Elle reproduit les mécanismes de ponte et de dérive larvaires puis les processus de mortalité qui ont lieu dans les nourriceries (densité-dépendants ou non) lors des premiers mois de vie.

D'autre part, trois modèles alternatifs ont été paramétrés et calibrés pour 3 hypothèses sur la structure du stock. Ils sont similaires en tout point sauf en ce qui concerne les paramètres densité-dépendants de l'équation de recrutement et les patterns de connectivités au stade adulte :

- Le premier modèle cherche à reproduire l'hypothèse qui est faite dans l'évaluation de stock (1 population unique et homogène). Les soles adultes partagent la même aire de reproduction est se redistribue dans toute la zone VIId après la période de reproduction.
- Le deuxième modèle est un modèle intermédiaire. Les soles partagent la même aire de ponte, mais retournent dans leur zone d'origine après la reproduction (homing).
- Le troisième modèle reproduit le modèle développé par Archambault et al. (2016). La connectivité est nulle tout au long de l'année : les soles migrent vers la zone de ponte la plus proche et restent dans la même subdivision tout au long de l'année.

*Exploitation*

Les flottilles françaises ont été modélisées de façon explicite dans le modèle ISIS : l'effort de chaque flottille (*i.e.* un groupe de bateaux ayant les mêmes caractéristiques : longueur, port d'attache, engins) est réparti dans l'espace, puis il est converti en mortalités par pêche desquelles on déduit les captures au pas de temps t et l'abondance au pas de temps t+1.

Les autres flottilles (*i.e.* les flottilles étrangères et les flottilles françaises trop petites pour être modélisées explicitement) sont modélisées de façon non explicite à travers un vecteur de mortalité aux âges qui se décompose dans le temps et l'espace au prorata des captures.

Les captures totales et des mortalités par pêche totales sont calculées en additionnant les captures et les mortalités par pêche associées aux deux flottilles.

### Stratégie de gestion

La sole de Manche-Est est gérée par un TAC unique. Il est calculé sur la base d'une règle de gestion s'appuyant sur des points de référence (une mortalité par pêche cible et une biomasse de précaution). Le modèle ISIS-Fish étant structurellement différent du modèle d'évaluation de stock, la mortalité par pêche cible (Frmd) a été recalculée à l'aide du modèle ISIS-Fish.

### Projections sur le long terme

Les modèles ont été projetés jusqu'à atteindre l'équilibre (40 ans) pour une gamme d'effort, l'effort étant maintenu constant tout au long de la simulation. Ces simulations permettent de tracer les courbes de captures à l'équilibre. Elles sont exprimées en fonction de la mortalité par pêche à l'échelle de la zone VIId et en fonction du multiplicateur d'effort à l'échelle des subdivisions. On peut alors en dériver des points de référence, et notamment le Frmd pour la règle de gestion.

### Les critères de performances

Six critères de performance ont été sélectionnés pour évaluer la stratégie de gestion actuelle :

- la SSB (biomasse féconde), les captures, la mortalité par pêche : ce sont des critères de performance absolue, ils renseignent du niveau prévisible de chacune de ces grandeurs sous chacune des hypothèses.

- La SSB sur la SSB au RMD (rendement maximum durable), les captures sur le RMD et la mortalité par pêche sur le Frmd : ce sont des critères de performances relatifs qui renseignent de l'état du stock et du diagnostic d'exploitation.

### Analyse d'incertitude

L'analyse d'incertitude se base sur une analyse par scénarios : les simulations ont été lancées pour des valeurs de paramètres alternatifs reflétant l'incertitude sur ces paramètres. Elle s'est concentrée sur deux variables : la productivité des nourriceries (*i.e.* le recrutement) et la distribution des soles dans les zones ISIS-Fish. Pour le recrutement, compte tenu du nombre de paramètres incertains, nous avons limité l'analyse aux paramètres densité-dépendants, les paramètres les plus sensibles de l'équation de recrutement.

Les scénarios alternatifs ont été sélectionnées de façon à ce qu'ils encadrent les paramètres dans leur gamme d'incertitude. Lorsque la variable est plus complexe (i.e. la distribution des soles), les scénarios ont été sélectionnés pour qu'ils constituent des scénarios crédibles mais bien distincts du cas de base.

## Résultats

Les projections sur le court terme n'ont pas été concluantes pour des raisons de constructions de modèle.

Malgré tout, que ce soit sur le long-terme ou sur le court-terme, la structure de stock a un effet sur la dynamique d'exploitation de la sole. De façon générale, les captures sont revues à la baisse lorsque la ségrégation est plus prononcée. Le diagnostic d'exploitation est plus pessimiste lorsque la connectivité est partielle alors que dans les deux autres cas les courbes à l'équilibre laissent penser que le stock serait pleinement exploité. D'autre part, il est probable que la subdivision UK aurait été surexploitée dans le cas où la ségrégation est totale ou partielle.

Pour ce qui est de l'analyse des scénarios alternatifs, à l'échelle de la zone VIId, la productivité des nourriceries et la structure de stock représentent les principales sources d'incertitudes. À l'échelle des subdivisions, la distribution spatiale des soles devient une autre source d'incertitude importante.

## Discussion

Si ce travail ne permet que de donner quelques éléments pour évaluer la stratégie de gestion actuelle, il met en évidence l'effet de la structure de stock sur l'exploitation de la sole de Manche-Est. Cette étude permet également d'identifier les principales sources d'incertitude de la performance de la stratégie de gestion à l'échelle de la Manche Est comme à l'échelle locale. Enfin, elle ouvre des perspectives en vue de l'évaluation de stratégies de gestion alternatives. En effet, les projections sur le long-terme fournissent des points de référence pour chaque subdivision qui pourraient être utilisés pour évaluer des stratégies de gestion spatialisées ou pour construire des HCR spatialisés. ISIS-Fish apparaît comme un outil de choix pour évaluer ces stratégies de gestion alternatives.

D'autre part, quelques modifications et ajouts devraient être apportés aux modèles afin de compléter les hypothèses sur la structure spatiale de la sole et de corriger la modélisation des flottilles « autres » et du recrutement.

Enfin, compte tenu de la sensibilité des résultats à la structure spatiale ainsi qu'à la distribution dans le temps et l'espace de la sole, les prochaines études devraient s'appuyer sur une connaissance plus précise de la dynamique spatio-temporelle de la sole, en particulier si l'objectif est d'évaluer la performance de stratégies de gestion (qu'elles soient spatialisées ou non) à l'échelle locale.

# Abstract

Management Strategy Evaluation (MSE) provides a rigorous approach for evaluating management strategies in context of uncertainty on stock structure. Such methodology was applied to the common sole of the English Eastern Channel (ICES division: area VIId), a stock where evidences suggest spatial structuration of the population between 3 sub-areas but where uncertainties remain. Three ISIS-Fish models have been parameterized and calibrated to reflect uncertainty on stock structure (1 model with high connectivity among sub-areas at the adult stage, 1 with null connectivity and 1 intermediate case). This study aimed to evaluate the current management strategy under the alternative hypothesis on connectivity. Long-term projections were run for plotting equilibrium curves and short-term simulations were run for evaluating the current management strategy. Both emphasize the effect of spatial structure on exploitation dynamics. However short-term projections weren't conclusive, current management entails local over-exploitation of the UK sub-area in case of intermediate and null connectivity and global overexploitation in case of intermediate connectivity. Uncertainty scenarios point out that recruitment and spatial structure are main sources of uncertainty and that sole distribution become another source of uncertainty at the local scale. Few modifications of ISIS-Fish models and a more accurate knowledge of sole spatio-temporal dynamics may allow a finer modelling for further evaluations of the current management strategy and alternative spatial strategies.

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# List of acronyms

BdV: Bay of Veys

Blim : limit stock pawning biomass

EastFR : Northeastern sub-area within EEC

EEC : English Eastern Channel

ICES : International Council for the Exploration of the Sea

Flim : limit fishing mortality

Fmsy : fishing mortality at maximum sustainable yield

HCR : Harvest Control Rules

MSY : Maximum Sustainable Yield

TAC : Total Allowable Catches

SSB : Stock Spawning Biomass

UK : UK sub-area within EEC

WestFR : Southwestern sub-area within EEC

# 1. Introduction

## 1.1. Stock spatial structure and management issues

A good understanding of population spatial structure and connectivity is critical for assessing and managing marine resources. In stock management, it is traditionally assumed that stocks are discrete units with homogenous characteristics (same mortality, growth, etc.) and that adjacent stocks are isolated from each other ("unit stock assumption" - Secor, 2014). However, such cases are exceptions rather than the rule (Kerr et al., 2016) leading to mismatches between stock limits and management boundaries.

These discrepancies can introduce significant biases in assessment model outputs (Cadrin et al., 2019; Guan et al., 2013; Punt, 2019) and in resulting target values (Goethel and Berger, 2017). Such bias is even more pronounced when exploitation patterns and population segment productivity are contrasted (Cope and Punt, 2011). It can lead to over-exploitation of less productive segments while under-exploitation of more productive ones and to a decrease in stock resilience, stability and productivity (Goethel et al., 2016).

However, in many cases stock spatial structure remains unknown or highly uncertain preventing the spatial management of marine populations (Goethel and Berger, 2017; Kerr et al., 2016). In other cases, although there are evidences of complex spatial structure, the lack of understanding of these phenomena and of their consequences, as well as their implications for fishing industry and the inflexible management process freeze any evolution of the management system and can impede fisheries in a non-sustainable situation.

In this context, Management Strategy Evaluation (MSE) provides a rigorous approach for evaluating consequences of mismatches between management unit boundaries and population spatial structure (Kerr et al., 2016). MSE is a simulation-based methodology which aims to assess the performance of management strategies regarding a set of performance criteria and thus to identify the trade-offs among the management objectives for each strategy (Punt, 2015; Punt et al., 2001; Smith, 1994). Spatially explicit MSEs allow evaluating strategies in context of uncertainty on stock spatial structure by assessing strategy performance for alternative stock structure configurations (Kerr et al., 2016). Such methodology was applied to the English Eastern Channel (EEC) common sole, a stock where evidences suggest spatial structuration of the population within the management unit boundaries.

## 1.2. Ecology of the English Eastern Channel Common Sole

Common sole (*Solea solea,* Linnaeus 1758) is a benthic nursery-dependent flatfish distributed over the eastern Atlantic Coast from Senegal to southern Norway and along the Mediterranean rim (Carpentier et al., 2009). Its lifecycle includes 3 successive stages: a pelagic stage (egg and larval life), a benthic stage in coastal and estuarine nurseries (juvenile) and an adult stage in deeper water (Le Pape, 2005).

In the EEC, reproduction occurs between February and June reaching a peak in April and May (ICES, 1992). Spawning areas are located in the north of the EEC along the Bay of Somme and to a lesser extent along the Normandy Coast and the English coast (ICES, 1992; Rochette et al., 2012). After spawning, eggs and larvae are transported for 7 weeks to nursery grounds (Figure 1) through hydrodynamic circulation and active tidal migration in the last development stages (Le Pape, 2005). After metamorphosis, juveniles stay in the same nursery grounds for two years before migrating and mixing with the adult population (Koutsikopoulos, 1991 in Le Pape, 2005). Adults then participate each year to reproduction until being fished or die from natural death.

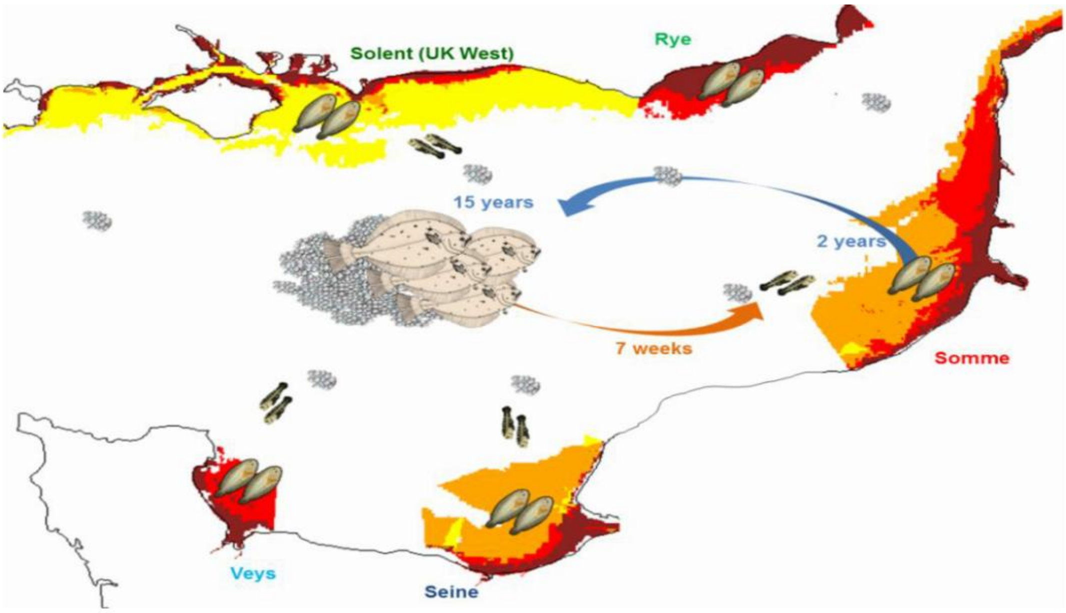



**Figure 1:** Life-cycle of the EEC common sole (Veron, 2016).

### 1.3. Exploitation and management

The EEC common sole is a high value harvested fish exploited by French (~ 50 % of the landings), British (~ 30 %) and Belgian (~ 20 %) fleets (Figure 2 - ICES, 2018, 2017). In 2016, it was the 4th most important landed species (Ifremer, 2018) in value. Besides, after restrictions on cod and skates (Ifremer, 2017), French fleets that target common sole have become dependent on this resource.

Common sole is currently assessed and managed as one single stock through Total Allowable Catches (TAC) and technical measures (minimum landing size: 24 cm, minimum mesh size for beam trawling and otter trawlers: 80 mm, minimum mesh size for fixed nets: 100 mm with an exemption to permit 90 mm - ICES, 2018). The stock has been over-exploited since the 80’s and fishing mortality has remained above fishing mortality at maximum sustainable yield (Fmsy) oscillating around the fishing mortality limit (Flim - Figure 3). Recently, in response to the transition from the precautionary approach to the MSY approach, fishing mortality has decreased to Fmsy. However, stock spawning biomass (SSB) remains low and stock status is concerning as SSB is close to Blim (Figure 3).

Furthermore, low recruitment (*i.e.* amount of fish added to the exploitable stock) since 2012 combined with the management strategy transition has led to a strong decrease in TAC which is hardly sustainable for the fleets relying on common sole (Ifremer, 2017).

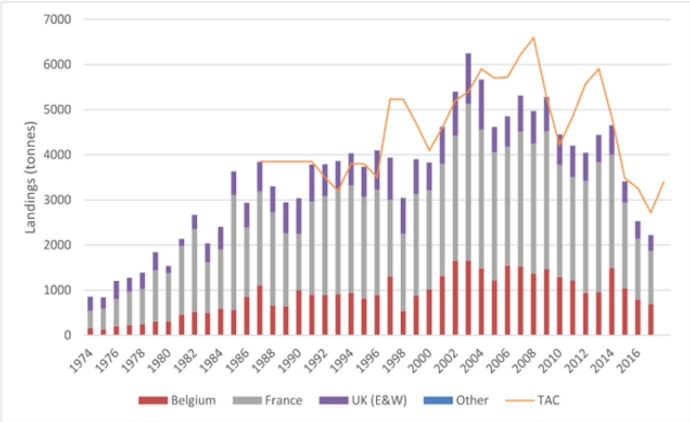



**Figure 2:** Common sole landings (tons) by country in area VII.d from 1974 to 2017 (ICES, 2018).

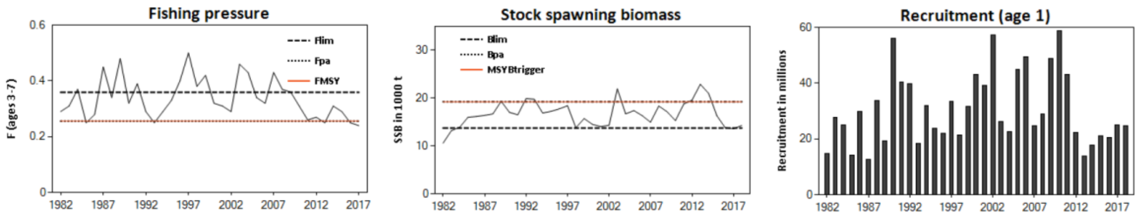



**Figure 3:** Summary of the stock assessment of Common Sole in division VII.d. (ICES, 2018).

## 1.4. Connectivity of the EEC common sole

Connectivity and spatial structure of the EEC common sole have been investigated for the 3 main life stages.

For egg and larval stages, a larval drift model showed high larval retention within 3 distinct areas suggesting low connectivity between them (Rochette et al., 2012 - Figure 4).

At juvenile stage, connectivity among nurseries is null as juveniles stay in the same nursery for 2 years (Koutsikopoulos, 1991 in Le Pape, 2005).

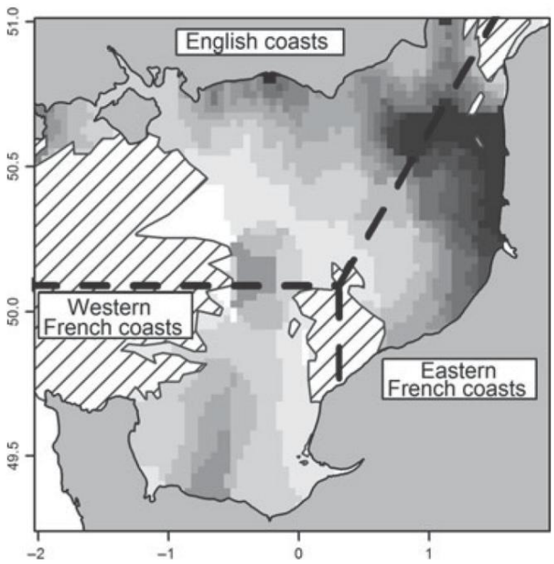



**Figure 4:** 1-day egg density average distribution over the spawning period. kriged map based on the data of the 1991 egg survey. Hatched areas: pebbles. Dashed lines: limits of the three spawning sub-areas deduced from the larval drift model (Rochette et al., 2012).

High uncertainty remained when considering adult stage. However, some recent research outlined evidences of low connectivity between the 3 sub-areas (Du Pontavice et al., 2018; Lecomte et al., 2019; Randon et al., 2018).

Contrasts in life history traits suggested spatial structuration of the EEC common sole population. Du Pontavice et al. (2018) and Randon et al. (2018) highlighted spatial differences in growth parameters between the 3 sub-areas identified by Rochette et al. (2012). Besides, Randon et al. (2018) showed spatial asynchrony of density-at-age-time series between sub-areas suggesting isolation of the South Western sub-area from the others.

When considering tag-recapture experiments, Burt and Millner (2008) and more recently Lecomte et al. (2019) emphasised the low mobility of individuals and the relatively low migration rates between the subunits within area VIId, the North Sea and the Western Channel.

Thus the hypothesis of metapopulation structure for EEC common sole appears more and more reliable (Archambault et al., 2016; Du Pontavice et al., 2018; Randon et al., 2018; Rochette et al., 2012) and questions the entire management process including the stock assessment and the stock boundaries. Such mismatch could lead to overexploitation of stock segments particularly in areas where fishing capacity is important *i.e* the North East of EEC (Archambault et al., 2016; Du Pontavice et al., 2018; Du Pontavice et al., 2016).

However, uncertainties on sole spatial structure remain and modifying management process and stock boundaries entail a long procedure before implementation (Kerr et al., 2016). Thus, one step before revising the management strategy consists in evaluating current management strategy while taking into account spatial structure uncertainty. In our case, we applied MSE approach with the spatially explicit model ISIS-Fish to alternative hypothesis reflecting uncertainty on spatial structure: either high connectivity, partial connectivity, null connectivity. These simulations were run on the short-term (10 years) and integrated uncertainty on other spatial parameters (nursery productivity, sole distribution) through alternative scenarios. Such scenarios allow identifying the main sources of uncertainty and give another insight on the effect of spatial structure on strategy performance. To support and complete short term-projections, we computed equilibrium curves by projecting the model on the long term. Such supplement helps interpret short-term results and brings complementary elements to evaluate the current management strategy and to assess the effect of spatial structure on fishery dynamics.

# 2. Materials and Methods

## 2.1. MSE and the ISIS-Fish model

Usually MSE combines:

- an operating model which represents the best knowledge we have on population and exploitation dynamics.
- a management model simulating the management procedures to be tested.
- Both models communicate through the observation modules ('monitoring data' in figure 5) that mimics sampling programs or surveys and a management regulation that mimics the way management would be implemented.

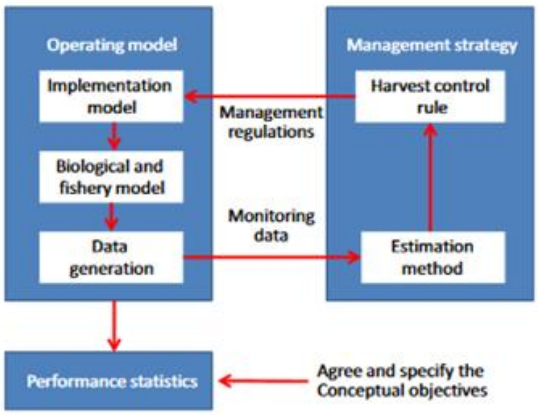



**Figure 5:** Conceptual overview of the management strategy evaluation modelling process (Punt et al., 2016).

The ISIS-Fish framework (version 4.4.2.4) is a mechanistic model, spatially and seasonally explicit with a monthly time step (Mahévas and Pelletier, 2004b; Pelletier et al., 2009b). It was designed for evaluating management measures on fisheries and it combines a population dynamics module, an exploitation module and a management module. In the context of MSE approach and compared with figure 5, the population dynamics and the exploitation modules correspond to the operating model while the management module was used to mimic the stock assessment process and corresponds to “management strategy”.

Recently, Lehuta et al. (2015) have developed an ISIS-Fish framework for the EEC mixed fishery. It was extended to consider alternative population structures for common sole population and a recruitment equation linking abundance of year y to recruits of year y+1.

## 2.2. Operating model

### 2.2.1. Biological module

The population dynamics is stage-structured (ages 1 to 11) and reproduce major biological processes in order to model the species life cycle in time and space (migration, growth, reproduction and recruitment).

#### *2.2.1.1. Population abundance and biomass*

ISIS-Fish biological equations are based on abundance by year, month, area and age group. They are spatial versions of the classical survival equation. At time step $\mathrm{t}$, in zone $\mathrm{zpop}$, abundance-at-age a ($\mathrm{N}_{\mathrm{a,zpop,t+1}}$) is a function of abundance-at-age of the previous time-step ($\mathrm{N}_{\mathrm{a,zpop,t}}$), natural mortality at age ($\mathrm{M}_{\mathrm{a}}$ = 0.1), fishing mortality-at-age ($\mathrm{Fisis}_{\mathrm{a,zpop,t}}$ – fishing mortality proper to ISIS-Fish, Cf. 2.2.2.) in $\mathrm{zpop}$, migrations ($\mathrm{D}_{\mathrm{a,zpop,t}}$) and, in January, change of stage ($\mathrm{CC}_{\mathrm{a,t}}$) and recruitment ($\mathrm{R}_{\mathrm{zpop,t}}$) (Formula 1). Change of stage, migrations, reproduction and recruitment occur instantaneously at the beginning of each time step and mortality processes occurs throughout the time step (Figure 6).

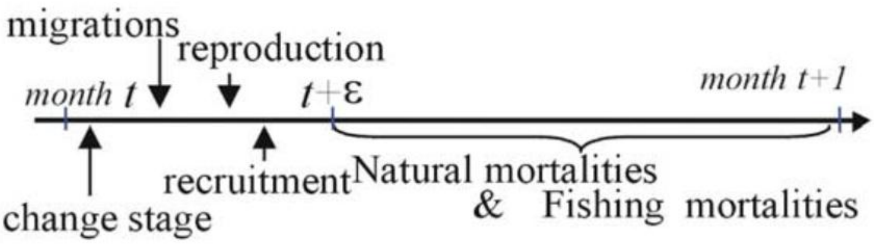



**Figure 6:** Chronology of processes underlying the simulation model (Mahévas and Pelletier, 2004b)

**(1)**

$$\mathrm{N}_{\mathrm{a,zpop,t+1}} = \underbrace{(\mathrm{R}_{\mathrm{zpop,t}} + \mathrm{D}_{\mathrm{a,zpop,t+1}} \times \mathrm{CC}_{\mathrm{a,t}} \times \mathrm{N}_{\mathrm{a,zpop,t}} + \mathrm{Nimig}_{\mathrm{a,zpop,t}})}_{\text{Abundance-at-age at time step t in zone zpop after recruitment, migrations and change of stage}} \times \underbrace{\exp^{-(\mathrm{Fisis}_{\mathrm{a,zpop,t}}+\mathrm{M}_{\mathrm{a}})}}_{\text{Survival rate}}$$

Total biomass ($\mathrm{B}$) and SSB are computed by combining abundance ($\mathrm{N_a}$), weight-at-age ($\mathrm{W_a}$) and maturity ogive ($\mathrm{Mat_a}$) through the formula (2) and (3):

**(2)** $\mathrm{B} = \sum_{cl=1}^{11} \mathrm{W_a} \times \mathrm{N_a}$ **(3)** $\mathrm{SSB} = \sum_{cl=1}^{11} \mathrm{W_a} \times \mathrm{N_a} \times \mathrm{Mat_a}$

Abundance is distributed in population zones ($\mathrm{zpop}$) through migration rates. Population zones were built on the basis of the Atlantis model developed by Girardin et al. (2018 - Figure 7). ISIS-Fish model distinguishes two kinds of functional zones: nursery zones and reproduction zones (see Appendix I).

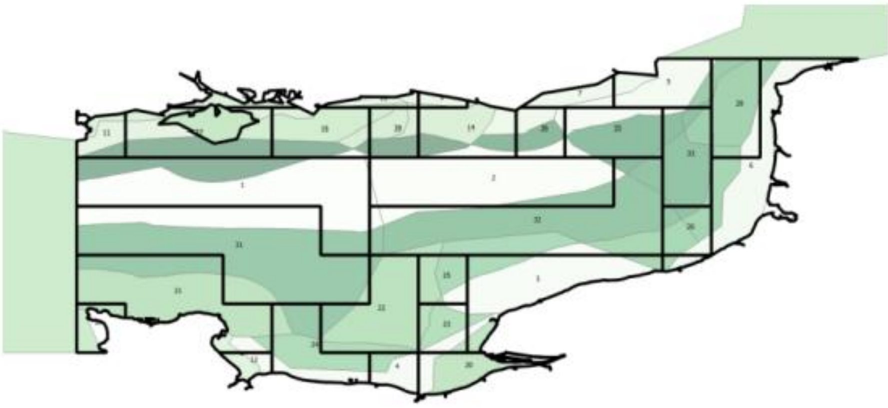


**Figure 7 :** Main habitats in the Eastern Channel as identified by Girardin et al. (2018) for the EEC Atlantis model and corresponding ISIS polygons (black boxes) (Lehuta et al., 2015).

#### *2.2.1.2. Recruitment equation: from spawning to adult stage*

The recruitment equation was implemented using the relationship and the parameters' estimates from the life cycle model developed by Archambault et al. (2016). This model links abundance in January of year y to recruitment of year y + 1 through deterministic and stochastic processes. Only the deterministic processes were considered in the ISIS-Fish model and are described beneath (Figure 8).

In year y and in each sub-area r, the amount of eggs spawned ($\omega_{y,r}$ - Formula 4) is computed as the combination of abundance-at-age a ($\mathrm{N_{a,y,r}}$) of the mature individuals ($a \geq 3$), the proportion of female in the population ($\mathrm{pf_a}$ - formula 5) and the fecundity of each individual ($\mathrm{fec_{a,y}}$ – Formula 6) depending on his weight ($\mathrm{w_{a,y}}$).

**(4)** $$\omega_{y,r} = \sum_{a \geq 3} \mathrm{N_{a,y,r}} \times \mathrm{pf_a} \times \mathrm{fec_{a,y}}$$

**(5)** $$\mathrm{pf_a} = 1/(1 + e^{-2.79E-3 \times a^2 + 1.58E-1 \times a + 1.58E-1})$$

**(6)** $$\mathrm{fec_{a,y}} = e^{5.6 + 1.17 \times \log(\mathrm{w_{a,y}})}$$

Eggs and larvae are then attributed to each nursery through a larval drift matrix ($\mathrm{D_{y,r,i}}$) which allocates individuals to nurseries according to probabilities (i.e. probability of an egg spawned in sub-area $\mathrm{r}$ to reach nursery sector i and to settle – Formula 7). Those probabilities were derived from the larval drift model developed by Rochette et al. (2012).

**(7)** $$L_{y,i} = \sum_{r=1}^{3} \omega_{y,r} \times D_{y,r,i}$$

Settling larvae ($L_{y,i}$ - post-larvae) then experience post-settlement density-dependent mortality (Iles and Beverton, 2000). Such mortality is modelled through a nursery specific Beverton and Holt relationship (formula 8) with $i$ the nursery, $\alpha_i$ the maximum survival rate (the survival rate without density dependence), $K_i$ the carrying capacity per unit of surface (the maximum number of age-0 juveniles that can survive per unit of surface) and $S_i$, the nursery surface (Table 1). Juveniles then experience a constant natural mortality (formula 9) from September to December and reach age-1 in January ($N_{1,y+1,i}$).

**(8)** $$N_{0,y,i} = \frac{\alpha_i \times L_{y,i}}{1 + \frac{\alpha_i}{K_i \times S_i} \times L_{y,i}}$$

**(9)** $$N_{1,y+1,i} = N_{0,y,i} \times e^{-1/3 \times M_0} \times cor$$

Age-1 juveniles stay one year in nurseries and experience the same natural mortality as adults (0.1). At age 2, individuals leave nurseries and migrate to reproduction zone mixing with the adult population.

Natural mortality at age 0 differs in the Life-cycle model (2.6) and in the ISIS-Fish model (0.1 – based on stock assessment). Consequently, life-cycle recruitment is approximately 12 ($e^{2.6-0.1}$) times higher than stock assessment recruitment and, on average, 17.56 times higher than recruitment used in ISIS-Fish calibration (i.e. recruitment from the 2015 stock assessment between 2008 and 2014 – ICES, 2015). Thus, we rescaled recruitment obtained through the life-cycle equations applying a correcting factor ($cor$ = 1/17.56) to fit with the recruitment used in calibration and stay in the range of calibration of recruitment when projecting the model (Appendix II).

**Table 1:** Parameters value for survival rate, carrying capacity and surface of nurseries from Archambault et al. (2016)

| | Survival rate | | Carrying capacity (1000 fish/km²) | | Surface (km²) |
|---|---|---|---|---|---|
| | 1 single population | 3 populations | 1 single population | 3 populations | |
| UK-West | 0.41 | 0.22 | 120 | 82 | 1650 |
| Rye | 0.5 | 0.48 | 370 | 220 | 504 |
| Somme | 0.24 | 0.34 | 110 | 160 | 1680 |
| Seine | 0.11 | 0.14 | 190 | 110 | 967 |
| BdV | 0.25 | 0.22 | 200 | 130 | 320 |

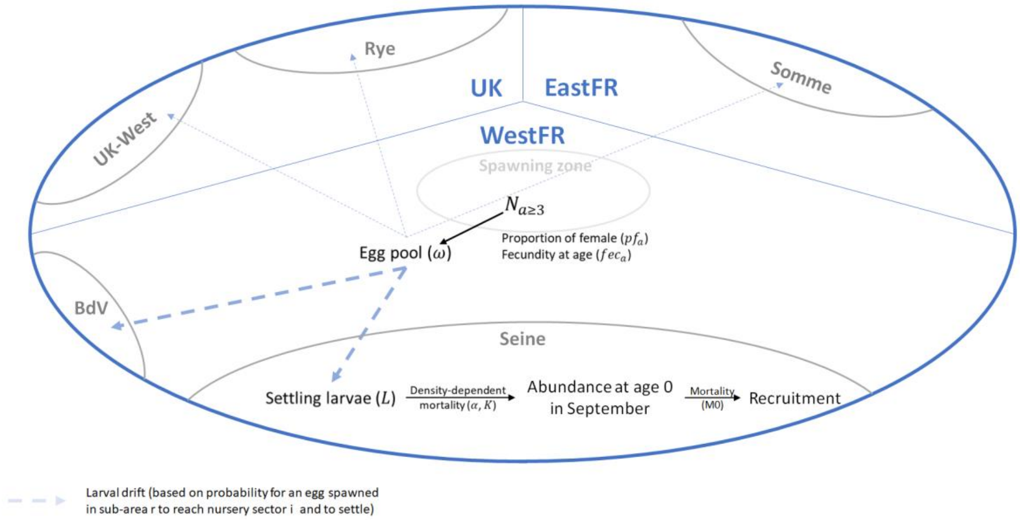



**Figure 8:** Diagram of the recruitment process based on Archambault et al. (2016)

#### *2.2.1.3. Migrations, connectivity and spatial structure: alternative models*

At the adult stage, each year is divided in two seasons:

- the reproduction season between February and June: soles concentrate in breeding areas.
- The foraging season between July and January: soles scatter and redistribute among ISIS polygons based on UK-BTS data (Appendix III).

3 alternative models have been parameterised and calibrated to reflect uncertainty on spatial structure of the EEC common sole at the adult stage. Each one of the three models seeks to reproduce the EEC common sole life cycle in space and time. They are similar in all respects except concerning the hypothesis on adult migrations and length-at-age relationships (Figure 9).

(1) The first model (H1 – "1_population") reproduces the stock assessment hypothesis. EEC common sole is structured in one single population and there is no segregation between sub-units at the adult stage. Soles share the same spawning area and redistribute in the entire area VIId after reproduction.

(2) The second model (H2 – "mixing_subpopulations") simulates a single stock but add segregation between the three subpopulations. As for the first model, soles share the same spawning area but each individual come back to its native sub-area after reproduction (homing). Connectivity only concerns reproduction period. In this case, there is 1 single population (soles share the same reproduction zones) divided into 3 mixing sub-populations (Kerr and Goethel, 2014).

(3) The third model (H3 – "3_populations") fits with the alternative stock structure hypothesis retained in Archambault et al. (2016) and divides the EEC common sole in three distinct populations. In February, sole groups in the nearest spawning areas and in July after reproduction, soles remain in the same sub-area. In this case, connectivity is null throughout the year.

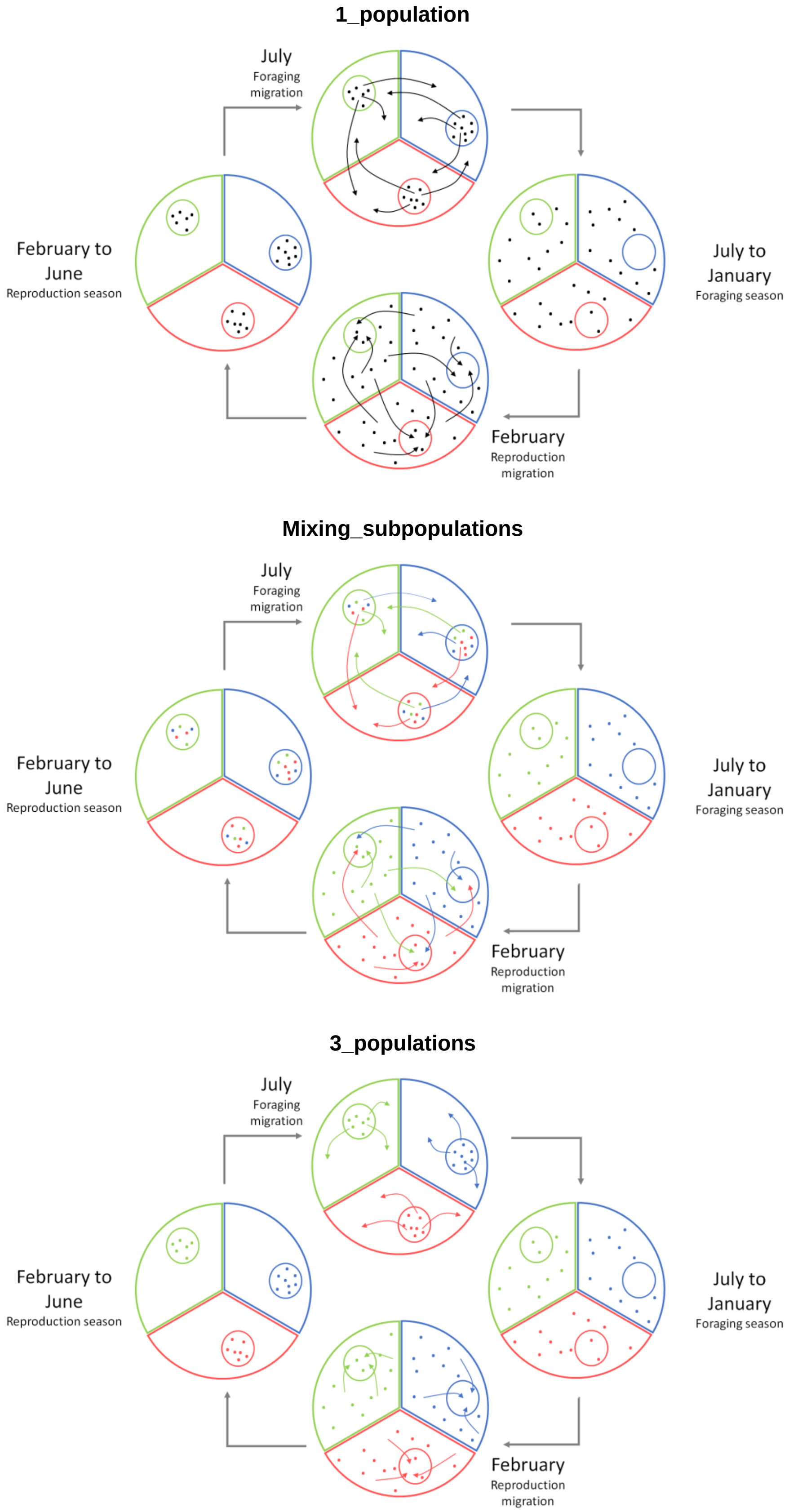



**Figure 9:** Diagram of alternative stock structure hypothesis.
Blue: EastFR. Green: UK. Red: WestFR. Circles: spawning zones. Points: soles. Arrows: migration patterns of individuals. When points and arrows are black, soles are not related to any sub-area. When they are coloured, soles can be related to one sub-area (i.e. segregation) and the color of the figure corresponds to the area they are related to.

#### 2.2.1.4. *Model calibration and adjustments*

Each model was calibrated on catchability-at-age to reproduce French catches at the scale of area VIId between 2008 and 2014. Recruitment and fishing mortality from the 2015 stock assessment were used to force recruitment and fishing mortality between 2008 and 2014 of other fleets (Cf. 2.2.2.1.).

As calibrated catchability-at-age (Cf. 2.2.2.2.) underestimated fishing mortality (Appendix IV), they were rescaled by a factor 1.5 to increase fishing mortality while reproducing catch and abundance (Appendix V).

### 2.2.2. Harvest module

The exploitation module is based on fishing effort and reproduces harvest processes at the fleet scale (i.e. set of vessels sharing the same characteristics), each fleet practising several métiers (i.e. combination of target species, a zone and a gear) throughout the year (Pelletier et al., 2009b). The exploitation zones correspond to the ICES delimitations.

#### 2.2.2.1. *Fleet, métier and strategy definition*

In the first model EEC ISIS-Fish model, French vessels were grouped into 17 fleets based on the gear they used (either netters, bottom trawlers, mixed trawlers or dredgers), their mean length and their home region (Lehuta et al., 2015 - see Appendix VI). Those fleets are explicitly modelled, and harvest processes are described in the following section. They are referred as strategy thereafter.

Other vessels (British and Belgian fleets and segments of fleets too small to be explicitly modelled) were grouped into another fleet called “Other fleets”. They are modelled through a seasonal and spatial mortality vector applied at each time step (Figure 10 – Appendix VIII).

#### 2.2.2.2. *From fishing effort to total fishing mortality*

Fishing effort ($\mathrm{StdEffort}_{\mathrm{strat,met,t}}$) of a métier ($\mathrm{met}$) belonging to one strategy ($\mathrm{strat}$) at time t in the entire area VIId is expressed as a function of fishing time ($\mathrm{FishingTime}_{\mathrm{strat,met,t}}$), number of vessels in strategy $\mathrm{strat}$ practising the métier $\mathrm{met}$ ($\mathrm{NbVesselsStrMet}_{\mathrm{strat,met,t}}$) and a standardised unit of effort per hour ($\mathrm{StdEffortPerHour}_{\mathrm{strat,met,t}}$) (Formula 10). Standardised unit of effort per hour depends on the number of fishing operations per day, the number of gears used in one fishing operation and on a standardisation factor (Formula 11 – see Appendix VII).

**(10)** $$\mathrm{StdEffort}_{\mathrm{strat,met,t}} = \mathrm{NbVesselsStrMet}_{\mathrm{strat,met,t}} \times \mathrm{FishingTime}_{\mathrm{strat,met,t}} \times \mathrm{StdEffortPerHour}_{\mathrm{strat,met,t}}$$

**(11)** $$\mathrm{StdEffortPerHour}_{\mathrm{strat,met,t}} = \mathrm{SF}_{\mathrm{gear}} \times \mathrm{NbFishOpePerDay}_{\mathrm{strat,met,t}} \times \mathrm{NbGearsPerOpe}_{\mathrm{strat,met,t}}/24$$

Effort per métier is then distributed uniformly over the exploitation grid cells where the métier is practised and reallocated to the corresponding population zones.

Fishing mortality of the population $pop$, an age class $\mathrm{a}$, at time step $\mathrm{t}$ for the métier $met$ belonging to the strategy $strat$ is then computed through the formula 12:

**(12)** $$\mathrm{Fisis}_{\mathrm{strat,met,pop,a,zpop,t}} = \mathrm{Sel}_{\mathrm{gear,pop,a}} \times \mathrm{q}_{\mathrm{pop,a}} \times \mathrm{TargetF}_{\mathrm{met,pop,a,month}} \times \mathrm{StdEffortZpop}_{\mathrm{strat,met,zpop,t}}$$

where :

- $\mathrm{StdEffortZpop}_{\mathrm{strat,met,zpop,t}}$ is the standardized effort in population zone $\mathrm{zpop}$.
- $\mathrm{Sel}_{\mathrm{gear,pop,a}}$ is the selectivity of the gear (gear-dependent factor).
- $\mathrm{TargetF}_{\mathrm{met,pop,a,month}}$ is the target factor. It quantifies the strength with which the population is targeted by a métier.
- $\mathrm{q}_{\mathrm{pop,a}}$ is the catchability-at-age: the probability that a fish is caught by a standardized unit of effort (gear-independent factor). This is the estimated parameter in calibration.
- $\mathrm{Fisis}_{\mathrm{strat,met,pop,a,zpop,t}}$ is the ISIS fishing mortality. Here, fishing mortality is a result of the combination of gear dependent and independent factor at the scale of each population zone. It is not strictly speaking the same as stock assessment fishing mortality.

ISIS fishing mortality is then summed over strategy and métier in each zone to compute abundance for the next time step in zone zpop and corresponding catch.

Fishing mortality of French fleets are computed by solving numerically Baranov equation with French catches over the current year, abundance in January and fishing mortality related to other fleets (Formula 13).

Catch of other fleets can be computed based on the related fishing mortality vector decomposed in time and space following the proportion of catch among quarters and subareas (Appendix VIII – Formula 14).

**(13)** $$\mathrm{Cfr}_{\mathrm{a,y}} = \frac{\mathrm{Ffr}_{\mathrm{a,y}}}{\mathrm{Ffr}_{\mathrm{a,y}} + \mathrm{M_a} + \mathrm{Foth_a}} \times (1 - \mathrm{e}^{-(\mathrm{F_{a,y}} + \mathrm{Foth_a} + \mathrm{M_a})}) \times \mathrm{B}_{\mathrm{a,y}}$$

**(14)** $$\mathrm{Coth}_{\mathrm{a,m,r}} = \frac{\mathrm{Foth_a} * \mathrm{prop}_{\mathrm{m,r}} * \frac{4}{12}}{\mathrm{Ffr}_{\mathrm{a,m}} + \frac{\mathrm{M_a}}{12} + \mathrm{Foth_a} * \mathrm{prop}_{\mathrm{m,r}} * \frac{4}{12}} \times \left(1 - \mathrm{e}^{-\left(\mathrm{Ffr}_{\mathrm{a,m}} + \frac{\mathrm{M_a}}{12} + \mathrm{Foth_a} * \mathrm{prop}_{\mathrm{m,r}} * \frac{4}{12}\right)}\right) \times \mathrm{B}_{\mathrm{a,m}}$$

With:

$\mathrm{a}$ : Age group.
$\mathrm{y}$ : Year.
$\mathrm{m}$ : Month.
$\mathrm{Cfr}_{\mathrm{a,y}}$ : French catch-at-age.
$\mathrm{Ffr}_{\mathrm{a,y}}$ : Fishing mortality at age of French fleets.
$\mathrm{M_a}$ : Mortality at age.
$\mathrm{Foth_a}$ : fishing mortality at age of other fleets.
$\mathrm{prop}_{\mathrm{m,r}}$ : Catch proportion of other fleets in sub-area r for the quarter of the month $m$.
$\mathrm{B}_{\mathrm{a,y}}$ : Biomass at the beginning of the time period (here, in January).
$\frac{4}{12}$ , $\frac{1}{12}$ : factor for converting mortality in $\mathrm{semester}^{-1}$ or in year$^{-1}$ to $\mathrm{month}^{-1}$.

Yearly fishing mortality of French fleets and of other fleets are then summed for computing total fishing mortality ($F_a$). $\bar{F}$ is the average total fishing mortality between age 3 and age 7. Total catches ($Ctot$) are computed by summing French catch and catch of other fleets on the full year (Figure 10).

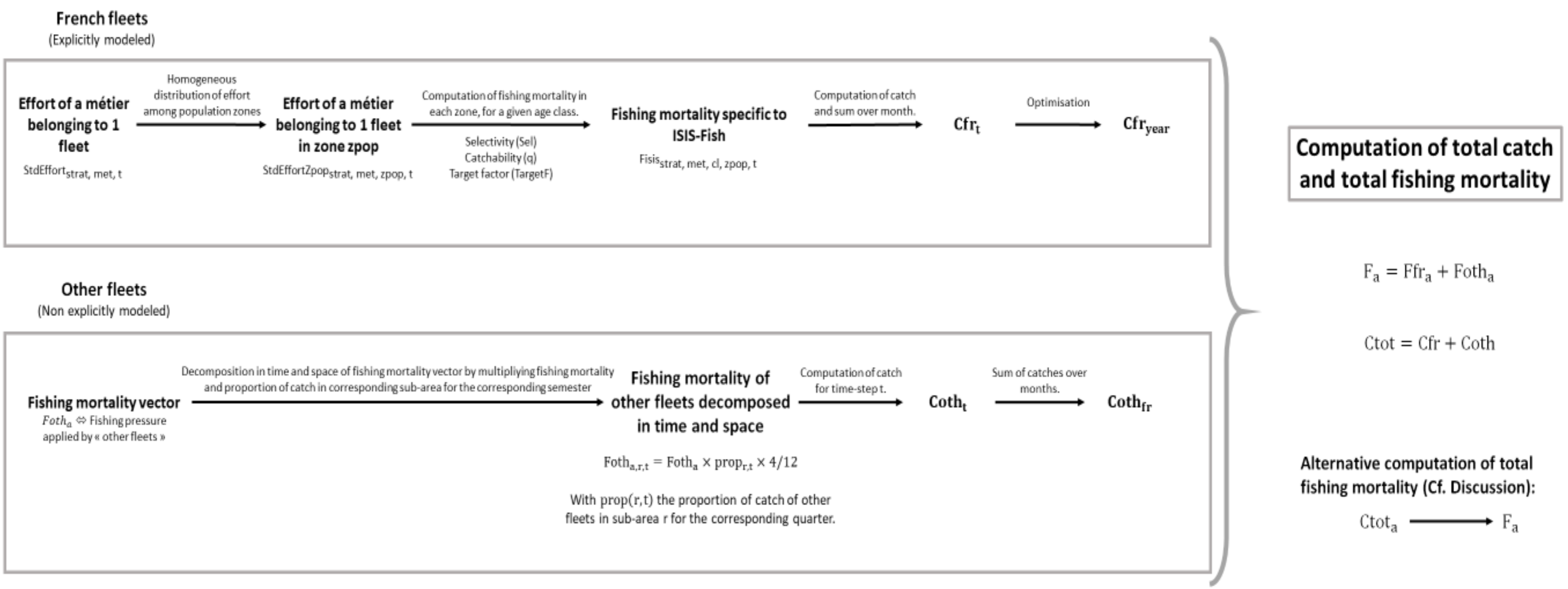



**Figure 10:** Exploitation model and computation of catch and fishing mortality.

## 2.3. Management Strategy

### 2.3.1. Estimation method

The management model here consists in the computation of annual TACs based on current stock status and reference points. In our case, the stock status is directly derived from ISIS-Fish outputs. Thus, compared to figure 5, “monitoring data” and “estimation methods” are very simple as catches, abundance, biomass, SSB, etc. were considered known without error.

### 2.3.2. Harvest Control Rules and reference points

Common sole in area VIId is currently managed through a typical ICES Harvest Control Rule (HCR - Formula 15). This HCR assumes that fishing mortality and SSB are available each year. It can be formulated as:

**(15)**
$$\begin{cases} \mathrm{Ftarget} = \mathrm{F_{MSY}} \text{ if } \mathrm{SSB} > MSYBtrigger \\ \mathrm{Ftarget} = \mathrm{F_{MSY}} \times \dfrac{\mathrm{SSB}}{\mathrm{MSYBtrigger}} \text{ if } \mathrm{SSB} \leq \mathrm{MSYBtrigger} \end{cases}$$

Such HCR requires two reference points: 1 MSYBtrigger and 1 Fmsy. The Stock assessment provides these reference points (respectively 19 251 t and 0.256 - ICES, 2018). However, the stock assessment model is structurally different from the ISIS-Fish model and reference points of both models may differ. Thus, we derived the Fmsy proper to ISIS-Fish model from long-term catch curve (Cf. 2.4. and 3.1.) of the model “1_population”. Applying the Fmsy from “1_population” to other models (“mixing_subpopulations” and “3_populations”) is equivalent to managing a complex population as if it was one single population, a more and more credible situation (Cf. 1.4.).

MSYBtrigger comes from the stock assessment of 2015 (MSYBtrigger = 8 000 t - ICES, 2015).

### 2.3.3. TAC computation and catch limitation

Each year, TACs were computed through the formula 16:

**(16)**
$$\mathrm{TAC_y} = \sum_{a=1}^{11} \frac{\mathrm{Ftarget_{a,y}}}{\mathrm{Ftarget_{a,y}} + \mathrm{M_a}} \times (1 - e^{-(\mathrm{Ftarget_{a,y}} + \mathrm{M_a})}) \times \mathrm{N_{a,y}} \times \mathrm{W_a}$$

Where $\mathrm{Ftarget_{a,y}} = \frac{\mathrm{Ftarget_y}}{\bar{\mathrm{F}}_{\mathrm{y}}} \times \mathrm{F_{a,y}}$ with $\mathrm{Ftarget}$ the fishing mortality defined by the management plan, $\mathrm{M_a}$ is the natural mortality, $\mathrm{N_{a,y}}$ the abundance-at-age and $\mathrm{W_a}$ is the mean weight at age $\mathrm{a}$.

TAC is then distributed between French fleets (57 %) and other fleets. We assume a perfect implementation of landing obligation and thus when French fleets reach the catch limit, they stop fishing. As other fleets are not explicitly modelled, we assumed they catch the remaining TAC and we computed corresponding fishing mortalities at age for the next year through the Baranov equation assuming a constant age structure for catches.

## 2.4. Long-term projections: equilibrium curves

Equilibrium curves for SSB and catch were computed by projecting each model until equilibrium (40 years) for a range of effort multiplier (0 to 4 with a step of 0.05) and by extracting sum of catches and mean SSB of the last year's simulation. Long term catch and SSB were computed at the scale of area VIId and at the scale of subdivisions.

**At the scale of area VIId**, we will talk about "global" equilibrium curves. In this case, **long-term catch and SSB can be expressed as a function of fishing mortality** (Cf. 3.1.1.).

At the scale of subdivision, we will talk about "local" equilibrium curves. In this case, fishing mortality over year cannot be computed in "1_population" and "mixing_subpopulations" as yearly catches in 1 sub-area are constituted of soles coming from other sub-areas (as there is connectivity between sub-areas). Thereby, biomass in January in 1 sub-area cannot be related to catches over year in the same sub-area except in model "3_populations" where connectivity is null throughout the year. **Thus, at the subdivision level long-term catches and SSB are expressed as a function of effort multiplier for all three models (Cf. 3.1.2.).** Nevertheless, fishing mortality reference points were computed for model "3_populations" and appear in part 3.1.4.

For integrating uncertainty to long-term projections, we projected models considering either low or high recruitment parameters in each nursery (for more detail see part "uncertainty analysis" – Cf. 2.6.2.1.). Such outputs figure in Appendix XII but do not appear in the body of the report.

## 2.5. Performance statistics

The performance of the management scenarios were compared through absolute and relative performance criteria at the scale of area VIId and at the scale of subdivisions (Table 2).

**Table 2:** Table of performance criteria

| Absolute performance criteria | Relative performance criteria |
|---|---|
| Catch | Catch / MSY<br>Catch maximization indicator |
| SSB | SSB / SSBmsy<br>Stock status indicator. |
| F | F / Fmsy<br>Exploitation status indicator.<br>(Only at the scale of area VIId) |

Absolute performance criteria allow comparing predicted levels of catch, SSB and fishing mortality for the 3 alternative stock structure hypothesis. Relative performance criteria provide indicators of stock status or exploitation status and evaluate each strategy regarding their capability to reach the reference points.

F / Fmsy was only computed at the scale of area VIId as it is impossible to compute fishing mortality at the subdivision level when there are exchanges between subdivisions ("1_population" and "mixing_subpopulations" – Cf. 2.4.).

To take into account exchanges between sub-areas, criteria on biomass consider the average SSB over the year and not the SSB in January.

## 2.6. Uncertainty analysis

### 2.6.1. Selection of variables

Many parameters act on the population and exploitation dynamics of an ISIS-Fish model (Lehuta, 2010). In our case, some are well documented and reliable estimates exist in literature. This is the case for growth (Du Pontavice et al., 2018; Randon et al., 2018), trammel net selectivity (Madsen et al., 1999) and ISIS-Fish exploitation parameters such as standardization factors and target factors (Lehuta et al., 2015).

Other parameters like natural mortality (ICES, 2018) or selectivity of bottom otter trawl, beam trawl and set gillnets have been poorly studied (Obsmer data). They have been fixed arbitrarily in this study because only little data is available and fixing uncertainty around these parameters would be arbitrary as well.

Finally, some parameters are highly uncertain, but the literature or scientific surveys provide estimates of these parameters with related uncertainty or credible alternative scenarios. This is the case of recruitment (Archambault et al., 2016) and sole spatial distribution (UK-BTS data). We focused on these parameters as they are key variables of population dynamics while being spatial variables. It allows assessing the effect of other spatial variables compared with effect of stock structure and then identifying the main sources of uncertainty.

### 2.6.2. Selection of parameters' modalities

Uncertainty was integrated to simulation by selecting alternative scenarios for each parameters of interest. As uncertainty is explored through discrete parameters, we adopted a full simulation design and we limited the number of simulations because of simulation time constraints (one simulation can last 15 minutes to 1 hour depending on the model).

#### *2.6.2.1. Recruitment*

A sensitivity analysis conducted on recruitment equation outlined the sensitivity of recruitment to carrying capacity and survival rates of nurseries (Figure 11 - Table 3); we retained these two parameters in the uncertainty analysis.

Archambault et al. (2016) provide posterior distribution of these two parameters for each nursery. For time constraints reasons, recruitment in each sub-area takes only 2 modalities in short-term projections:

- Medium: carrying capacity and survival rates equal the mean of the posterior distributions in each nursery of the sub-area.
- Low: carrying capacity and survival rates equal the quantile 10 % of the posterior distributions in each nursery of the sub-area.

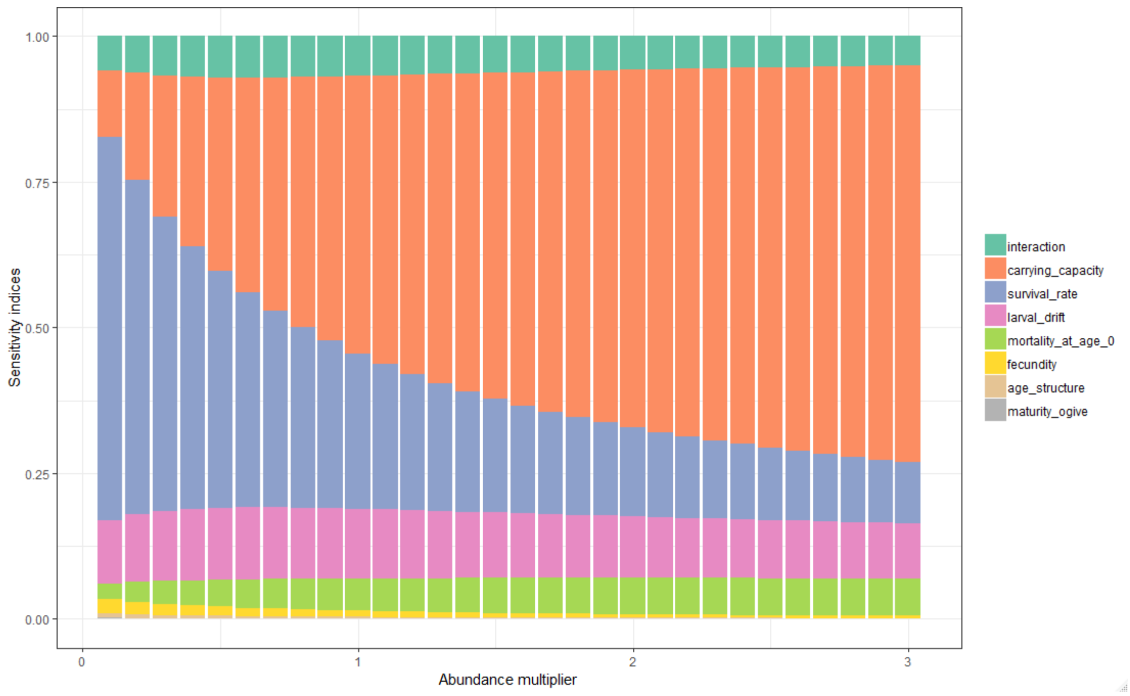



**Figure 11:** Sensitivity indices conducted on recruitment equation for a range of abundance multiplier (1 to 3 step = 0.1).

**Table 3:** modalities of recruitment equation parameters selected for the uncertainty analysis.

| Parameters | Modality | Sources |
|---|---|---|
| Carrying capacity | Base case: mean of the posterior distribution | Archambault et al., 2016 |
| | Alternative scenarios: quantile 10 and quantile 90 of the posterior distribution | |
| Survival rate | Base case: mean of the posterior distribution | Archambault et al., 2016 |
| | Alternative scenarios: quantile 10 and quantile 90 of the posterior distribution | |
| Mortality-at-age 0 | Base case : 1,5 | Archambault et al., 2016<br>Rochette et al., 2013 |
| | Alternative scenarios: brackets of +/- 20 % | |
| Fecundity | Base case: function from the report of fecundity of sole and plaice | ICES, 1992 |
| | Alternative scenarios : brackets of +/- 20 % | |
| Larval drift | Base case: mean over last 3 years | Rochette et al., 2012 |
| | Alternative scenarios: 4 alternative extreme cases from the larval drift outputs (for more details see Appendix IX) | |
| Age structure<br>(abundance-at-age and weight-at-age) | Base case: mean over the time series | ICES, 2015 |
| | Alternative scenarios: data of the year where either maximum or minimum | |
| Maturity ogive | before and after benchmark | ICES, 2015 ; ICES, 2018 |

#### 2.6.2.2. Spatial distribution

In ISIS-Fish EEC, years are divided in two seasons: the reproduction period (sole gather in reproduction zones) and the foraging season (soles distribute in ISIS polygons following UK-BTS data - 2.2.1.3.). Larval drift matrix relies on soles distribution during reproduction period. Thus, modifying soles distribution in this period would be inconsistent with the larval drift matrix. Then alternative scenarios only focus on distribution during foraging season which are based on UK-BTS data.

UK-BTS survey provides spatial abundance indices for each year since 1989. The base case for projection is the mean distribution of sole between 2008 and 2014. As alternative scenarios, we selected two years (1990 and 2001 – Figure 12) where sole distribution in ISIS polygons was clearly distinct from the base case. To select these scenarios, we made an ACP on soles distribution in ISIS polygons based on UK-BTS data (Appendix X).

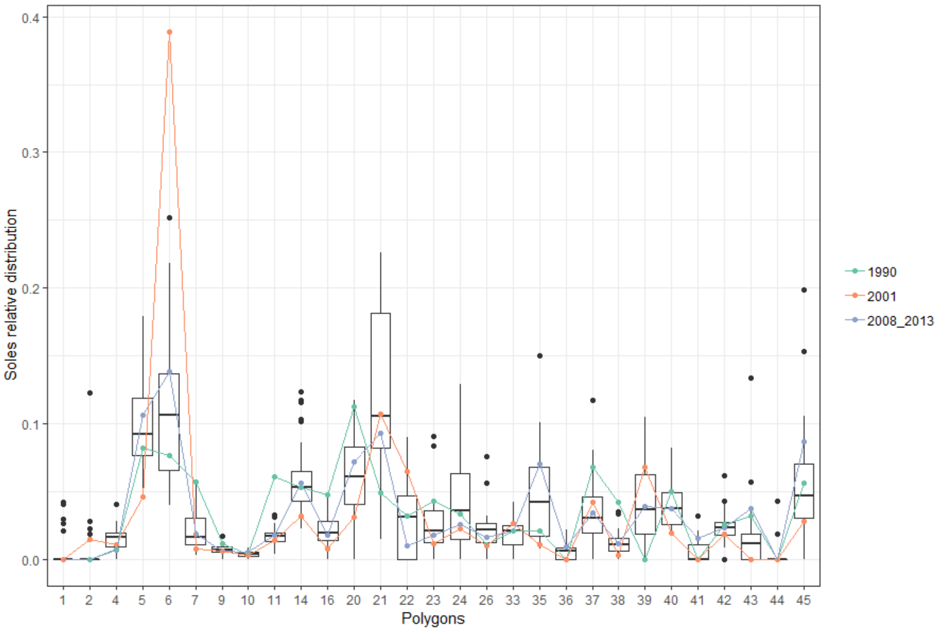



**Figure 12:** Sole distribution among ISIS polygons.
Boxplot: full dataset. Blue points: distribution based on 1990 UK-BTS data. Red points: distribution based on 2001 UK BTS data. Violet points: distribution based on the mean of UK BTS data between 2008 and 2013. Polygons with related numbers appear in Figure 13.

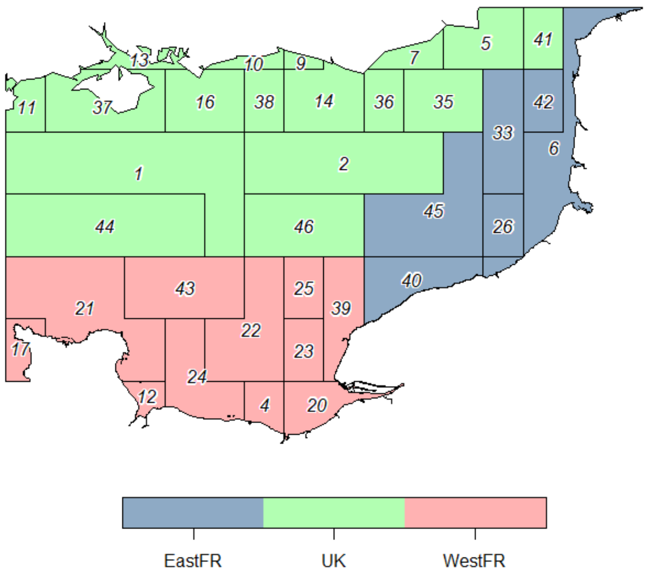



**Figure 13:** ISIS polygons number with related sub-areas.

### 2.6.3. Simulation design

For short-term projections, 3 sets of 24 simulations (full simulation design with 8 recruitment scenarios and 3 spatial distribution scenarios) have been run over the period 2008-2018 to evaluate the performance of the current management strategy under the 3 hypothesis on spatial structure.

### 2.6.4. Interpretation of simulation plan outputs

The selected alternative scenarios allow evaluating a credible range of uncertainty for performance metrics according to nursery productivity and spatial distribution of sole. Furthermore, such approach allows quantifying the effect of spatial variables (stock structure, soles distribution and nursery productivity) on strategy performance through sensitivity indices and then identifying the main source of uncertainty among variables.

Linear models used to compute sensitivity indices follow the general formula:

$$\mathrm{Y} \sim \mathrm{Stock\ structure} + \mathrm{R_{EastFR}} + \mathrm{R_{WestFR}} + \mathrm{R_{UK}} + \mathrm{Distribution} + \mathrm{interactions}$$

With:
$\mathrm{Y}$ : All performance criteria.
$\mathrm{Stock\ structure}$ : The effect related to stock structure (i.e. the 3 models).
$\mathrm{R_{EastFR}}$ : The effect related to recruitment in EastFR (either high or low).
$\mathrm{R_{WestFR}}$: The effect related to recruitment in WestFR (either high or low).
$\mathrm{R_{UK}}$: The effect related to recruitment in UK (either high or low).
$\mathrm{Distribution}$ : The effect related to soles spatial distribution scenarios (base case, 1990, 2001).
$\mathrm{Interactions}$ : All two-way interactions.

Note that the selection of alternative scenarios strongly differed:

- Migration rates scenarios are plausible scenarios based on UK-BTS survey data
- Recruitment scenarios bracket the credible range of uncertainty.

Furthermore, recruitment parameters vary among models: “1_population” and “mixing_subpopulations” do not have the same recruitment parameters values as “3_populations” (Table 1). Thus, sensitivity indices must be interpreted with cautious. They only provide a quantitative way of looking at variability in outputs for a better understanding of the effect of spatial variables on strategy performance and for identifying the main sources of uncertainty.

# 3. Results

## 3.1. Long-term projections: Equilibrium curves.

### 3.1.1. Area VIId

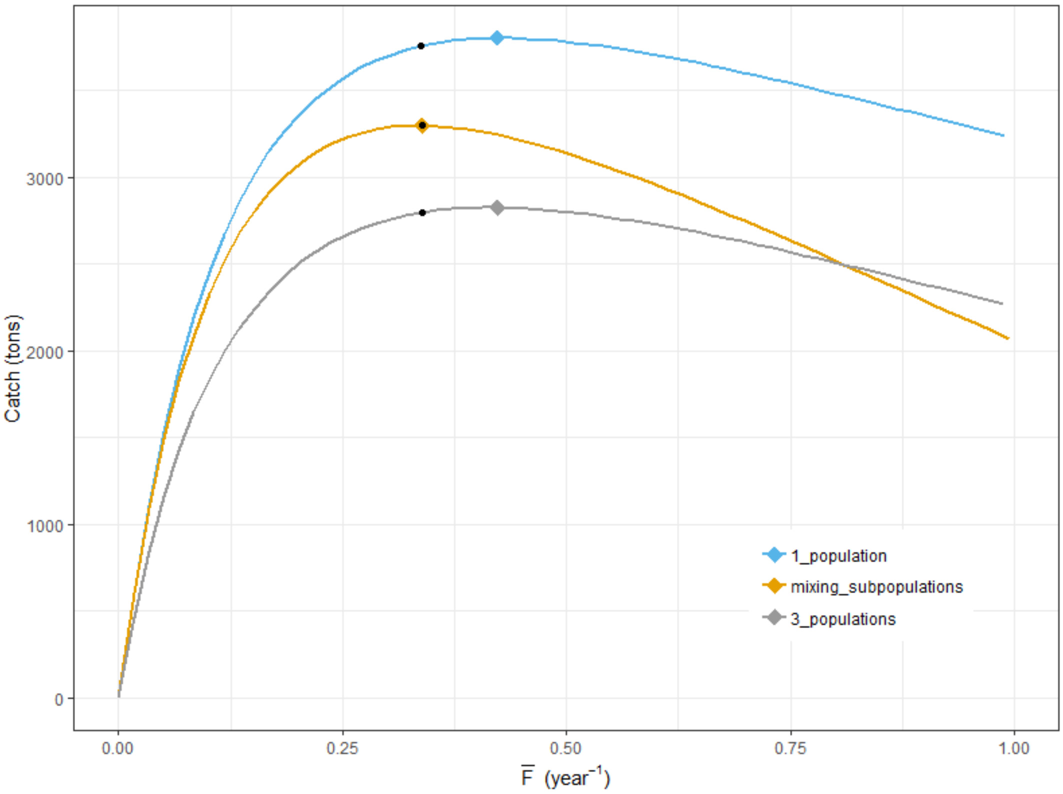



**Figure 14:** Catch equilibrium curves at area VIId scale.
Points: Statu quo situation (effort multiplier = 1). Colored square: reference points.

A for any equilibrium catch curve, for each model long-term catches increase when fishing mortality increases until reaching a maximum (Fmsy, MSY) and then decreasing (Figure 14). However, all three curves differ indicating that spatial structure affects long-term yields.

At the scale of area VIId, long-term yields decrease when segregation is sharper : compared to “1_population” model, MSY is 1.15 times lower in case of “mixing_subpopulations” and 1.35 lower in case of “3_populations”.

Regarding fishing mortality, Fmsy are equal in “3_populations” and “1_population”. On the other hand, Fmsy is 20 % lower in “mixing_subpopulations”. Moreover, when fishing mortality reach greater value than Fmsy, the curve is steeper than in the two other cases. This can be interpreted as if “mixing_subpopulations” was more sensitive to fishing pressure (long-term catches decrease sooner and faster) than “1_population” and “3_populations”.

When looking at the status quo situation (black dots on figure 14), “1_population” and “3_populations” are under-exploited ; Fstatu.quo is 20% lower than the corresponding Fmsy while in “mixing_subpopulations” sole appears fully exploited (Fstatu.quo = Fmsy).

Long-term curves for SSB figure in Appendix XI.

### 3.1.2. Sub-areas

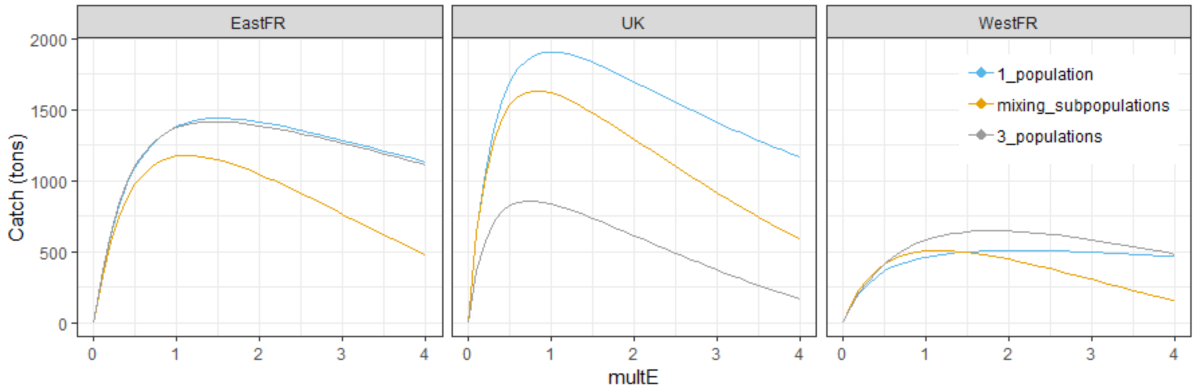



**Figure 15:** Catch and SSB equilibrium curves as a function of effort multiplier at each subdivision scale (multE = 1: statu quo situation).

At subdivisions scale, differences between models are more contrasted (Figure 15). When comparing sub-areas, maximum yields remains between 1000 and 1500 tons in the WestFR segment and between 500 and 750 tons in the UK segment. Long-term catches are more sensitive to stock structure hypothesis in the UK segment: in "1_population" and "mixing_subpopulations", catches are higher than in any other sub-areas (local MSY is up to 1500 tons) while they are lower in "3_populations" hypothesis (MSY = 859,55 tons). Thus, depending on stock structure hypothesis, long-term catches distribution among sub-areas differs (Figure 16). At Fmsy, in "1_population" and in "mixing_subpopulations", EastFR, UK and WestFR gather respectively 40%, 50 % and 10% of long-term catches while in "3_populations" they gather 50 %, 30 % and 20 % of long-term catches.

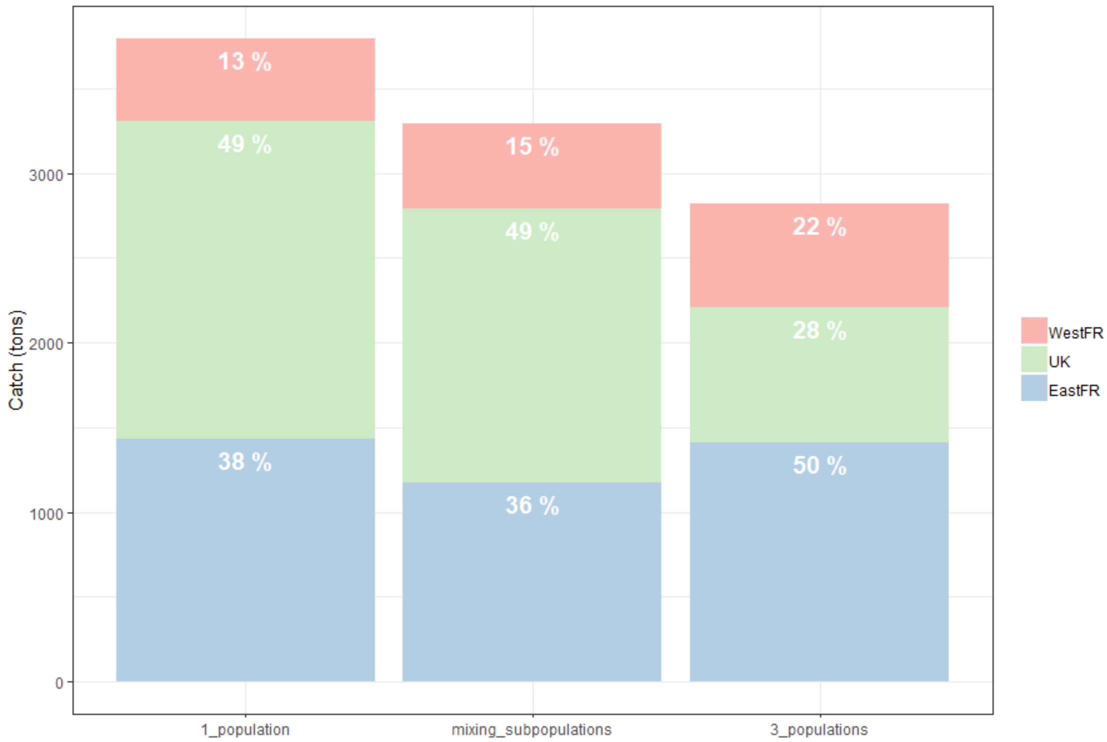



**Figure 16:** catch distribution among areas under the alternative stock structure hypothesis (F = Fmsy).

Moreover, fishing effort multipliers at local MSY (and thus exploitation status) vary among sub-areas and among hypothesis (Figure 15). In all hypothesis, EastFR and WestFR segments appears under-exploited (multE(MSY) > 1). For EastFR sub-area, multE at local

MSY is 15 % higher than the status quo situation (multE = 1) in “mixing_subpopulations” and 50 % higher in models “1_population” and “3_populations”. For WestFR segment, fishing multiplier is 2 times higher than the status quo situation in “1_population” and “3_populations” and 1.15 higher in “mixing_subpopulations” case. Conversely, UK segment appear fully exploited in “1_population” and 20 % over-exploited in “mixing_subpopulations” and “3_populations”.

When comparing models at the subdivision scale, EastFR long-term catch curves are fairly similar in “1_population” and “3_populations”. “mixing_subpopulations” shows lower long-term catches: local MSY is 20% lower than in the 2 other models.

UK catch equilibrium curves show even higher contrasts. Local MSY is the highest in “1_population” model (1907,49 tons) and is the lowest in “3_populations” model (859,55 tons) with “mixing_subpopulations” being an intermediate case (1634,57 tons).

For WestFR segment, long-term catches are higher when considering 3 distinct stocks (648,37 tons) than 1 population (510 tons for both other models). Moreover, this segment appears more robust to fishing effort in “1_population” than in the two other cases as the curve after MSY is flatter and multE at local MSY is higher (2.15 versus 1.80 for “1_population” and 1.15 for “mixing_subpopulations”).

### 3.1.3. Differences in long-term catch can be related to differences in recruitment parameters and connectivity patterns.

Explaining contrasts in long-term catches is more qualitative than quantitative. They can be related to differences:

- in recruitment parameters between models (nursery productivity varies depending on stock structure hypothesis – Table 1 and Appendix XIV).
- in connectivity patterns among sub-areas.

For example, UK nursery carrying capacity is 2 times higher in case of total segregation at the adult stage which seems to explain the higher MSY of UK segment in case of 3 distinct stocks compared to other hypothesis.

However, for EastFR segment, Somme carrying capacity may be 45 % higher in “3_populations” than in “1_population”, long-term catches are nearly similar. In “mixing_subpopulations”, consistently with recruitment parameters differences, they appear 30 % lower on average.

Only connectivity patterns explain such differences: as there are no exchanges between sub-populations in “mixing_subpopulations”, other sub-populations will only supply the EastFR sub-area during the reproduction period (February to June). Thus, catches in EastFR subarea during foraging season will only rely on the EastFR sub-population and on corresponding recruitment parameters. As nursery productivity in the EastFR segment is lower in “mixing_subpopulation” compared with “3_populations”, long-term catches in EastFR are lower on the whole year. Conversely, in “1_population” other sub-areas supply the EastFR segment before and after reproduction and thus long-term catches are higher.

### 3.1.4. Summary of reference points

Table 4 summarizes all the reference points derived from equilibrium curves. They were used in the management strategy and in the computation of performance criteria. Note that the sum of local MSY is slightly higher than global MSY (in “1_population” 1.5 % higher, in “metapopulation” 0.8 % higher, in “3_populations” 3.6 % higher). It suggests that managing 3 distinct populations as one structured population with one TAC is slightly suboptimal.

Local long-term catches as a function of fishing mortality for “3_populations” model appears in Appendix XIII. Long-term catch differences have been outlined previously. Besides, fishing reference points vary among areas: Fmsy is two times higher in EastFR than in UK and WestFR. It suggests that a spatial management strategy would allow a more accurate management of sub-populations in this case for slightly higher yields.

**Table 4:** Summary of the main reference points at the scale of area VIId and at the scale of each subdivision.

| Model | Area | MSY (tons) | Bmsy (tons) | Fmsy ($year^{-1}$) |
|---|---|---|---|---|
| 1_population | VIId | 3800.52 | 11360.16 | 0.423 |
| Mixing_subpopulations | VIId | 3296.88 | 12606.84 | 0.339 |
| 3_populations | VIId | 2824.19 | 9243.26 | 0.423 |
| 1_population | EastFR | 1440.34 | 3221.50 | |
| 1_population | UK | 1907.49 | 5738.52 | |
| 1_population | WestFR | 509.15 | 1431.11 | |
| Mixing_subpopulations | EastFR | 1179.72 | 3153.79 | |
| Mixing_subpopulations | UK | 1634.57 | 5832.40 | |
| Mixing_subpopulations | WestFR | 508.34 | 3355.05 | |
| 3_populations | EastFR | 1418.22 | 2639.47 | 0.393 |
| 3_populations | UK | 859.55 | 3717.97 | 0.238 |
| 3_populations | WestFR | 648.37 | 2585.25 | 0.219 |

## 3.2. Short-term projections : evaluation of the current strategy

### 3.2.1. Area VIId

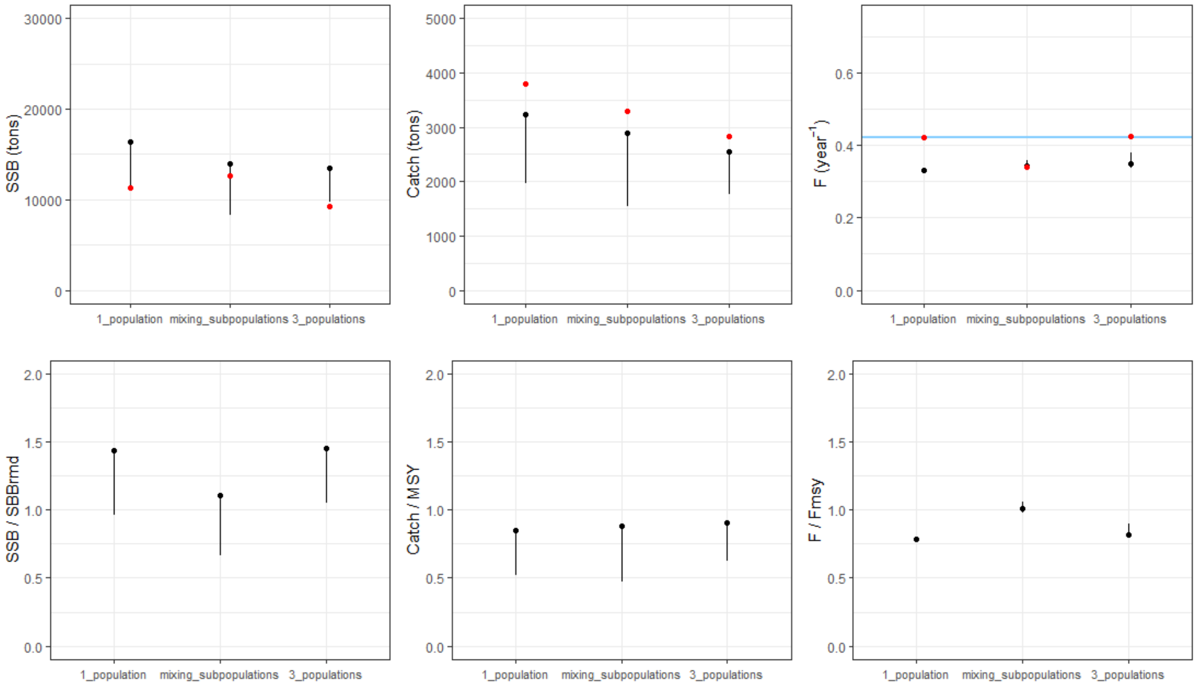


**Figure 17:** Performance metrics of the current management strategy at the scale of area VIId. Black points: base case. Black lines: uncertainty range. Red points: reference points. Blue line: fishing target.

In ISIS-Fish, exploitation model is built so that effort can decrease but not increase. As effort multiplier at fishing target (multE = 1.25 and F = 0.42 $year^{-1}$) is higher than the effort multiplier to status quo (multE = 1 and F = 0.34 - see Appendix XI), the exploitation model is unable to reach fishing target and thus fishing mortality remains to F = 0.34 $year^{-1}$ in each case (Figure 17).

Moreover, SSB and catch show high range of uncertainty making difficult the interpretation of results. However, few points stand out.

"1_population" and "3_populations" are under-exploited as fishing mortality is ¾ of corresponding Fmsy (0.42). Consequently, SSB is 40 % higher than SSBmsy and catches are 10 % lower than MSY in each case.

On the other side, by chance, "mixing_subpopulations" is fully exploited (F/Fmsy = 1). Consequently, SSB is close to SSBmsy (SSB/SSBmsy = 1.1) though catch remains under MSY (Catch/MSY = 0.88).

As with catch equilibrium curves (Cf. 3.1.1.), catches seems to decrease when segregation is sharper. When considering the base case, catches are 10% lower in "mixing_subpopulations" than in "1_population" and 20% lower in "3_populations".

In case fishing mortality reached target values (F = 0.42 $year^{-1}$), "1_population" and "3_populations" would be fully exploited (Ftarget equals Fmsy) while "mixing_subpopulations" would be over-exploited (Ftarget is 30 % higher than Fmsy).

### 3.2.2. Sub-areas

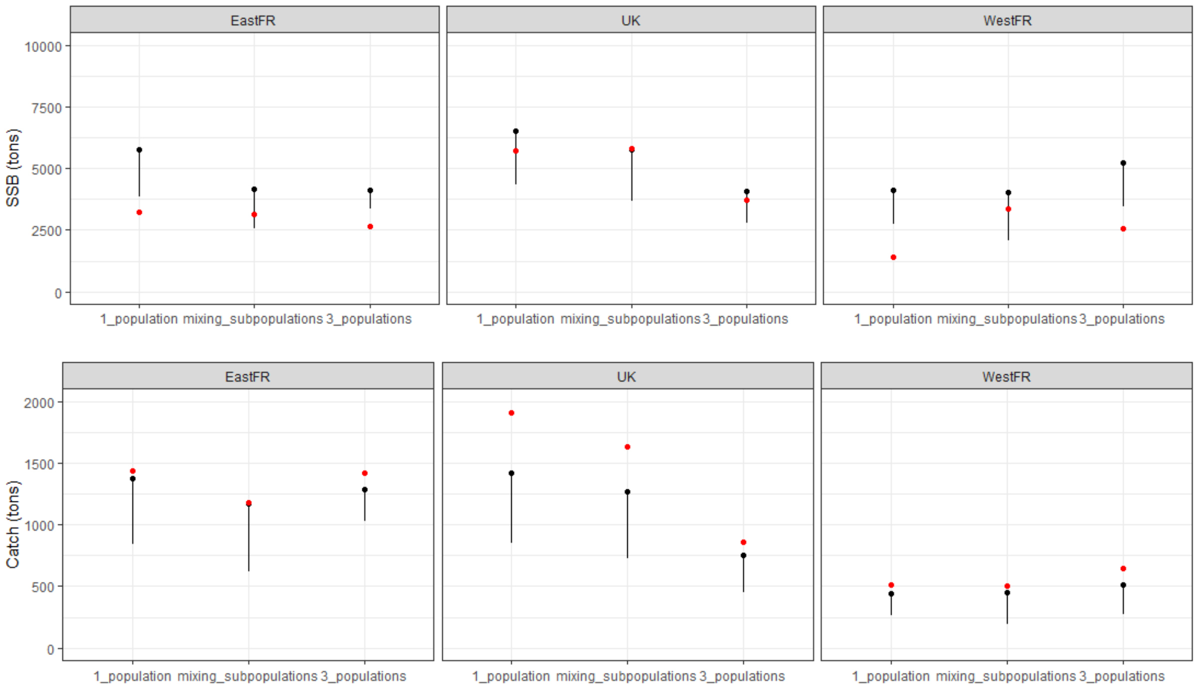



**Figure 18:** Absolute performance criteria at subdivisions scale.
Black points: base case. Black lines: uncertainty range. Red points: reference points.

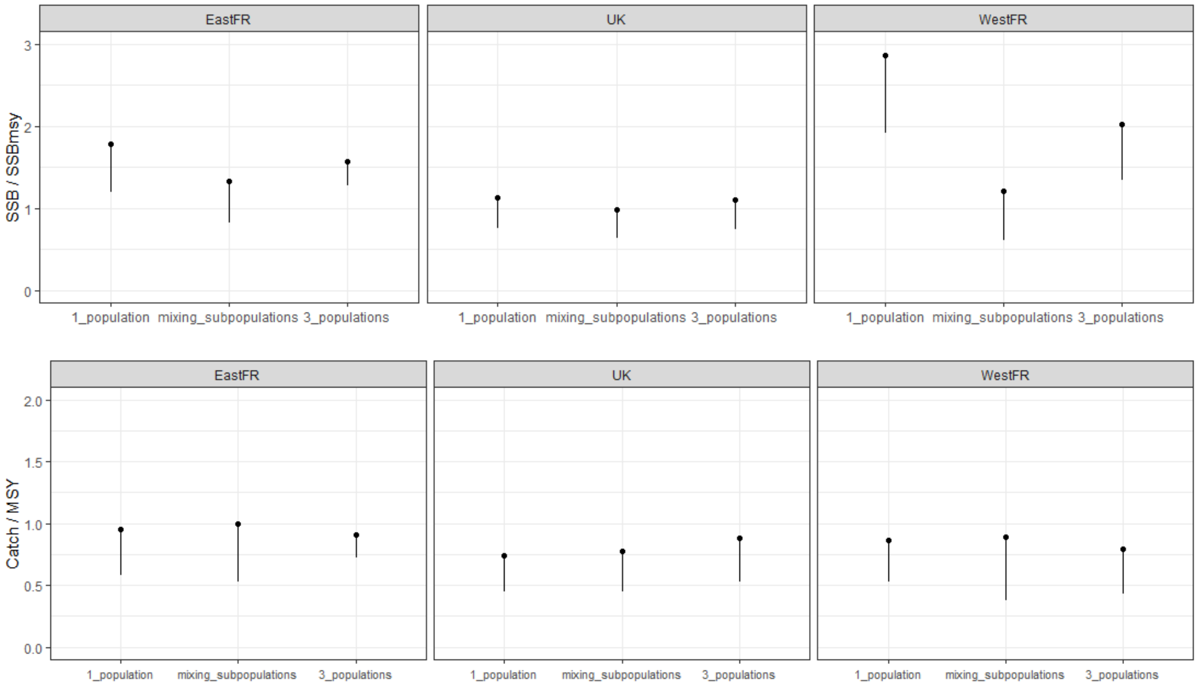



**Figure 19:** Relative performance criteria at subdivisions scale.
Black points: base case. Black lines: uncertainty range.

As any model met the fishing target and because of high uncertainty range, results at the subdivision scale aren't valuable (Figure 18, Figure 19). Nevertheless, it remains that local performance metrics differ among sub-areas and stock structure hypothesis and that absolute and relative performance criteria do not give the same insight on strategy performance.

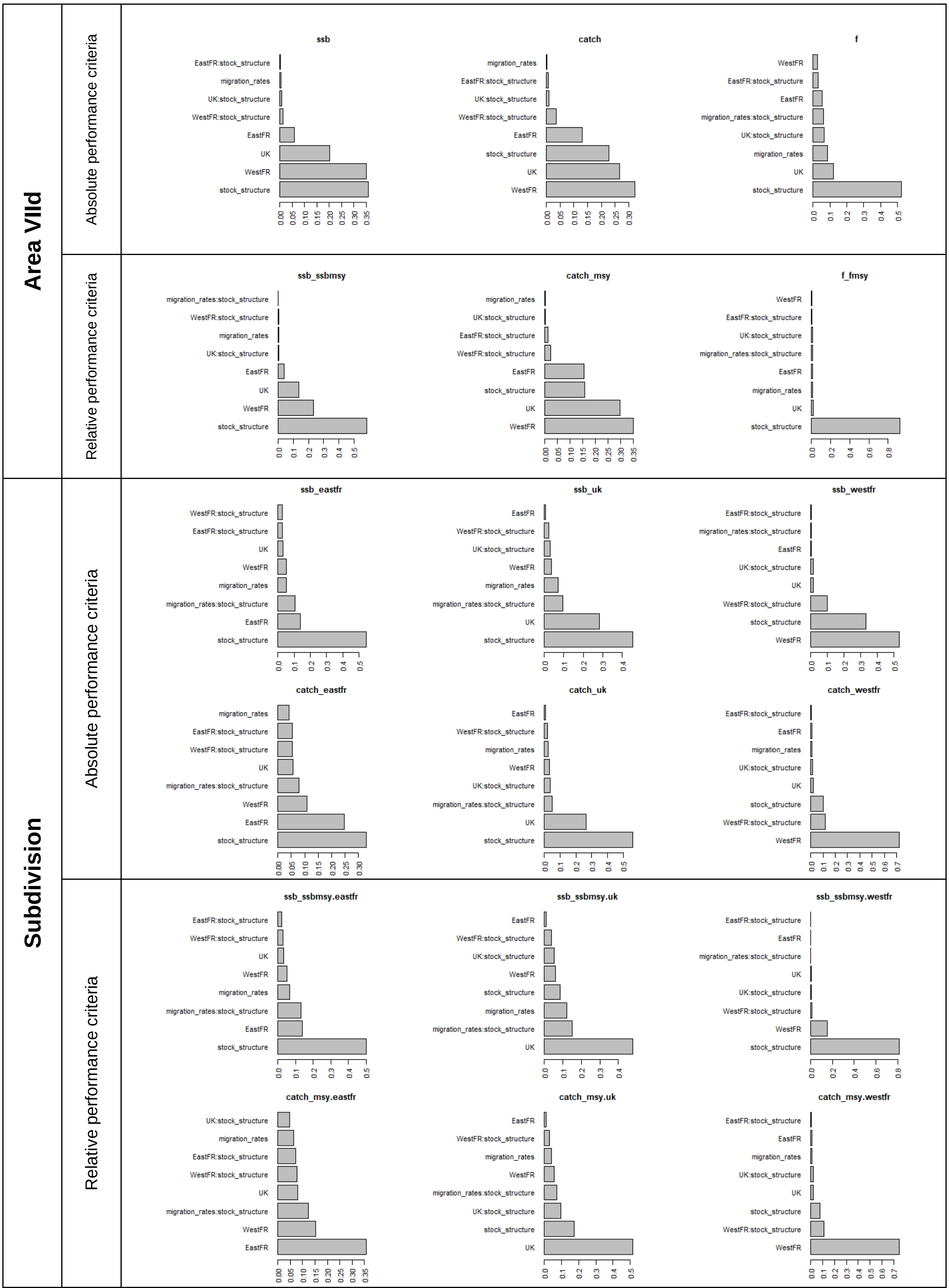
In WestFR, catch remains around 500 tons in each case and SSB is 30 % higher in "3_populations" than in other models. However, stock status is more contrasted as SSB / SSBmsy is 2 times over 1 in "1_population" and "3_populations", compared with "mixing_subpopulations" where SSB / SSBmsy equals 1. In the first case, WestFR segment could be more exploited even though catches wouldn't be much higher (Catch / MSY = 0.9) while in the second case WestFR segment is almost fully exploited (SSB / SSBmsy = 1 and Catch / MSY = 0.9).

Catches in UK sub-area contrasts with WestFR. Catches as SSB are 50 % lower in "3_populations" than in the two other models. These differences can be related to long-term catches curves: for the UK sub-area, "1_population" and "mixing_subpopulations" long-term catches are 2 times higher than "3_populations" long-term catches (Figure 15). However, in all cases, exploitation status is the same: this segment seems almost fully exploited as SSB / SSBmsy = 1.1 and catch / MSY nearly equals 0.75 in "1_population" and "mixing_subpopulations" and 0.9 in "3_populations". Increasing fishing mortality would probably mean decreasing SSB out of SSBmsy. In this case, UK segment diagnostic would be more worrying.

Finally, catches in EastFR segment remain around 1250 tons while SSB in "metapopulation" is 60 % lower than in "1_population" and 25 % lower than in "3_populations". However, in all cases, stock status remains the same as SSB / SSBmsy equals 1.5 and catch / MSY vary from 1 in metapopulation to 0.9 in the other cases.

### 3.2.3. Sensitivity indices: effect of spatial parameters

**Table 5:** sensitivity indices for performance criteria at the scale of area VIId and at the scale of subdivisions.




$R^2 > 0.99$ in each case. migration_rates ≡ soles distribution

At the scale of area VIId, performance metrics are mainly sensitive to the hypothesis on spatial structure and recruitment parameters (in all cases they explain more than 80 % of total variability). Recruitment parameters effect are ordered as follows in each case: WestFR, UK, EastFR. This is mainly a consequence of the choice of the recruitment alternative scenarios. We selected the brackets of credibility intervals of recruitment parameters of each nursery. Thereby, as credibility intervals are higher in WestFR nurseries compared to UK or EastFR (Appendix XIV), related sensitivity indices are higher.

Stock structure appears as another sensitive factor. It is one of the main factor (SI > 0.15) when regarding catch and SSB criteria and it is the main factor when regarding fishing mortality. It can be related to differences in recruitment parameters and connectivity patterns at the adult stage. Thus, stock structure appears as a high source of uncertainty on strategy performance.

Besides, there are several small interactions between nursery carrying capacity and stock structure hypothesis. When summed, related sensitivity indices are generally between 0.05 and 0.1. This is probably a consequence of differing recruitment parameters between models'. It could also be interpreted as a contrasted effect of nursery productivity among hypothesis: each nursery modality doesn't have the same effect following the stock structure hypothesis. For example, one nursery productivity parameter could have more effect in "1_population" than in "metapopulation" and "3_populations" because of connectivity differences.

When regarding local performance criteria, Stock structure and nursery productivity remain important factors, but they do not appear systematically as main effects (i.e. SI < 0.1). Furthermore, they are ordered differently: among nursery productivity effects, the main effect corresponds to the sub-area nursery productivity and then to other nursery productivity.

Moreover, two new effects come out: sole spatial distribution ('migration rates') and the interaction between stock structure and sole spatial distribution.

As sole proportion in each sub-area varies in each distribution alternative scenario (Appendix X), logically catches and SSB are highly sensitive to this variable at subdivisions scale.

The interaction shows that sole distribution effect varies across stock structure hypothesis. This is the consequence of connectivity patterns: as in "1_population" sole redistributes in the entire area VIId while they return to their home area in "mixing_subpopulations". Thereby, redistribution of biomass is completely different among hypothesis, affecting both SSB and catches at local scale.

Although these processes do not affect catch and biomass at the scale of area VIId but they can be detected at the subdivision level and they constitute another source of uncertainty at this scale.

Surprisingly, WestFR SSB and catch criteria only depend on WestFR productivity or/and on state of nature. Particularly, WestFR catch criteria only rely on WestFR nursery productivity. There seems that whatever the stock structure, catch in WestFR mainly relies on recruitment and then stock structure doesn't have major effect on yields in this sub-area.

# 4. Discussion

## 4.1. Effect of stock structure on long-term exploitation dynamics: main outcomes and perspectives

Our results outline the effect of stock structure on the long-term dynamics of the EEC common sole at the scale of area VIId or at the scale of subdivisions. Besides, equilibrium curves provide a new insight on sole local and global dynamics.

At the scale of area VIId, long-term catches is affected downwards when connectivity is sharper. At the scale of sub-areas, long-term yields vary depending on stock structure hypothesis. Particularly, the UK segment is strongly affected by connectivity patterns. Consequently, proportions of catches in each sub-area vary following the hypothesis.

Finally, stock status is slightly affected by spatial structure. At the scale of area VIId, "mixing_subpopulations" is fully exploited while the 2 other models are under-exploited. At the subdivision scale, UK sub-area appears overexploited or fully exploited while EastFR and WestFR appear under-exploited.

Surprisingly, at the scale of area VIId, in any case common sole appear underexploited while the 2015 stock assessment indicates a worrying exploitation diagnosis, F being higher than Fpa between 2008 and 2014 (Appendix XV). This can be explained by an overly optimistic stock-recruitment relationship compared to stock assessment projections and probably also to the way other fleets are modelled (Figure 10 - Cf. 4.2.3.).

These contrasts result from differences in connectivity patterns and recruitment parameters. Thereby, ignoring spatial structure would mean ignoring a factor impacting long-term yields and, to a lesser extent, exploitation status, two key variables of fisheries management.

Long-term projections integrating uncertainty on growth or recruitment could contrast our results (Appendix XII). Moreover, the effect of spatial structure on reference points remains poorly studied (Goethel et al., 2016), and further study could focus on the sensitivity of long-term yields to some key variables (including spatial variables).

Furthermore, each subdivision shows a proper local MSY and stock status at local scale differs. It suggests that a spatial strategy could provide a more accurate management of common sole. Goethel et al. (2016) emphasized some spatial strategies in context of spatial complexity. Managing the stock through spatial HCRs appears as the most straightforward option. The life cycle model (Archambault et al., 2016) provides necessary reference points while accounting for connectivity at young stages and at the adult stage. However, profit of such strategy compared to current strategy looks small as the sum of local MSY is only few percent higher than global MSY (Cf. 3.1.4.).

Determining the optimal distribution of fishing effort may be another option. Only few studies focused on this issue (Goethel et al., 2016; Le Quesne and Codling, 2008; Okamura et al., 2014; Wilberg et al., 2008). Such method must account for distribution of fishing effort in time and space in relation with population spatio-temporal dynamics. This last variable remains highly uncertain (Cf. 4.2.1.). Nevertheless, VMS (Vessel Monitoring System) data offer new opportunity to infer on fish spatio-temporal dynamics at a precise spatio-temporal scale (Kerr and Goethel, 2014). Further research may enable estimating an optimal allocation of effort and then corresponding spatial reference points (Goethel et al., 2016). As effort distribution play an important role in management strategy efficiency, this issue is of interest and the ISIS-Fish model provides a suitable framework for conducting these researches.

Finally, local reference points were computed by projecting the models for a range of effort multiplier assuming a constant effort multiplier throughout the simulation. However, when there is connectivity between sub-areas, abundance and catches in one sub-area depend on abundance and catches in other sub-areas. Thus, long-term yields and SSB in one sub-area rely on long-term yields and long-term SSB in other sub-areas. It means that local reference points are conditional to catches and SSB in other sub-areas. Therefore, determining local reference points as we did appears artificial in the cases "1_population" and "mixing subpopulations". The only way to compute local reference points that maximize yields at the scale of area VIId, is to project each model for triplets of effort multiplier (1 effort multiplier for each sub-area) and to identify the one that maximizes yields. Nevertheless, these curves constitute a first step for estimating spatial reference points and, in future research, appraising spatial harvest control rules.

## 4.2. Evaluation of the current management strategy and of the main sources of uncertainty

On the short term, although projections were not conclusive, some valuable outcomes can be noticed.

### 4.2.1. Comment on performance criteria

First, as reference points vary across each hypothesis, absolute and relative performance criteria do not give the same vision of strategy performance. While absolute performance criteria predict a credible range for key values of exploitation dynamics, relative performance criteria provide information about exploitation status.

For example, at the scale of area VIId (Figure17), catches and SSB decrease when segregation is sharper while remaining in the same range of uncertainty. When considering relative performance criteria, catch / MSY remains at the same level (0.8) while stock status (SSB / SSBmsy) is more concerning in "mixing_subpopulations" than in two other models. Thereby, absolute and relative criteria give contrasted but complementary insights of each situation because of contrasted long-term dynamics. Thus, the computation of reference points specific to each model appears as a necessary step when evaluating management strategy for alternative stock structure hypothesis.

### 4.2.2. Management diagnosis

As fishing target is not met, we do not observe any catch limitation in short-term projections and performance criteria are more optimistic than expected. Thereby, no conclusion can be made for management purposes from performance criteria.

Nevertheless, if the fishing target was met, "mixing_subbpopulations" would be globally overexploited as fishing mortality would be over Fmsy. Catch and SSB would be lower and they would be further from reference points. In the two other cases, SSB and yields would be closer to reference points.

At the subdivision scale, SSB in UK area would pass under SSBmsy while catches would decrease. This sub-area would appear overexploited (especially in model "mixing_subpopulations"). Predicting results in other sub-areas seems more difficult as there remains a big difference between SSB, catch and corresponding reference points.

### 4.2.3. Sources of uncertainty

In our case, the uncertainty analysis is more a quasi-quantitative analysis than a rigorous statistically based analysis. Such method is appropriate for eliminating management actions that are likely to perform poorly (Hill et al., 2007). However, as the management rule was not implemented effectively, highlighting such situation has little interest.

It remains that crossing all alternative scenarios through a full simulation design enables computing sensitivity indices. These indices quantify the effect of each factor on performance criteria and help determine the main sources of uncertainty. Moreover, as alternative scenarios focus on spatial parameters, this analysis provides another insight on the effect of spatial structure on strategy performance.

At the scale of area VIId, stock structure and nursery productivity appear as the main sources of uncertainty. However, sensitivity indices related to stock structure must be contrasted as recruitment parameters vary among models. Consequently, these indices reflect both differences in connectivity patterns and in recruitment parameters value.

At the scale of subdivisions, migration rates (i.e. sole distribution) combined with connectivity patterns appears as another major source of uncertainty. The effect related to migration rates result from the varying proportion of sole in sub-areas following the distribution scenarios. The interaction between stock structure hypothesis and sole distribution reflects the contrast in redistribution patterns between models: soles spread in the entire area VIId, come back to their native sub-area or stay in the same sub-area.

Thereby, when looking at local performance criteria, new sources of uncertainty appear in addition to nursery productivity and stock structure. Thus, evaluating strategy at local scale appears highly uncertain as more complex and uncertain processes (like distribution of soles) become more important and are added to other highly uncertain variables (recruitment).

### 4.2.4. Choice of alternative scenarios

The choice of uncertainty scenarios remains questionable. First, we only focus recruitment uncertainty on density dependent parameters because they are the most sensitive parameters in recruitment equations. Other less sensitive parameters remain uncertain (larval drift matrix, natural mortality at age 0). They are arbitrarily fixed in this study as they are less sensitive than density-dependent parameters. However, this is debatable as some sensitivity scenarios were arbitrarily fixed too (Table 3).

Second, we choose alternative distribution scenarios with a had-oc method: we use an ACP on UK-BTS data to isolate distinct distribution scenarios (Figure 12, Appendix X). Such method allows evaluating if another credible spatial distribution would affect management performances; But it does not allow a rigorous way of assessing spatial distribution uncertainty, only to assess the effect related to some extreme spatial distributions.

Thirdly, some key parameters aren't integrated in projections: growth, natural mortality, initial biomass, selectivity… For well-documented parameters, such approach consists in considering that available estimates are reliable and that there is no inter-individual variability. However, when considering uncertain parameters as natural mortality, they are fixed based on stock assessment because no better estimates exist (ICES, 2018). Methods exist for estimating such parameters (*e.g.* Cady method for natural mortality –

Gascuel, com. perso.) but they are not developed in this report. However, it is noteworthy that natural mortality, which is probably a major source of uncertainty in our case, would act as a scaling factor and wouldn't change the main conclusions of our results.

Finally, these alternative scenarios only provide a range of uncertainty that relies mainly on the modality we chose. We could have run Monte Carlo simulations for uncertain parameters that are associated to a probability distribution. Such method allows computing probability of reaching some catch levels or falling down some SSB levels, etc. but require a high number of simulations.

### 4.3. Recruitment hypothesis

As a highly sensitive and unpredictable variable, recruitment is a critical issue in model development. Appreciating recruitment variability while understanding its determinism remains a challenging issue (Houde, 2008). Until now, no stock-recruitment relationship has been identified for the EEC common sole and current stock assessment projections assume a constant recruitment when SSB is over Blim and a linearly decreasing recruitment below Blim (Hockey-Stick relationship - ICES, 2017b). The life-cycle model developed by Archambault et al. (2016) is an integrated framework that attempt to capture both variability and determinism of such processes for 2 alternative hypotheses on stock structure (1 stock or 3 stocks). However, to do so, Rochette et al. (2012) and Archambault et al. (2016) first made assumptions on the global recruitment processes and then fixed some parameters before estimating others. In addition, we make own assumptions to adapt the recruitment equations to the ISIS-Fish framework and this raises questions.

First, we chose to model recruitment through the deterministic terms of life-cycle equations (Archambault et al., 2016). Thus, the projections assume a constant recruitment throughout the simulation. This approach enables quantifying the effect of recruitment among other factors and then identifying the main source of uncertainty. Incorporating stochasticity of the process would have been more realistic but would have avoided such analysis.

Second, life-cycle model hypothesised density-dependent process in nurseries following the concentration hypothesis (Iles and Beverton, 2000). However, it implies a high number of parameters and then low precision. In this case, Hill et al. (2007) suggest running models with alternative simpler process hypothesis. This would mean comparing the current model based on density-dependence in nurseries with models based on simpler processes such as Hockey-stick relationships linking directly SSB to recruitment and assuming a constant recruitment over Blim and a linearly decreasing recruitment under Blim.

Thirdly, as the life-cycle model and the stock assessment have different parameters value, using data from both models can lead to inconsistencies. In our case, natural mortality at age 1 is the same as the stock assessment (0.1 - ICES, 2018). On the other hand, natural mortality at age 1 equals 2.6 in the life cycle model. Consequently, recruitment in the stock assessment are about 12 times lower than in the life cycle model. Archambault et al. (2016) encountered the same issue when fixing priors on the survival rates. Thus, we rescaled recruitment by a factor 17.5 so that mean recruitment obtained through the life cycle equations fit with the recruitment used in the calibration of the ISIS-Fish models (recruitment between 2008 and 2014 from the 2015 stock assessment). In this case, it enables conserving the mechanisms from Rochette et al. (2012) and Archambault et al. (2016) while staying in the range of recruitment used in calibration. Adopting natural mortality at age 1 of the life-cycle model (2.6) in the ISIS-Fish model and then calibrating with recruitment outputs from Archambault et al. (2016) would solve this inconsistency.

## 4.4. Other fleets: computation of catches and fishing mortality

Other fleets are modelled through a fishing mortality vector that is decomposed in time and space following the distribution of catch among sub-areas (Figure 10 and Appendix VIII). However, such approach assumes a linear relationship between catch and fishing mortality. Even if it allows dividing fishing mortality by the proportion of catch in each sub-area to spatialize fishing mortality, it distorts the modelling of fishing mortality related to other fleets.

Consequently, computing fishing mortality by summing fishing mortality of other fleets and fishing mortality of French fleets on the whole year do not give the same result as computing fishing mortality based on total catch (Figure 10). In the second case, fishing mortality are scaled down (Figure 20).

Moreover, another artefact related to the computation of other fleets' catches concerns the distribution of catches among fleets in equilibrium curves. While distribution of catches among fleets should be constant (about 50 % for French fleets and 50 % for other fleets), here it varies depending on fishing mortality (Figure 21).

These two artefacts questioned the way other fleets are computed. The hypothesis retained for spatialising fishing mortality of other fleets should consider abundance in each zone while it doesn't in the current hypothesis (linear relationship between catch and fishing mortality). Otherwise, modelling other fleets directly through a fleet grouping all non-explicitly modelled vessels may allow a more straightforward implementation. Anyway, this suggests recalibrating models and reconducting analysis. However, there is slight chance that this affects the conclusions we draw concerning effect of stock spatial structure on short-term and long-term dynamics because in all three models, fishing mortality as total catch was computed following the same method.

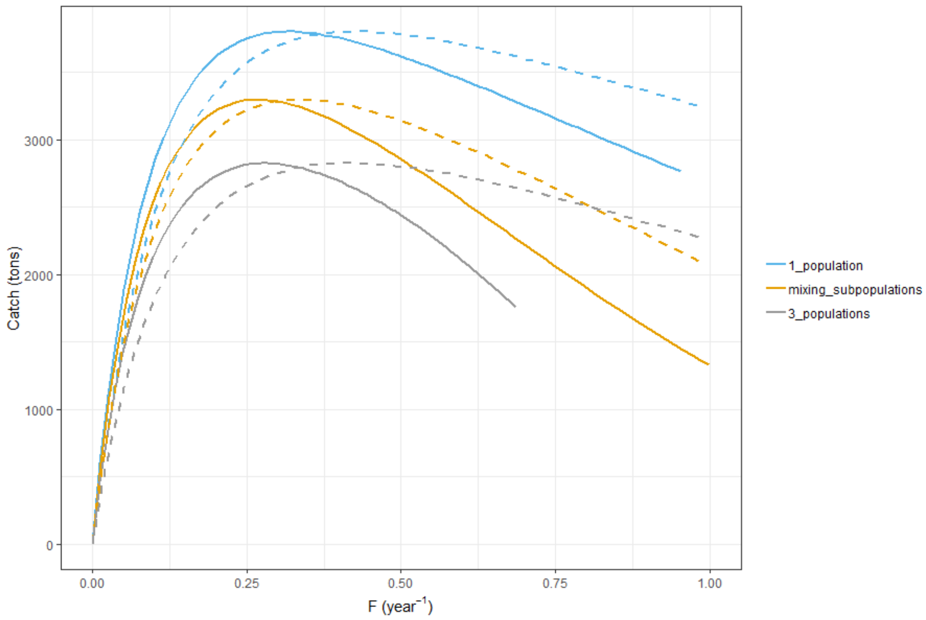



**Figure 20:** Equilibrium curves with fishing mortality computed on total catch (solid line) compared with fishing mortality computed by summing French fishing mortality and other fleets fishing mortality (dashed line).

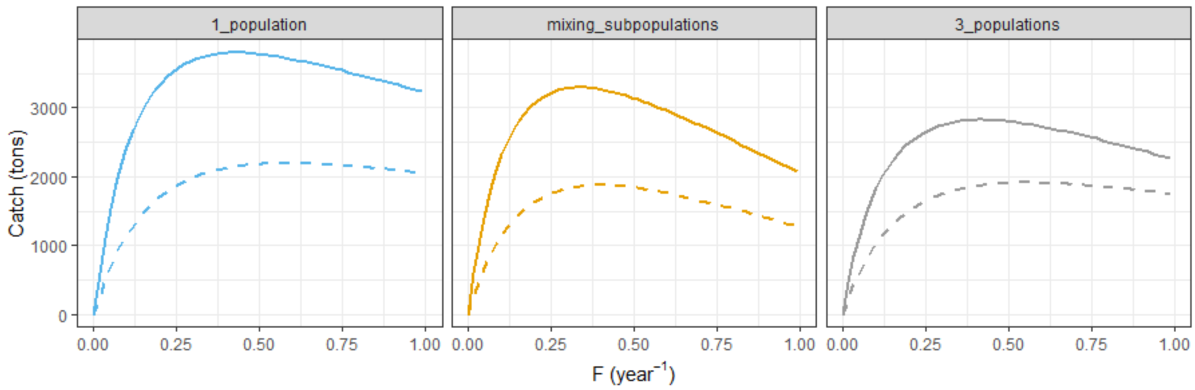



**Figure 21:** Equilibrium curves with total catches (solid line) and French catches (dashed line)

## 4.5. Stock spatial structure hypothesis

Stock structure alternative hypothesis were chosen to reflect uncertainty on spatial structure. They were based on few credible types of population structure: one single population, three distinct populations and an intermediate case where soles share the same reproduction zones and come back to their native sub-area after reproduction.

Kerr and Goethel (2014) emphasized the necessity of simulating alternative hypothesis on spatial structure and connectivity to gain further insight into stock structure implications. They outlined four main types of population structure (Figure 22): (a) single populations while having heterogeneous spatial structure (in our case “1_population”), (b) isolated populations (“3_populations”), (c) overlapping populations with natal homing (“mixing_subpopulations”) and (d) metapopulation composed of several self-sustaining segment with some exchanges.

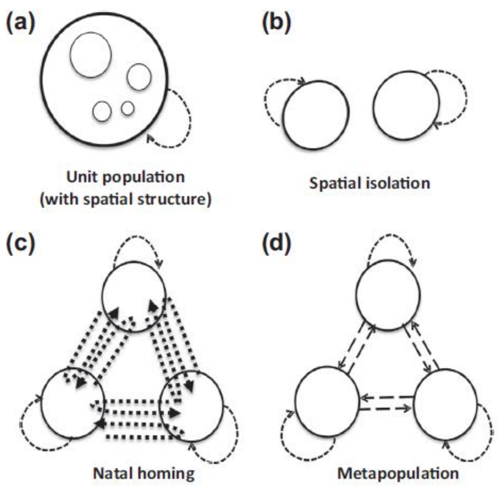



**Figure 22:** The four main types of population spatial structure from Kerr and Goethel (2014).
Circles: population segments, straight arrows: movement
between models, curved arrows: scale of recruitment.

The last case is the only one which wasn’t modelled in our study because data was only available recently. However, recent studies conducted by Lecomte et al. (2019) on mark recapture data provide estimates of exchanges between sole subunits. They outline low exchanges between sub-areas within EEC and support the hypothesis of metapopulation structure.

This new information could be incorporated in the ISIS-Fish framework as an additional alternative hypothesis. This alternative model would fit with the recent modification of the life cycle model conducted by Veron (2016) and Lecomte in his post postdoctoral research. It would integrate new estimates of recruitment parameters and migration rates between EEC subunits and adjacent zones (West Channel and North Sea - see Appendix XVI and XVII).

However, this would bring new issues in the way of modelling flows between sub-populations. Indeed, exchanges with adjacent zones cannot be neglected and modelling corresponding immigration rates means to model abundance in departure zones (North Sea and in Western Channel). Assuming constant abundance in adjacent zones is a straightforward approach as it implies constant migration rates and a simple implementation in ISIS-Fish. Otherwise, adjacent stocks could be modelled through a non-age structured dynamic model as Marchal and Vermard (2013) did with a deterministic Schaefer production model or through an age structure model equivalent to the stock assessment model of both zones.

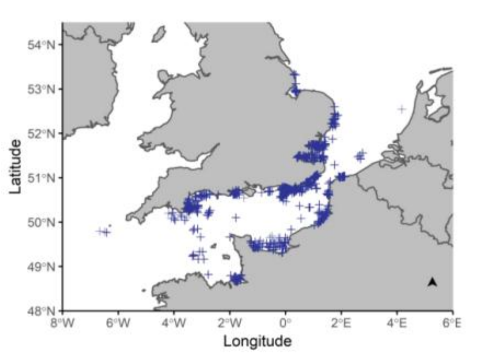



**Figure 23:** Release locations of tagged common sole in the English Channel, east of the Western Channel and West of North Sea (Lecomte et al., 2019).

Even when integrating adjacent stock dynamics, other issues would raise. For example, exchanges were computed based on individuals released in the south west of the North Sea (Figure 23). However, the stock assessment only provides abundance at the scale of area IV which is much larger than the area covered by mark-recapture data. Thus, computing number of migrating individuals based on stock assessment outputs would not be consistent with migration rates derived from Lecomte et al. (2019). Such approach would require abundance estimates at the scale of the study area of Lecomte et al. (2019).

Spatially explicit simulation models also enable identifying gaps in our knowledge where further study may be needed (Goethel et al., 2016). Stock structure is a main source of uncertainty, but research tends to increase the knowledge on this point (Du Pontavice et al., 2018; Lecomte et al., 2019; Randon et al., 2018; Rochette et al., 2012). Sole spatial distribution in time and space is a much more uncertain variable as it is based on coarse data : one single egg-survey for reproduction period (ICES, 1992) and for foraging season, UK-BTS data, a yearly survey occurring during the 3$^{rd}$ quarter (ICES, 2017a). More generally, sole spatio-temporal dynamics remains largely unknown or incomplete while it is a major source of uncertainty at the local scale. Consequently, evaluating strategies at a local scale doesn’t seem cautious as long as more information is not available.

Usually, such information is provided by yearly surveys (here UK-BTS) which collect standardized information and precise data on fish biology. Nevertheless, the temporal coverage of this data is limited due to their annual recurrence. On the other side VMS (Vessel Monitoring System) data provide spatial coordinates of fishing vessels (> to 12 m) at a fine temporal scale. Combining this data with landing data give a more precise knowledge of catches distribution in time and space. However, such information is biased as fishers target valuable species and productive zones. Combining survey data and VMS data through an integrated framework may provide a precise description of soles spatio-temporal dynamics that would allow a finer modelling of EEC sole in the ISIS-Fish framework.

### 4.6. Management process

In short-term projections, we assume a perfect estimation of fishing mortality and abundance in management module. This is a strong hypothesis as in reality abundance and fishing mortality are derived from catches through a stock assessment model. Full MSE approaches simulate these processes by adding random noise in catch or surveys and by coupling the operating model with a stock assessment model. This would raise questions particularly concerning the modelling of surveys: the scale of modelling and the noise related to observation errors.

However, building a full MSE loop would enable to quantify the bias induced by stock assessment while taking into account issues related to stock structure issues and the advantages that could bring a spatially explicit assessment model as the life-cycle model on strategy performance.

# 5. Conclusion

Common sole of the EEC is a stock managed as one single unit whereas evidences suggest spatial structuration of the population within the management unit boundaries. To reflect uncertainty on spatial structure, three ISIS-Fish models have been parameterized and calibrated for three alternative hypotheses on stock structure (one model with high connectivity, one with null connectivity and an intermediate case). In this study, we projected each models on the short term and on the long-term to evaluate the current management strategy. Long-term projections completed short-term projections by providing equilibrium curves and reference points.

Even if short-term projections weren't conclusive, both long-term and short-term projections were affected by stock structure. Catches were affected downwards when stock structure was sharper. Stock status was pessimistic in the case of intermediate connectivity, while sole appeared fully exploited in the two other cases. Finally, UK segment appeared overexploited in case of segregation between sub-units.

Moreover, this study allowed to quantify the effect of stock structure and, in the case of short-term projections, to compare it to other sources of uncertainty (nursery productivity *i.e.* recruitment, sole spatial distribution). At the scale of area VIId, main sources of uncertainty were recruitment and stock spatial structure. When looking at a more precise scale, sole spatial distribution became another main source of uncertainty. Thus, evaluating management strategy at a local scale with the ISIS-Fish model would involve considering additional highly uncertain variables.

Few modifications of models and a more accurate knowledge of stock spatio-temporal dynamics may allow a finer modelling of exploitation dynamics for further evaluation of the current management strategy and alternative spatial strategies with the ISIS-Fish model. Besides, coupling the ISIS-Fish model with alternative stock assessment model (spatially explicit or not) would allow the evaluation of their predictive capacity at the same time as a more realistic evaluation of alternative management strategies.

However, even in this case, adopting a spatial management for common sole would be challenging as it would raise questions about TACs distribution among countries and producers' organisations, a thorny issue in EU fishery management.

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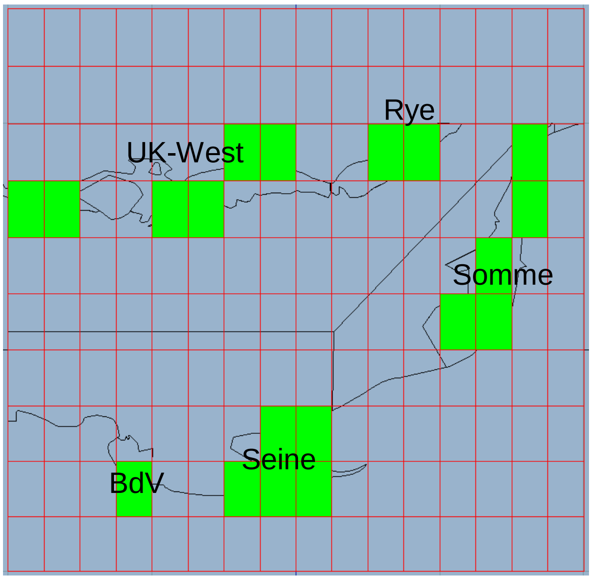
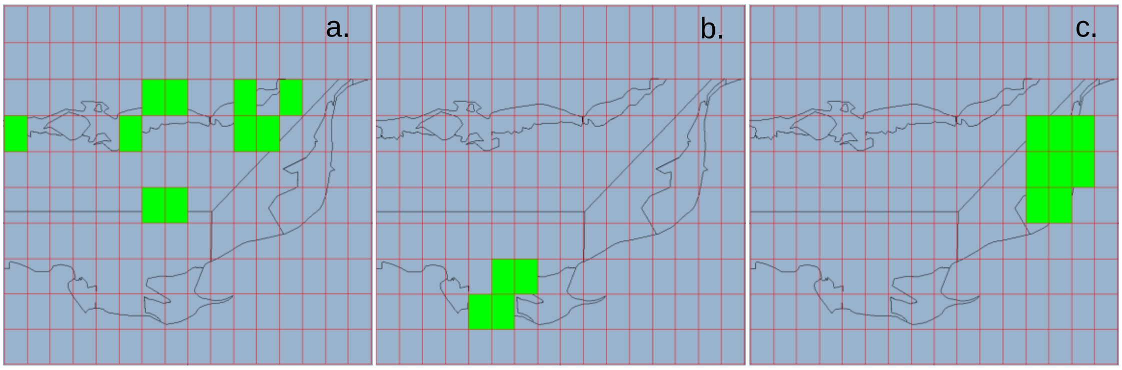
# Appendices

**Appendix I:** Functional zones in ISIS-Fish EEC.

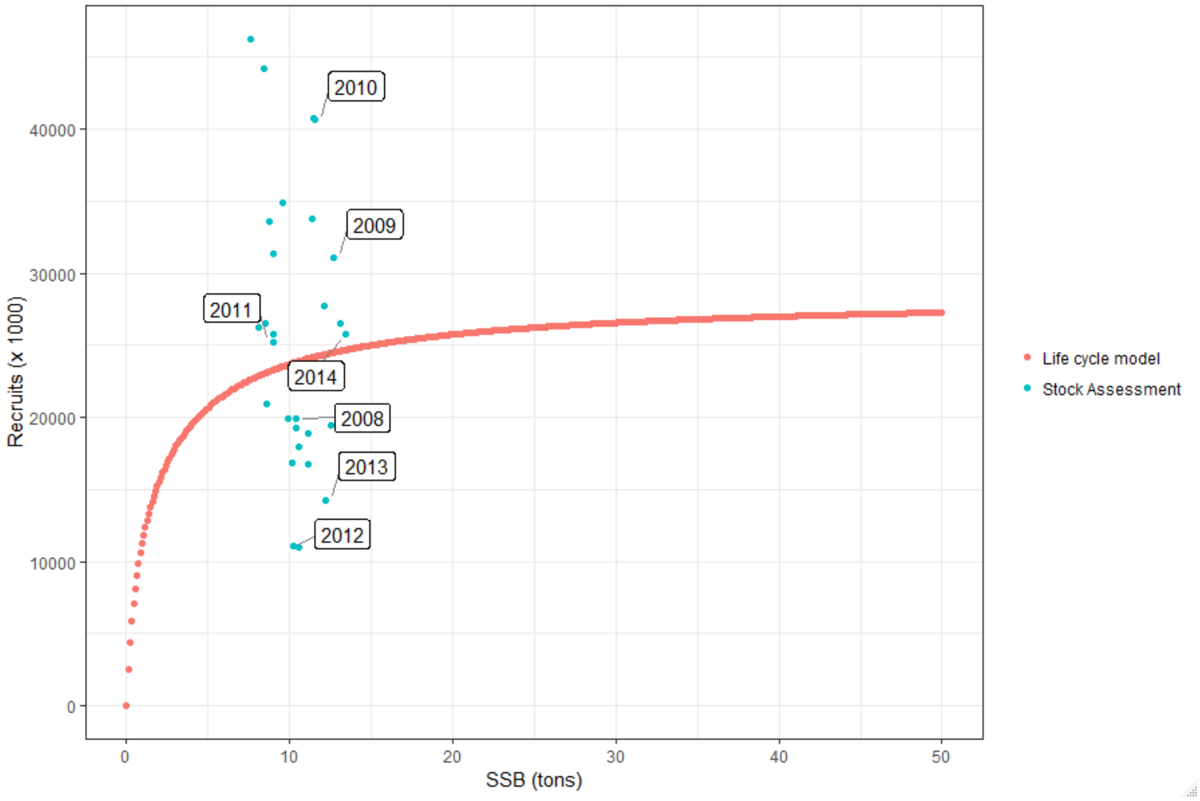



Nursery zones

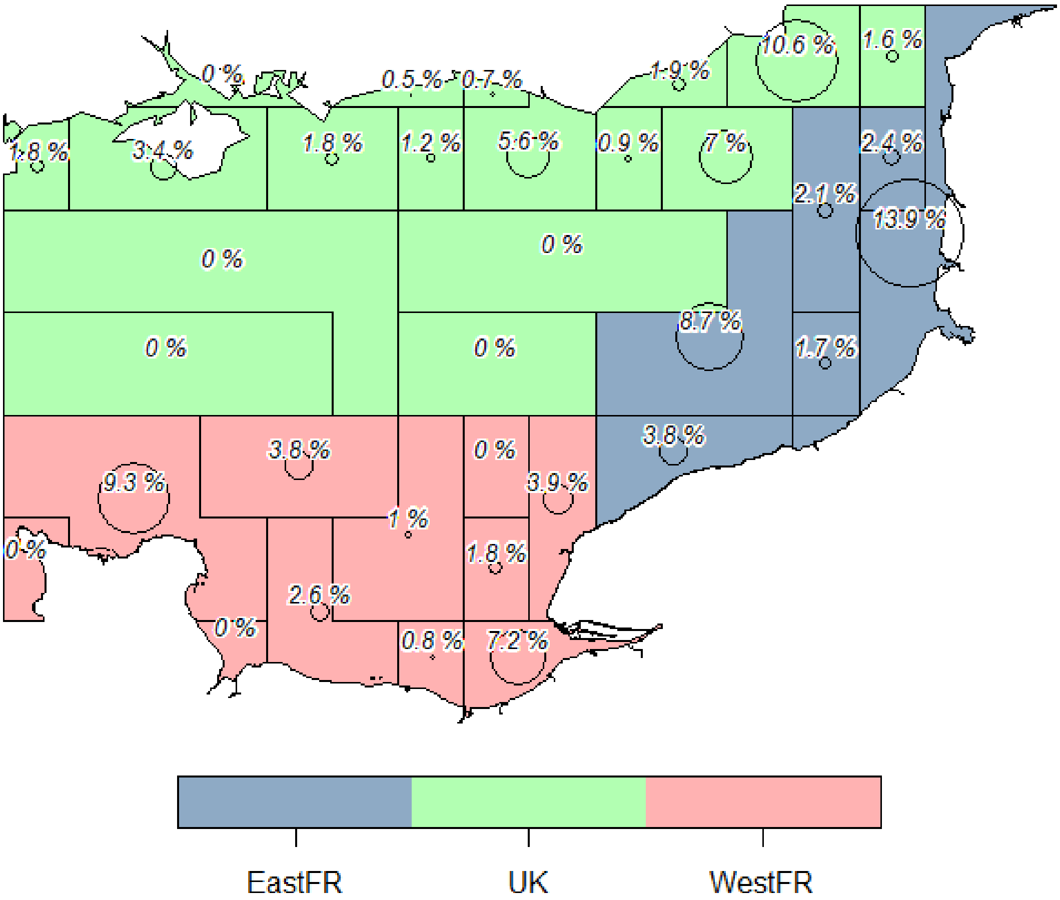



Spawning zones : (a.) UK (b.) WestFR (c.) EastFR

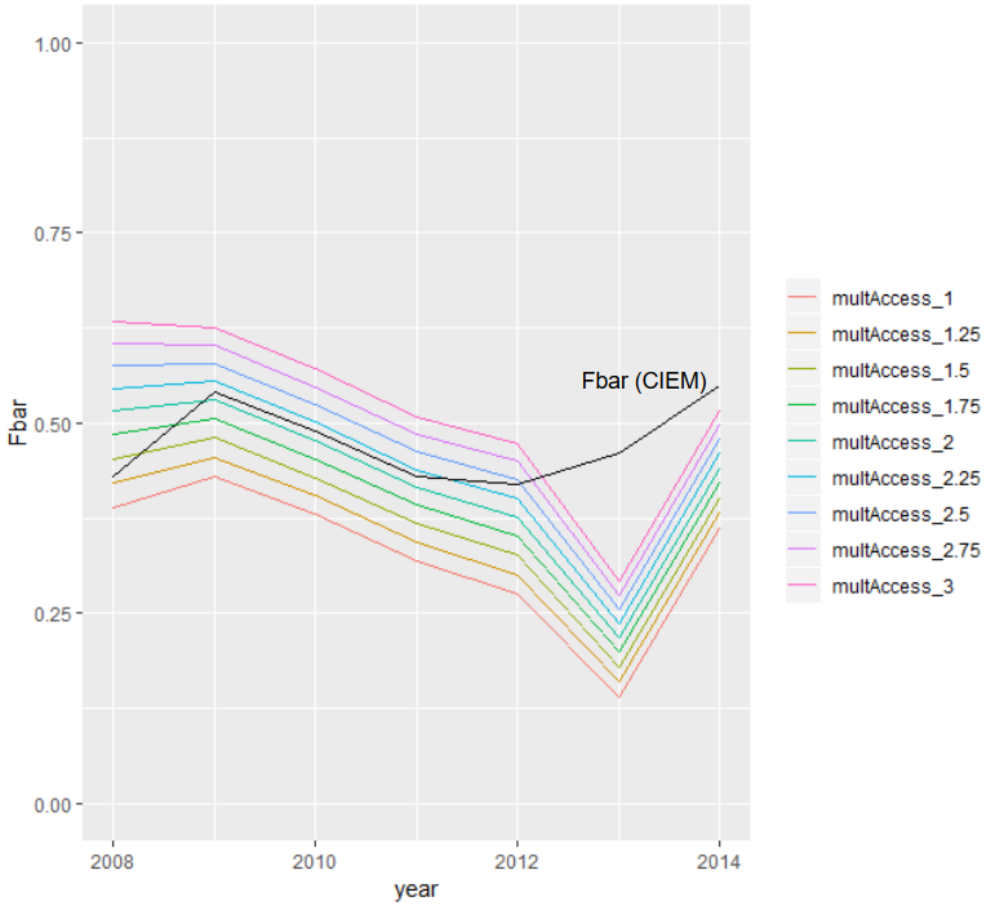
**Appendix II:** Rescaled stock recruitment relationship. Blue points: recruitment from the 2015 stock assessment. Red points: stock recruitment relationship rescaled to fit with the recruitment used in calibration (2008-2014).



**Appendix III:** Soles distribution in ISIS polygons based on UK-BTS data.



**Appendix IV:** Comparison of fishing mortality in stock assessment and in ISIS-Fish on the calibration period (2008-2014) for a range of accessibility multiplier (1 to 3, step = 0.25)



**Appendix V:** Goodness of fit of ISIS-Fish model 1_population for catch, abundance and fishing mortality for alternative accessibility multiplier.

**Percentage of error between observed and simulated values for a range of accessibility multiplier (1 to 3, step = 0.25)**

Fishing mortality

| | sp | err |
|---|---|---|
| 1 | multAccess_1 | -17.1532260 |
| 2 | multAccess_1.25 | -11.1978260 |
| 3 | multAccess_1.5 | -5.2858234 |
| 4 | multAccess_1.75 | 0.5642463 |
| 5 | multAccess_2 | 6.3844656 |
| 6 | multAccess_2.25 | 12.1644814 |
| 7 | multAccess_2.5 | 17.8932216 |
| 8 | multAccess_2.75 | 23.5888647 |
| 9 | multAccess_3 | 29.2315110 |

Catch

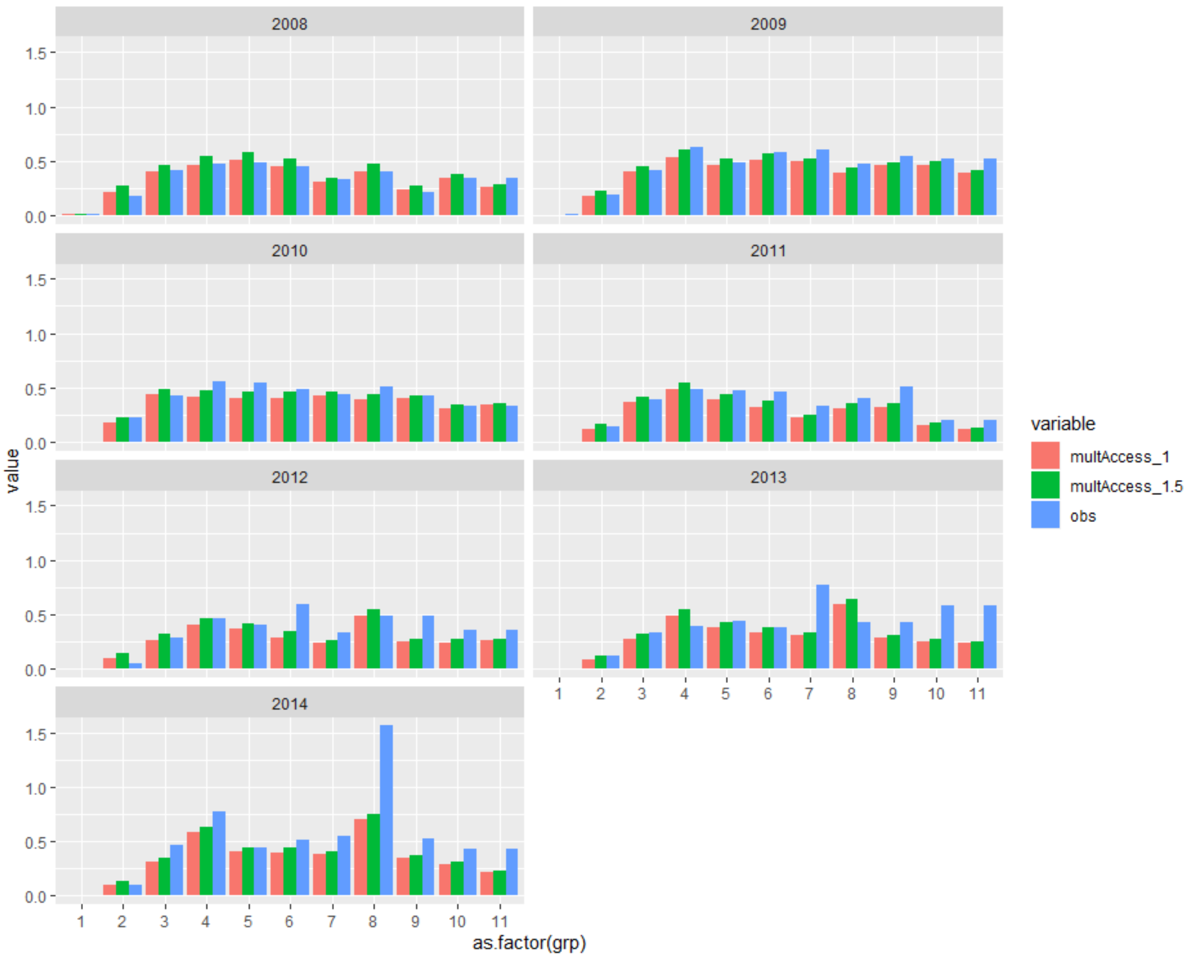
| | sp | err |
|---|---|---|
| 1 | multAccess_1 | -18.697768 |
| 2 | multAccess_1.25 | -4.800113 |
| 3 | multAccess_1.5 | 7.298523 |
| 4 | multAccess_1.75 | 17.872914 |
| 5 | multAccess_2 | 27.152268 |
| 6 | multAccess_2.25 | 35.328308 |
| 7 | multAccess_2.5 | 42.561842 |
| 8 | multAccess_2.75 | 48.988102 |
| 9 | multAccess_3 | 54.721111 |

Abundance

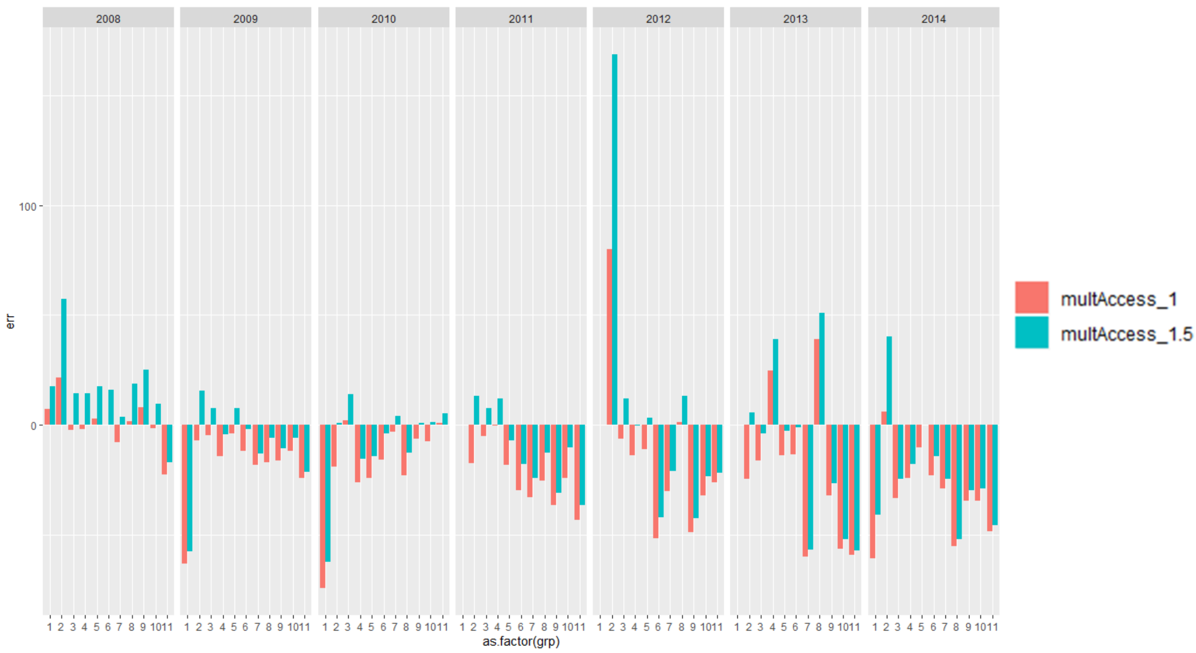
| | sp | err |
|---|---|---|
| 1 | multAccess_1 | 82.98369 |
| 2 | multAccess_1.25 | 70.60041 |
| 3 | multAccess_1.5 | 59.55926 |
| 4 | multAccess_1.75 | 49.68775 |
| 5 | multAccess_2 | 40.83833 |
| 6 | multAccess_2.25 | 32.88445 |
| 7 | multAccess_2.5 | 25.71728 |
| 8 | multAccess_2.75 | 19.24296 |
| 9 | multAccess_3 | 13.38039 |

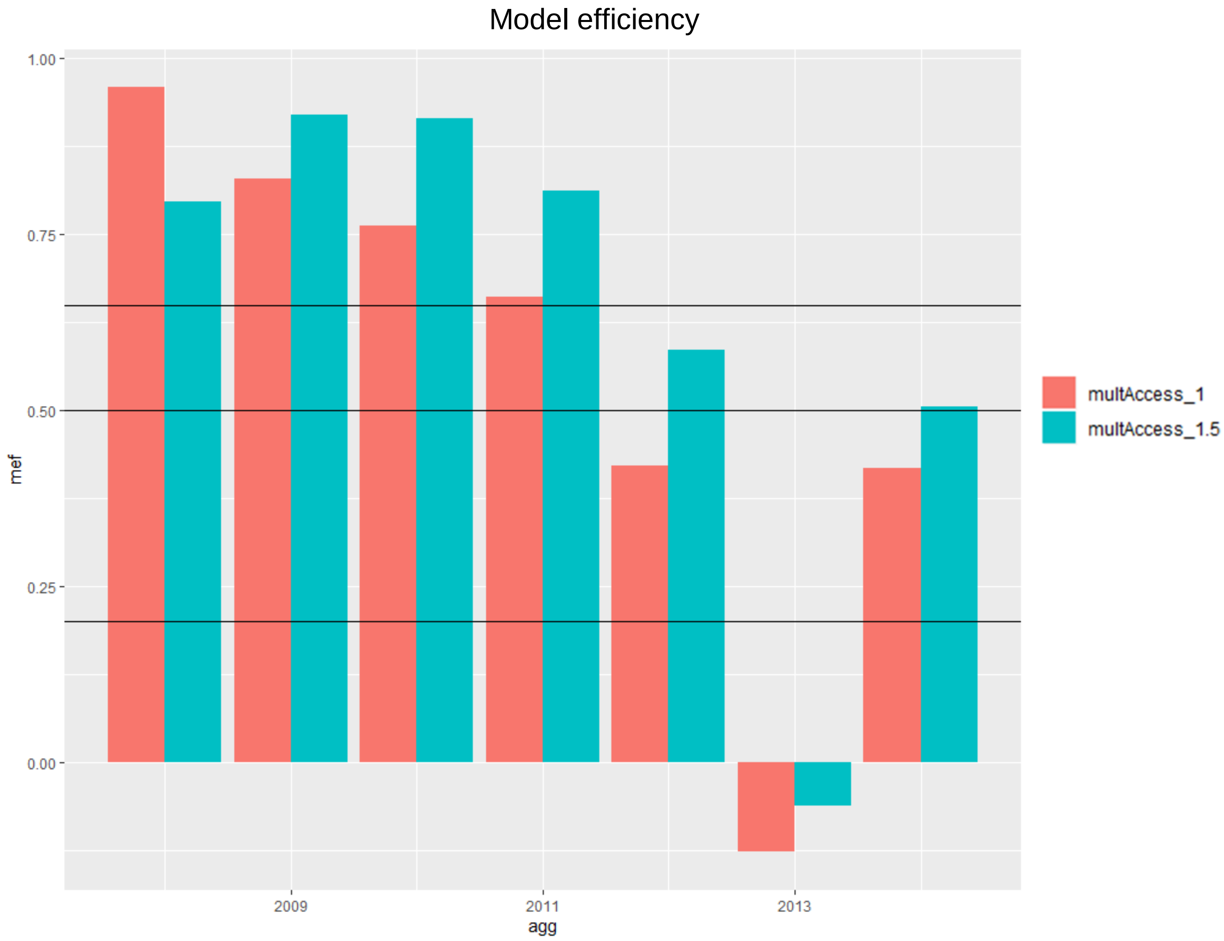
**Fishing mortality**

Simulated vs. Observed



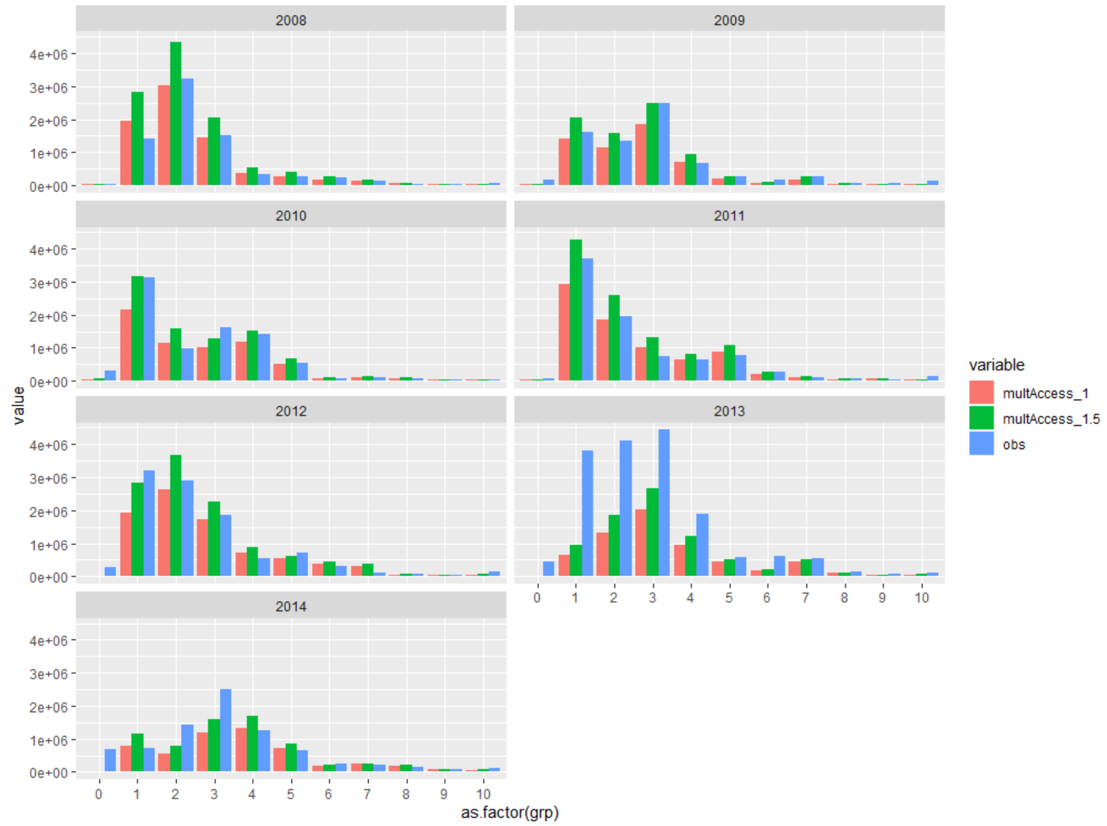

Percentage of error



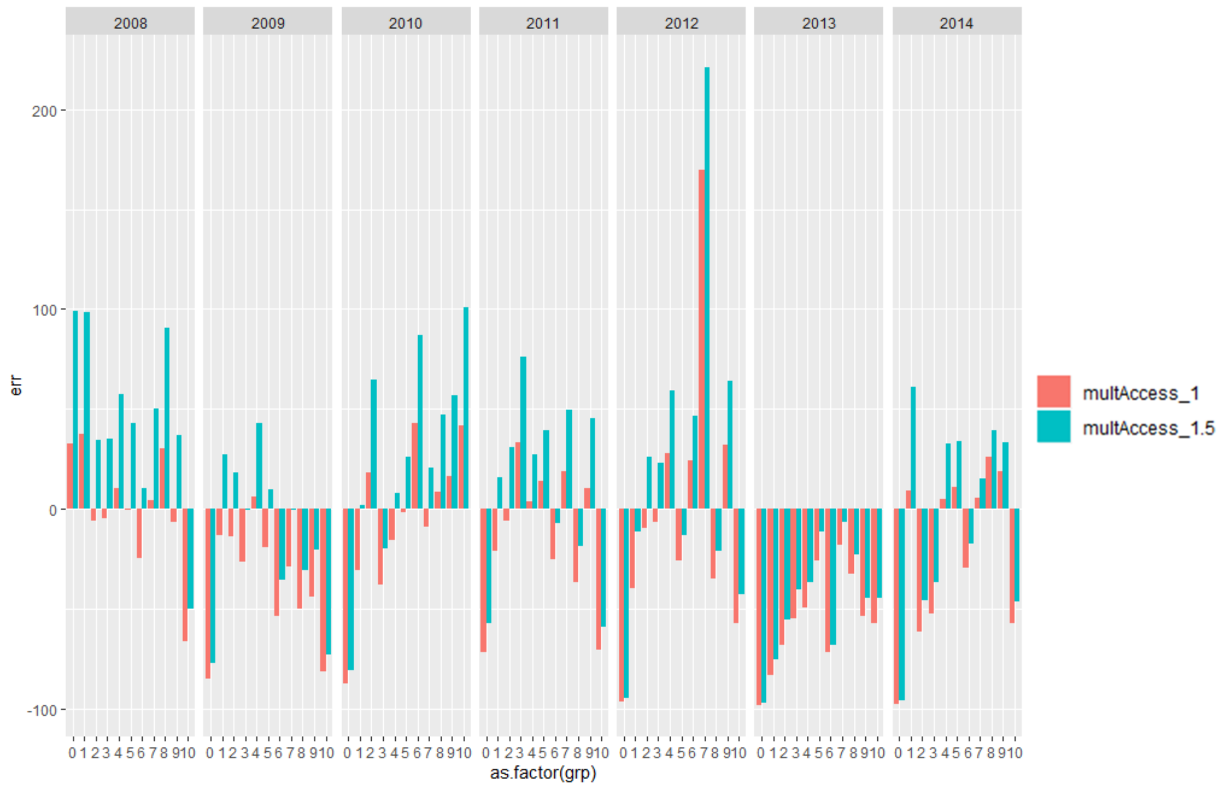

Model efficiency
1.00
0.75
0.50
0.25
0.00
mef
2009
2011
2013
agg
multAccess_1
multAccess_1.5

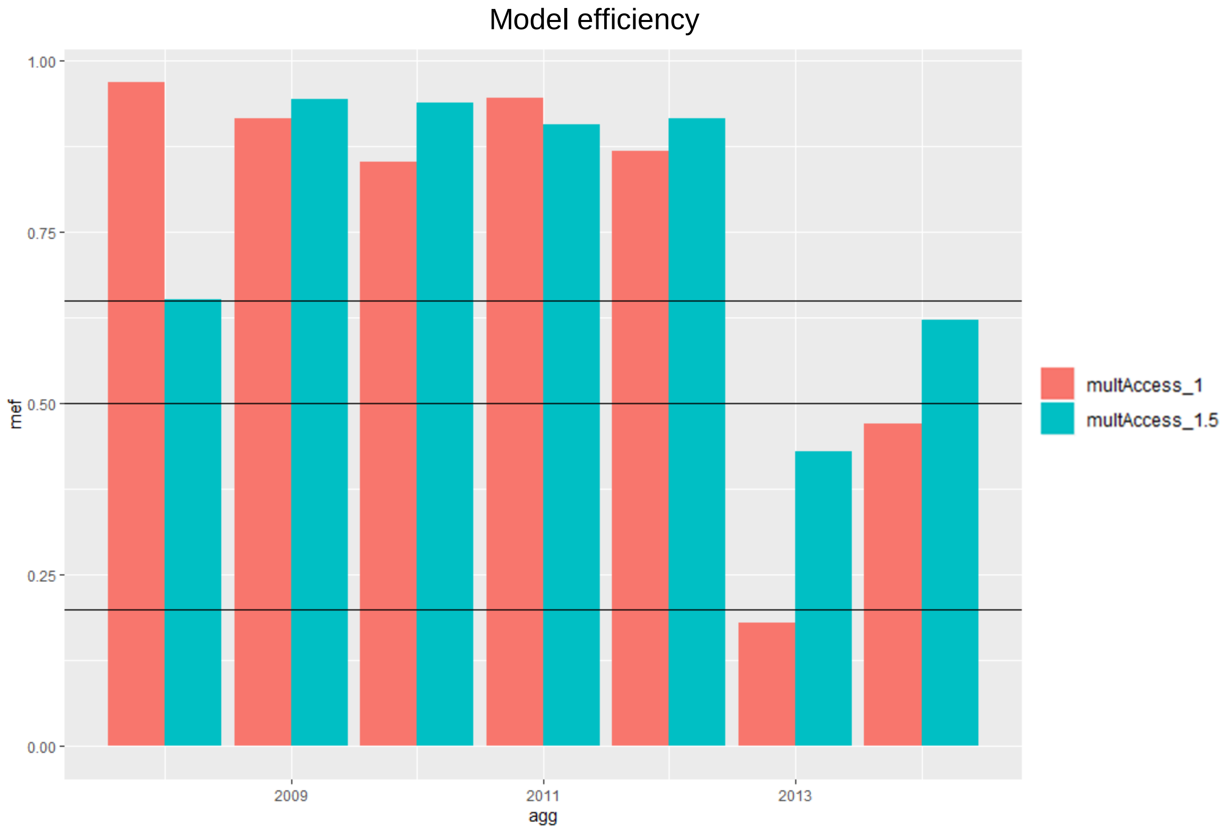
**Catch**

Simulated vs. Observed

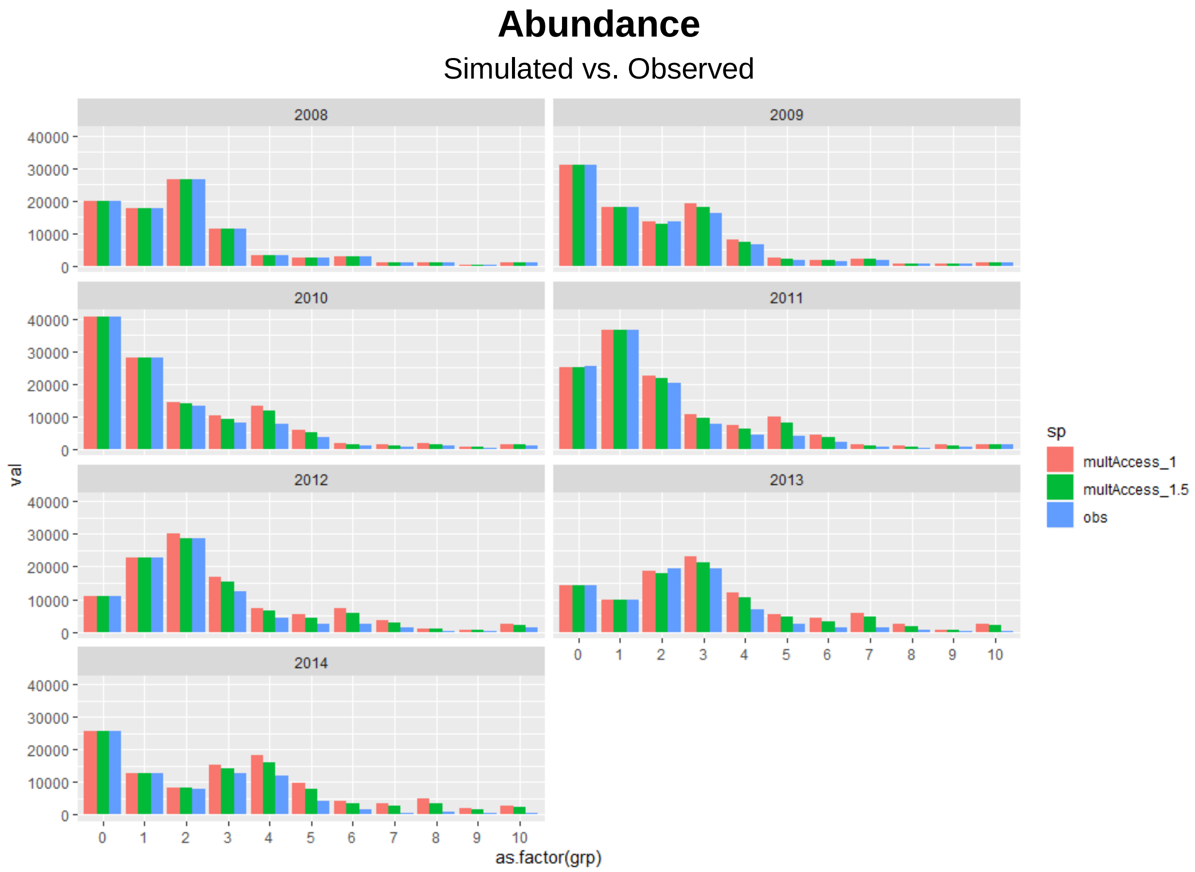


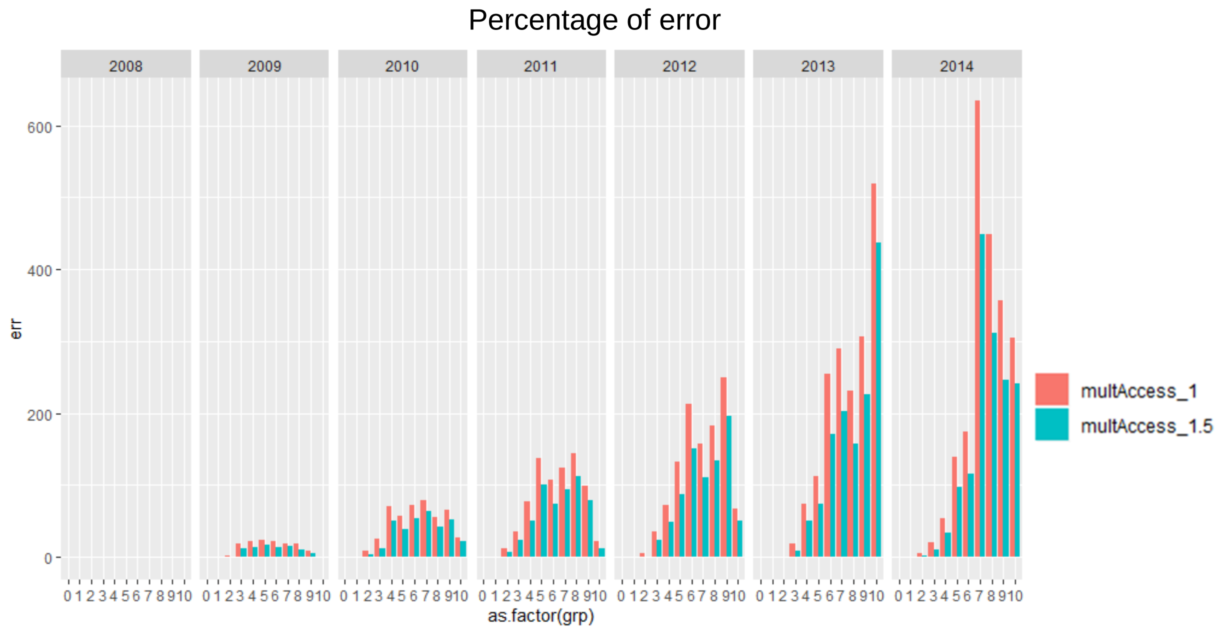

Percentage of error

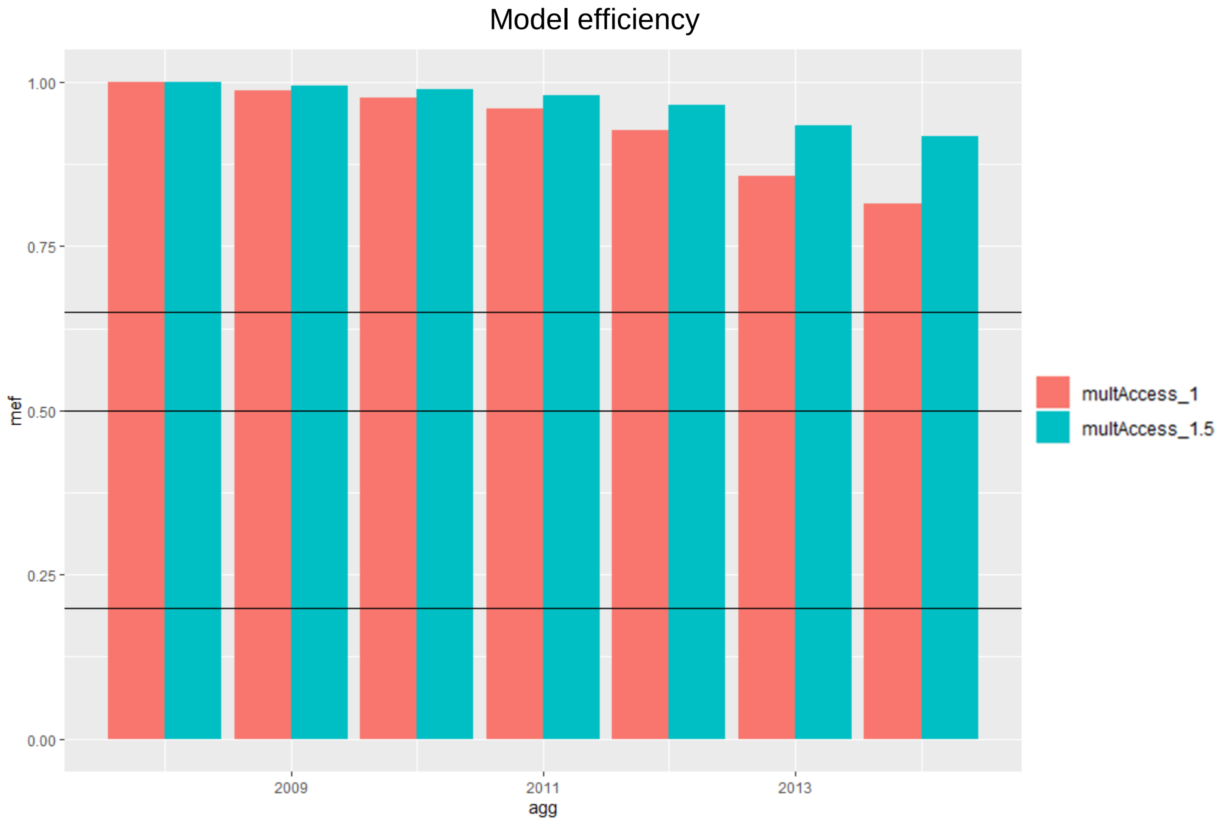




Model efficiency
1.00
0.75
0.50
0.25
0.00
mef
2009
2011
2013
agg
multAccess_1
multAccess_1.5


Abundance
Simulated vs. Observed
2008
2009
2010
2011
2012
2013
2014
40000
30000
20000
10000
0
val
0 1 2 3 4 5 6 7 8 9 10
as.factor(grp)
sp
multAccess_1
multAccess_1.5
obs


Percentage of error
2008
2009
2010
2011
2012
2013
2014
600
400
200
0
err
0 1 2 3 4 5 6 7 8 9 10
as.factor(grp)
multAccess_1
multAccess_1.5



Model efficiency
1.00
0.75
0.50
0.25
0.00
mef
2009
2011
2013
agg
multAccess_1
multAccess_1.5

**Appendix VI:** Strategies described in the model, with indication of their main gear, home harbour, vessel length class, average number of boats participating over the period 2008-2010, estimated technical efficiency and availability of VMS data (Lehuta et al., 2015).

| IFR-Fleet | Harbor | Vessel size | Average number of boats (2008-2010) | Technical efficiency | VMS |
|---|---|---|---|---|---|
| **Bottom trawlers** | Normandy | <12m | 16 | 0.081 | no |
| **Bottom trawlers** | Normandy | 18-40m | 17 | 0.013 | yes |
| **Bottom trawlers** | North | 18-40m | 15 | 0.024 | yes |
| **Mixed trawlers** | Normandy | 18-40m | 7 | 0.02 | yes |
| **Mixed trawlers** | North | 18-24m | 11 | 0.021 | yes |
| **Mixed trawlers** | North | 24-40m | 8 | 0.024 | yes |
| **Dredgers-trawlers** | Normandy | <10m | 9 | 0.054 | no |
| **Dredgers-trawlers** | Normandy | 10-12m | 50 | 0.056 | no |
| **Dredgers-trawlers** | Normandy | 12-18m | 103 | 0.041 | yes |
| **Dredgers-trawlers** | Normandy | 18-24m | 5 | 0.04 | yes |
| **Dredgers-trawlers** | North | 10-12 | 14 | 0.109 | yes |
| **Dredgers-trawlers** | North | 12-18m | 9 | 0.034 | yes |
| **Netters** | Normandy | <10m | 22 | 0.009 | no |
| **Netters** | Normandy | 10-12m | 12 | 0.012 | no |
| **Netters** | North | <10m | 7 | 0.009 | no |
| **Netters** | North | 10-12m | 51 | 0.04 | no |
| **Netters** | North | 12-18m | 12 | 0.027 | yes |

**Appendix VII:** Estimates of the parameters of effort standardization (gear:species) (Lehuta et al., 2015).

| | CuttleFish | Red mullet | Plaice | Scallops | Sole | Squid |
|---|---|---|---|---|---|---|
| **Dredge** | 29.7 | 4.3 | 55.5 | 15230.6 | 60.2 | 32.5 |
| **Gillnet** | 61.5 | 403.3 | 110.0 | 0.0 | 716.8 | 2.0 |
| **Trammel net** | 254.9 | 24.3 | 670.4 | 1.2 | 2898.8 | 0.0 |
| **Bottom trawl** | 590.8 | 346.2 | 279.8 | 340.4 | 133.4 | 1365.9 |
| **Beam trawl** | 190.8 | 8.0 | 613.3 | 1130.4 | 991.0 | 0.0 |

**Appendix VIII:** Fishing mortality vector of other fleets (a.) and proportion of catch of other fleets per quarter and per sub-area (b.).

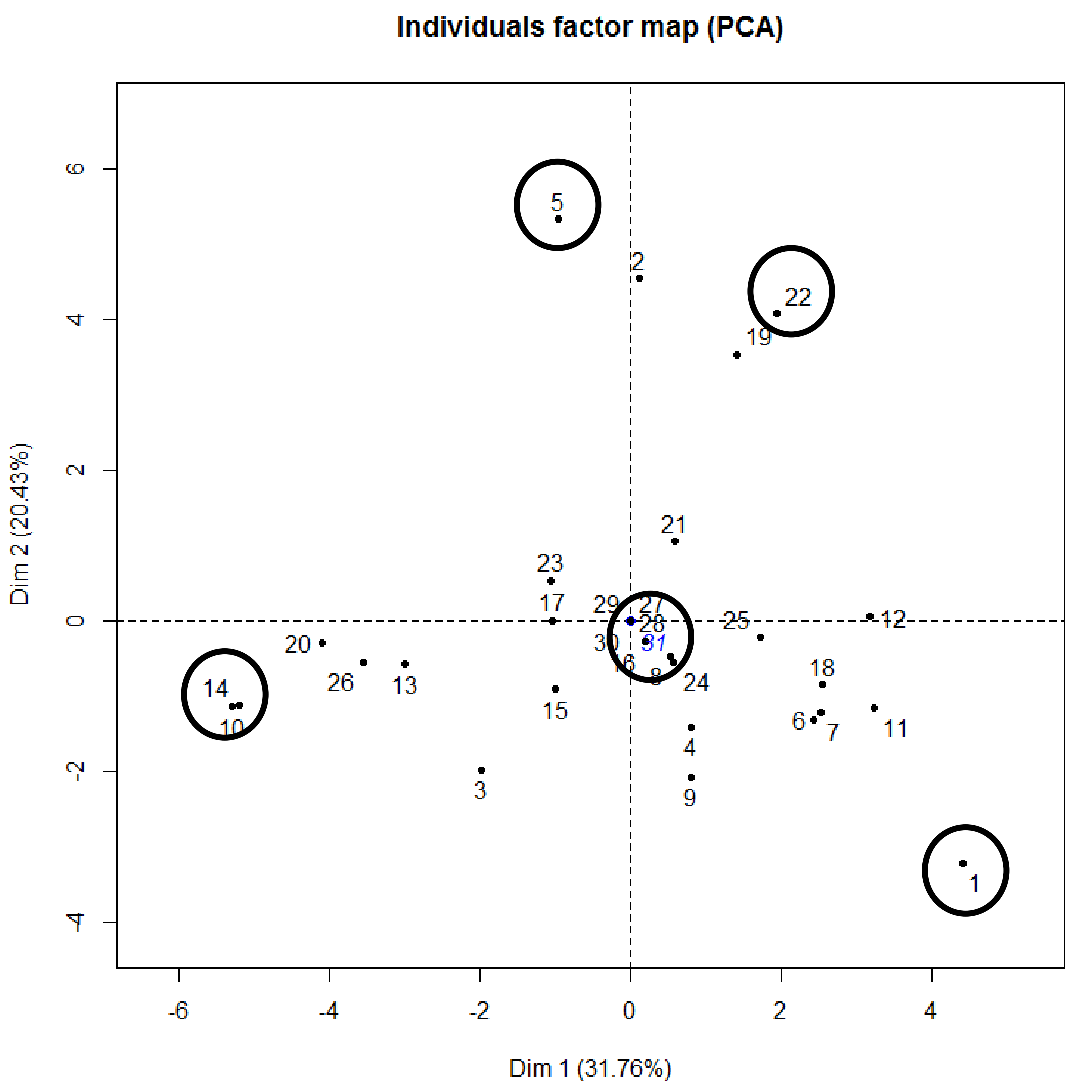
a.

| Age 1 | Age 2 | Age 3 | Age 4 | Age 5 | Age 6 | Age 7 | Age 8 | Age 9 | Age 10 | Age 11 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.003 | 0.088 | 0.295 | 0.33 | 0.332 | 0.326 | 0.342 | 0.274 | 0.297 | 0.303 | 0.303 |

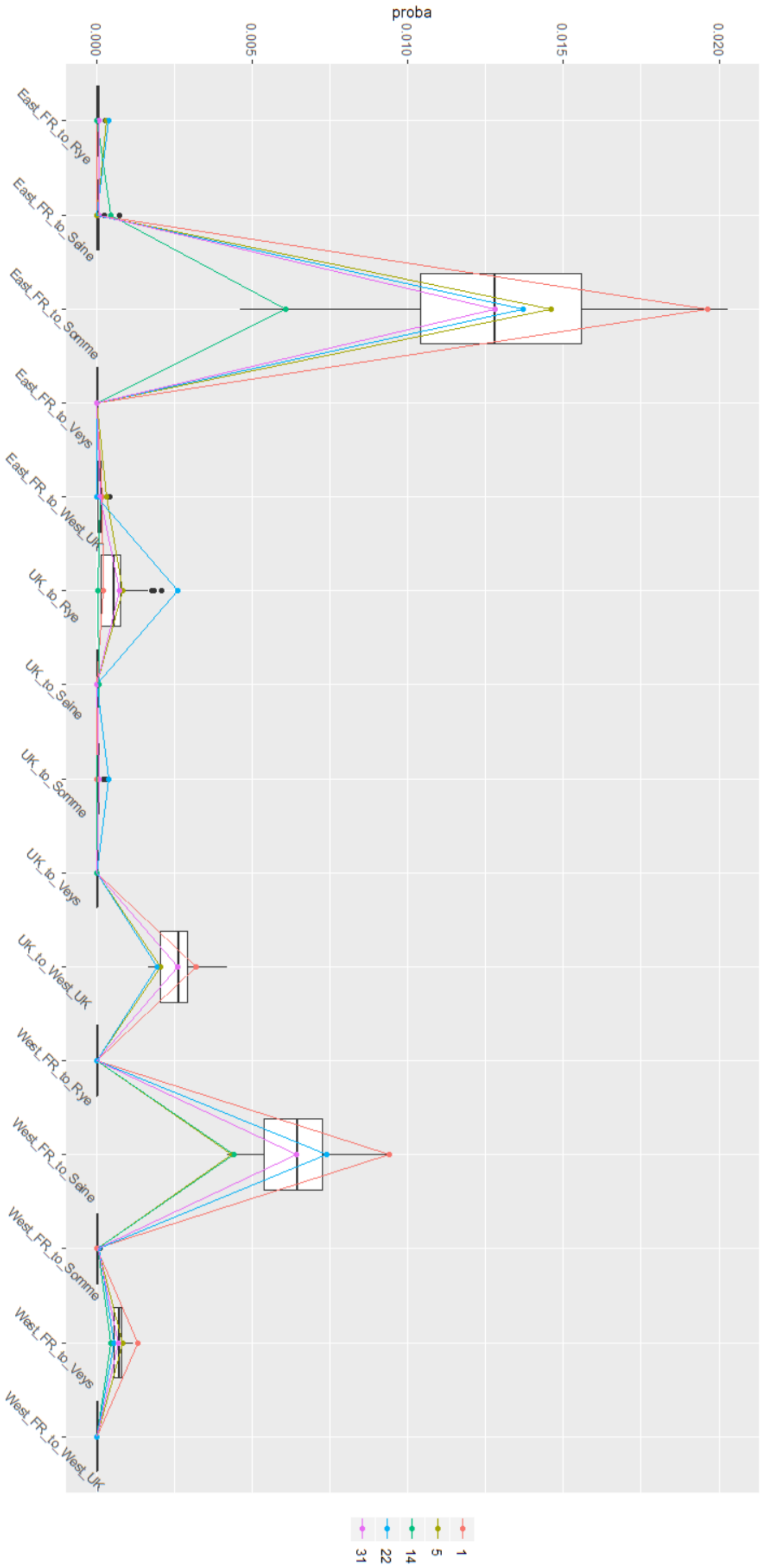
b.

| | 1st quarter | 2nd quarter | 3rd quarter | 4th quarter |
|---|---|---|---|---|
| EastFR | 0.043 | 0.023 | 0.018 | 0.043 |
| UK | 0.260 | 0.153 | 0.154 | 0.197 |
| WestFR | 0.080 | 0.016 | 0.004 | 0.009 |

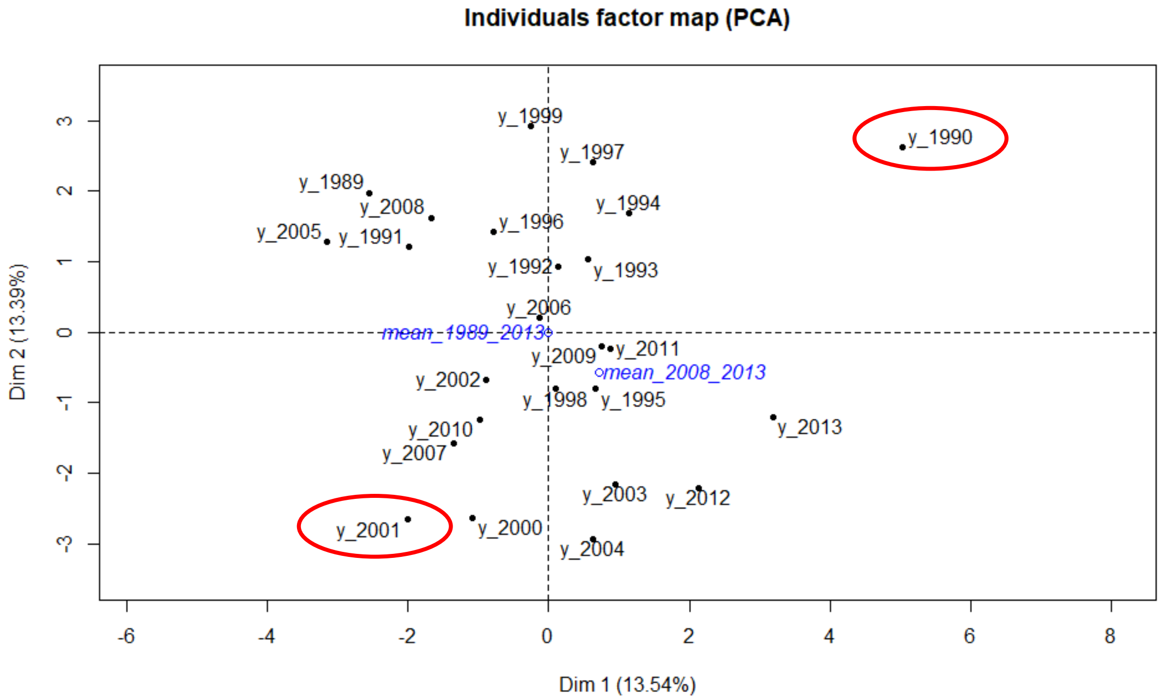
**Appendix IX:** Choice of larval drift scenarios




| | Variable : Probability for an egg to reach nursery i knowing it was spawned in sub-area r. |
|---|---|
| Individuals<br>Years | |

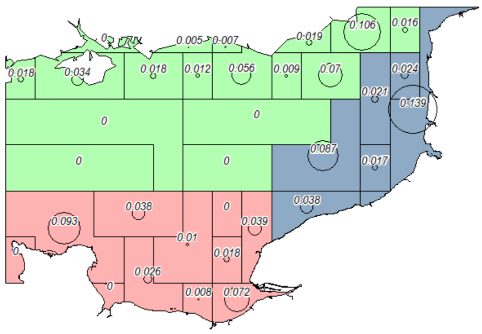

proba
0.000
0.005
0.010
0.015
0.020
East_FR_to_Rye
East_FR_to_Seine
East_FR_to_Somme
East_FR_to_Veys
East_FR_to_West_UK
UK_to_Rye
UK_to_Seine
UK_to_Somme
UK_to_Veys
UK_to_West_UK
West_FR_to_Rye
West_FR_to_Seine
West_FR_to_Somme
West_FR_to_Veys
West_FR_to_West_UK
1
5
14
22
31

**Appendix X:** Alternative scenarios for soles distribution.

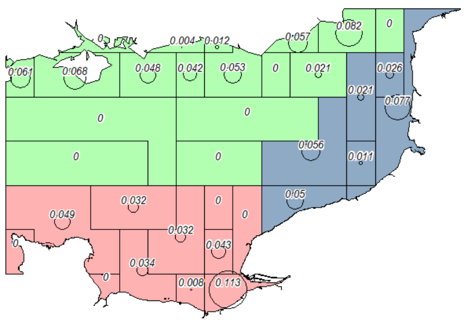



| | Variable : Proportion in ISIS polygons |
|---|---|
| Individuals<br>Years | |

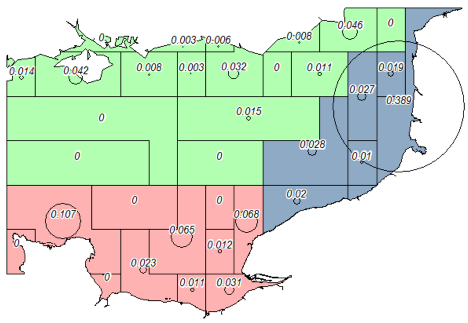
Sole distribution in ISIS polygons (base case)



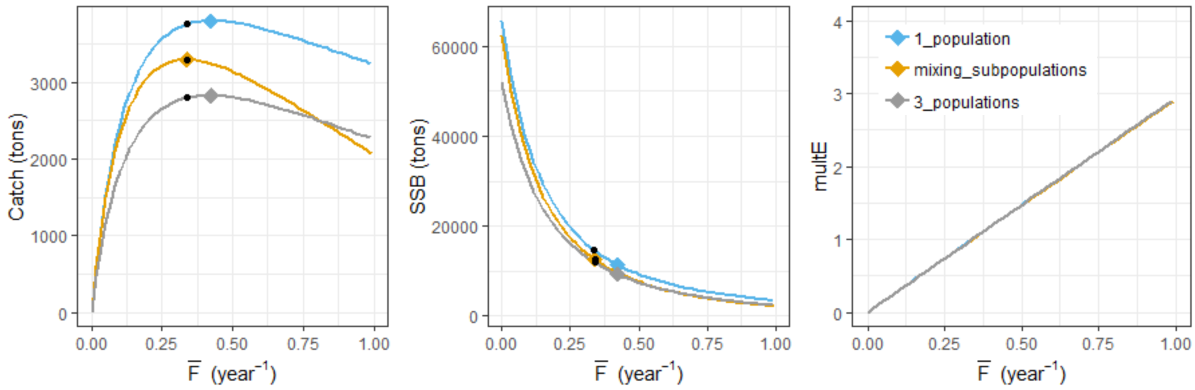
Sole distribution in ISIS polygons (1990)



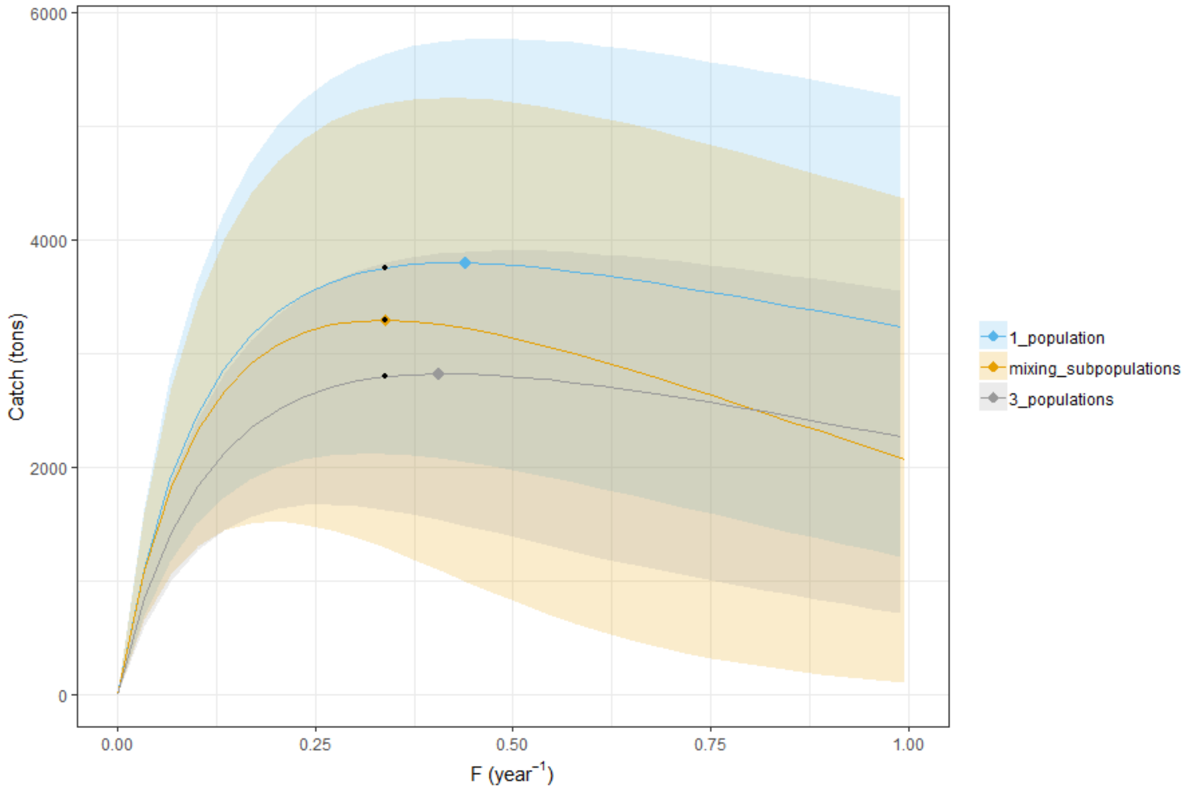
Sole distribution in ISIS polygons (2001)

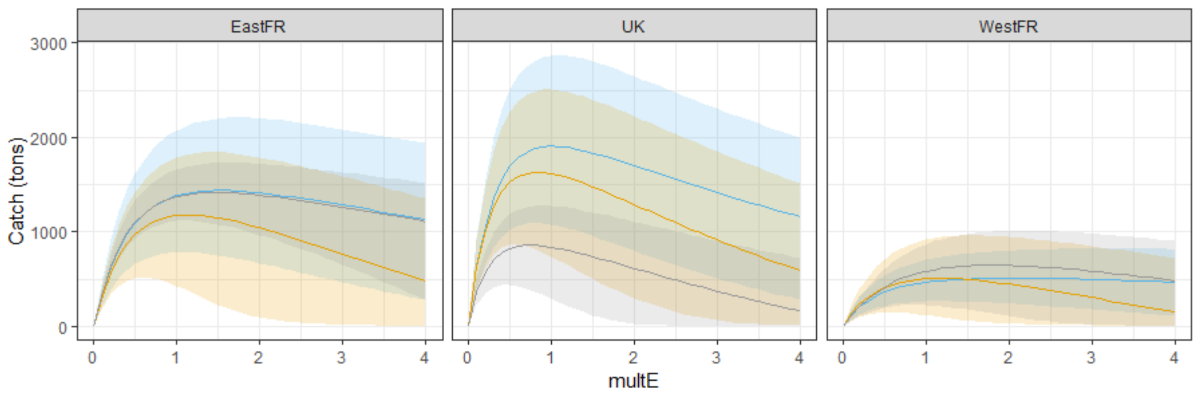


**Appendix XI:** Long term catch (a.), SSB (b.) and effort multiplier (c.) as a function of fishing mortality at the scale of area VIId.

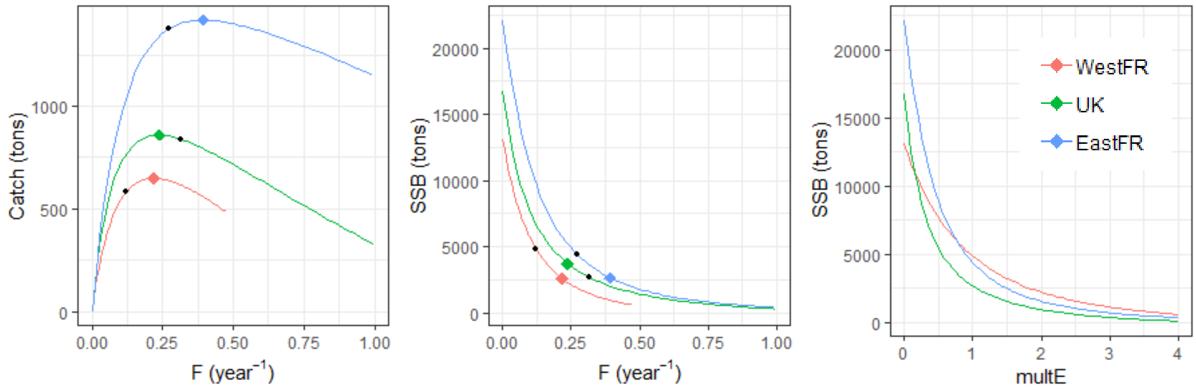


**Appendix XII:** long-term catch with related uncertainty range at the scale of area VIId and at the scale of subdivisions.

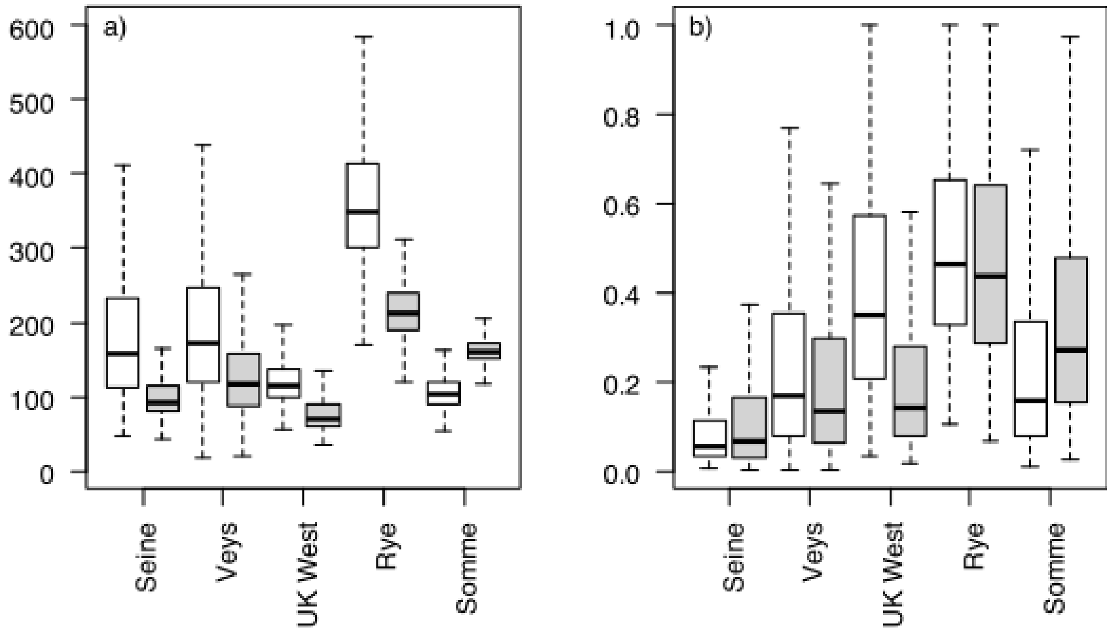


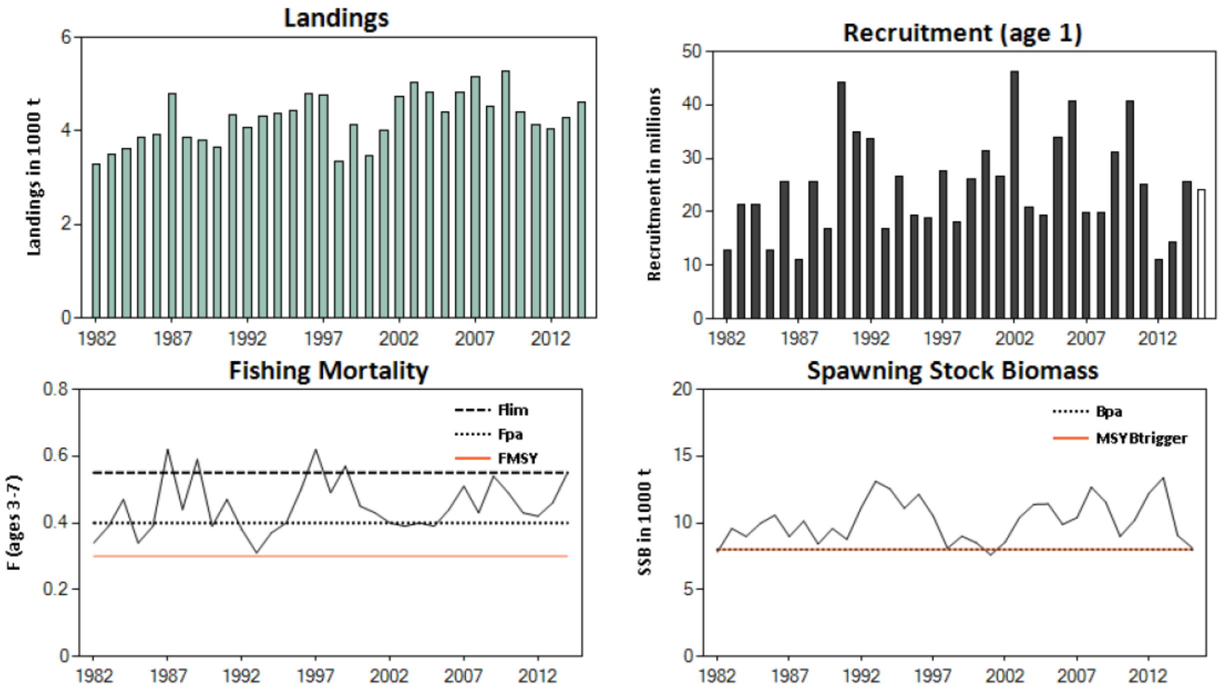
**Appendix XIII:** local equilibrium curves for model “3_populations”



**Appendix XIV:** Marginal posterior distributions of the nursery-specific Beverton-Holt parameters $K$ (a) and $\alpha$ (b) obtained with the model considering one homogeneous adult population (white) and with the model considering three isolated subpopulations (gray). $K$ is in thousands of fish per km$^2$. $\alpha$ is a maximum survival rate. (Archambault et al., 2016).



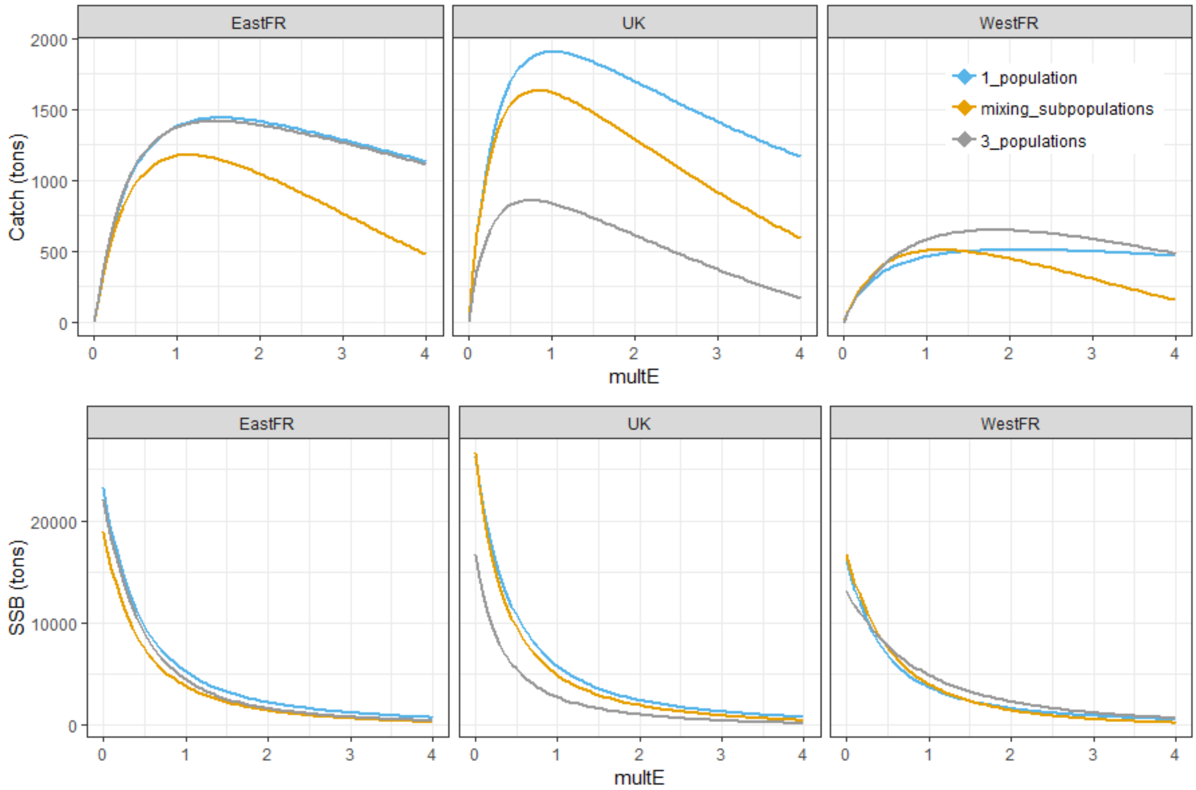
**Appendix XV:** Sole in Division VIId. Summary of stock assessment (weights in thousand tonnes). Assumed values are not shaded.



**Appendix XVI:** Table of estimates of fish movement probabilities between seasons (Lecomte et al., 2019). bold: migration rates between and adjacent zones.

| From | To | Spawning - Foraging | Foraging - Overwintering | Overwintering - spawning |
|---|---|---|---|---|
| WC | WC | 0.99 | 0.94 | 1.00 |
| WC | UK | 0.00 | **0.06** | 0.00 |
| WC | FrW | **0.01** | 0.00 | 0.00 |
| WC | FrE | 0.00 | 0.00 | 0.00 |
| WC | NS | 0.00 | 0.00 | 0.00 |
| UK | WC | **0.04** | 0.00 | **0.15** |
| UK | UK | 0.96 | 1.00 | 0.79 |
| UK | FrW | 0.00 | 0.00 | 0.00 |
| UK | FrE | 0.00 | 0.00 | 0.00 |
| UK | NS | 0.00 | 0.00 | **0.06** |
| FrW | WC | **0.22** | 0.00 | 0.00 |
| FrW | UK | 0.00 | 0.00 | **0.02** |
| FrW | FrW | 0.76 | 0.98 | 0.98 |
| FrW | FrE | **0.03** | 0.00 | 0.00 |
| FrW | NS | 0.00 | **0.02** | 0.00 |
| FrE | WC | 0.00 | 0.00 | 0.00 |
| FrE | UK | 0.00 | **0.04** | 0.00 |
| FrE | FrW | 0.00 | **0.05** | 0.00 |
| FrE | FrE | 1.00 | 0.91 | 0.84 |
| FrE | NS | 0.00 | 0.00 | **0.16** |
| NS | WC | 0.00 | 0.00 | 0.00 |
| NS | UK | **0.06** | **0.02** | 0.00 |
| NS | FrW | 0.00 | 0.00 | 0.00 |
| NS | FrE | **0.03** | 0.00 | 0.00 |
| NS | NS | 0.91 | 0.98 | 1.00 |

**Appendix XVII:** Long term catch and SSB at the scale of subdivisions.



**Appendix XX:** Bibliographic synthesis - The MSE approach: Generalities and a focus on spatial structure issues.

# Synthèse bibliographique :

## L'approche MSE (Management Strategy Evaluation)

Généralités et focus sur la structure spatiale.

## Table des matières



Baptiste Alglave – Avril 2019

# I. Quelques généralités

## A. La théorie MSE (Management strategy evaluation)

**Pourquoi l'approche MSE ?**

L'approche MSE est une méthodologie basée sur la simulation de pêcherie qui a été théorisée dans les années 1990-2000 en réponse aux limites du système de gestion classique basée sur l'évaluation des stocks et l'application de TAC (Smith, 1994 ; Holland, 2010). En effet, le manque de connaissances sur la dynamique des populations rend leur gestion difficile. L'incertitude sur la croissance des individus, sur la composition des stocks, sur leur structure spatiale et la stochasticité des processus tel que le recrutement font que même les évaluations où la donnée est disponible sont incertaines. Fixer des TAC en se basant sur les projections de ces modèles paraît donc hasardeux. D'autre part, l'approche de précaution préconisée par la FAO (i.e. le maintien de la biomasse au-dessus d'un seuil permettant le renouvellement du stock et les captures au RMD) est plus une règle de gestion générique et ad-hoc qu'une règle de gestion robuste à l'incertitude permettant effectivement de réduire les risques de surpêche. D'où la nécessité de disposer d'un cadre de travail intégrant l'incertitude et permettant d'évaluer des règles de gestion alternatives possiblement plus robustes à l'incertitude.

**Définition de l'approche MSE et objectifs**

L'approche MSE vise à évaluer des stratégies de gestion en adoptant une approche par simulation. Les pêcheries sont modélisées avec un modèle opératoire dans lequel des stratégies de gestion sont implémentées puis évaluées à l'aide de critères de performance précis (Smith, 1994 ; Punt et al., 2001 ; Punt, 2015).

Punt et al. (2001) définissent ainsi 4 objectifs propres à l'approche MSE. Ils peuvent être formulés sous la forme de 4 questions :

- Quelles stratégies permettent d'atteindre les objectifs de gestion ? Quels sont les compromis associés à chaque stratégie au regard des objectifs de gestion (i.e. pour chaque stratégie, dans quelle mesure les objectifs sont-ils atteints) ?
- Les évaluations de stocks fournissent-elles des estimations fiables des grandeurs d'intérêts (biomasse, recrutement, mortalité par pêche) utilisées dans la gestion ?
- Les critères de performances détectent-ils les phénomènes qu'ils sont censés identifier ?
- Les programmes de recherches sont-ils bénéfiques et à quel point ?

Le premier objectif est toutefois le cœur de la problématique et la plupart des cas d'études se contentent de répondre à cette question.

**L'incertitude dans les modèles**

Smith (1994) identifie 6 classes d'incertitudes qui devraient explicitement être prises en compte dans les cas d'étude :

- les erreurs de spécification des paramètres (ex : la mortalité naturelle)
- la variabilité des processus (ex : la variabilité du recrutement)

- les erreurs d'observations (ex : erreur d'échantillonnage, erreur d'estimation de l'âge)
- les biais dans les estimateurs
- le manque de contraste dans les données (captures et effort)
- l'incapacité à implémenter les mesures de gestion.

En intégrant du bruit au modèle et en faisant varier les paramètres dans leur domaine d'incertitude, il est possible d'explorer l'incertitude associée aux mesures de gestion et de déterminer quelles sont les mesures les plus robustes à l'incertitude. Toutefois, les auteurs se restreignent généralement à l'étude de l'incertitude sur quelques paramètres clés des modèles (Cf. conclusion sur les cas d'étude).

**La modélisation des mesures de gestion nécessitant une évaluation de stock**

L'approche de précaution préconisée par la FAO passe nécessairement par une évaluation de stock. Pour modéliser ce processus, la méthode utilisée consiste à coupler un modèle d'évaluation à l'OM et à évaluer le stock du modèle opératoire. C'est ce qui est plus couramment appelé "boucle MSE" (Punt et al., 2001 ; Punt et al., 2016a – Figure 1). Elle peut être résumée en 4 étapes :
- Génération des données nécessaires à l'évaluation de stock à partir de l'OM.
- Évaluation du stock à partir du modèle d'évaluation.
- Fixation du TAC pour l'année suivante sur la base de la règle de gestion (HCR).
- Implémentation du TAC dans l'OM.

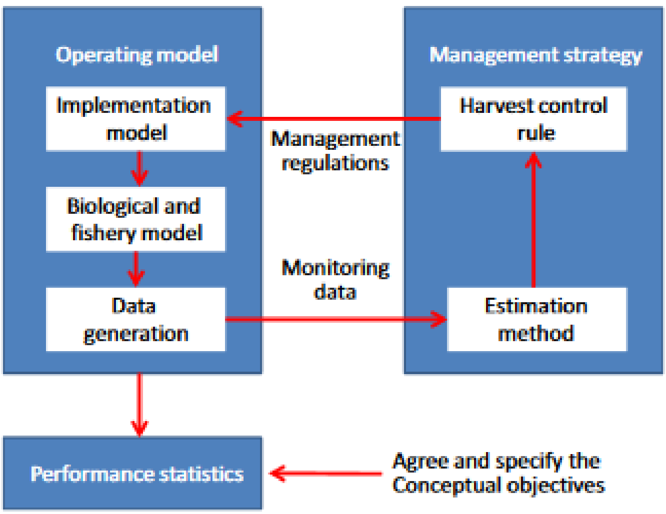



Figure 1 : Diagramme conceptuel d'une boucle MSE (Punt et al., 2016a)

**Les bonnes pratiques MSE**

De nombreux articles traitent des bonnes pratiques pour la construction d'une MSE et pour l'analyse et la présentation des résultats issus du processus de modélisation (Marasco et al., 2007 ; Levin et al., 2013 ; Punt, 2015 ; Punt et al., 2016a). Punt (2015) souligne notamment l'importance de définir clairement les objectifs de gestion et les stratégies à évaluer. Ce travail devrait être fait en collaboration avec les acteurs notamment parce qu'il permet de clarifier pour eux aussi les objectifs de gestion. D'autre part, il propose une batterie de mesures de performance en vue d'estimer les effets de chaque mesure de gestion au regard des objectifs définis au préalable. Ces critères de performance ne doivent pas être trop nombreux et ils doivent être présentés à travers des graphes synthétiques intégrant l'incertitude en vue de leur utilisation dans la prise de décision.

Le processus de décision fait donc nécessairement interagir scientifiques et gestionnaires dans le but d'identifier des stratégies de gestion robustes à l'incertitude et de quantifier leurs performances au regard d'objectifs bien définis. Cela dans le but de fournir les informations nécessaires aux gestionnaires pour qu'ils sélectionnent une stratégie de gestion.

## B. Les cas d'application MSE

L'annexe liste les quelques cas d'applications de l'approche MSE qui ont permis de réaliser cette synthèse. Le paragraphe qui suit cherche à synthétiser quelques traits communs et quelques différences notables des différents cas d'étude.

Chaque cas d'application a comme dénominateur commun la simulation de règles de gestion. Pour le reste, chaque cas d'étude vise à répondre à une problématique précise pour un système particulier. En d'autres termes, il existe une grande diversité de cas d'application MSE qui diffèrent soit par les mesures de gestion implémentées soit par les modèles opératoires utilisés (espèces intégrées aux modèles, complexité des modèles, etc.).

Ainsi, certains cas d'étude se limitent à évaluer des règles de gestion avec un simple modèle monospécifique, tout en prenant en compte les incertitudes sur certains paramètres clés tel que le recrutement, là où d'autres modèles intègrent des processus écologiques, économiques, etc. ainsi que la dimension spatiale des pêcheries. Ces modèles plus complexes permettent d'évaluer des mesures de gestion alternatives - AMP, fermetures saisonnières, règles de gestion spatialisées, etc. – au regard de critères de performance plus diversifiés – critères économiques, écologiques, etc.

# II. La structure spatiale, la connectivité et les mouvements de population dans l'approche MSE

## A. Modéliser la structure spatiale d'une population dans un modèle opératoire

La structure spatiale des stocks et la connectivité des populations peuvent avoir un impact sur l'évaluation et la gestion des ressources aquatiques. De nombreux travaux de modélisation ont démontré que si un modèle d'évaluation n'est pas consistant avec la structure du stock alors les sorties ainsi que les niveaux de référence obtenus par ces modèles sont biaisés (Guan et al., 2013 ; Goethel and Berger, 2017 ; Cadrin et al., 2018, Punt, 2019). Ce biais est d'autant plus prononcé que les patterns d'exploitation et la dynamique des sous-populations sont contrastés (Cope and Punt, 2011). Cela peut provoquer la surexploitation de certains segments du stock et à l'inverse la sous-exploitation d'autres segments (Goethel et al., 2016) ce qui peut conduire à la diminution de la résilience, de la stabilité et de la productivité du stock.

D'où la nécessité de les prendre en compte dans les approches de types MSE. Kerr et Goethel (2014) distinguent 4 grands types de structure de population (Figure 2) :

- (a) la population unique n'étant pas distribuée uniformément sur toute la zone.
- (b) les populations complètement isolées entre elles.
- (c) les populations chevauchantes une partie de l'année et isolées le reste de l'année. C'est le cas des espèces migratrices partageant la même aire d'alimentation et présentant un comportement de homing.
- (d) la métapopulation où les sous-populations sont connectées, mais ne présentent aucune fidélité à une aire de reproduction particulière.

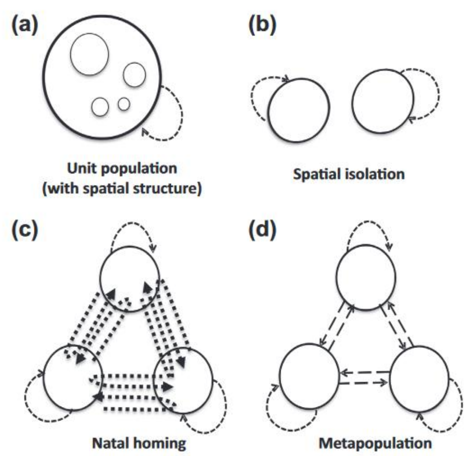



Figure 2 : Les grands catégories de structure de population (Kerr et Goethel, 2014)

Pour modéliser la structure et la connectivité des populations, 3 éléments doivent être intégrés aux modèles opératoires (Goethel et al., 2011 ; Kerr and Goethel, 2014) :

- l'hétérogénéité spatiale : elle peut être modélisée soit en disposant de données de campagne pour chaque zone, soit à l'aide de modèles d'habitat, soit en répartissant la biomasse d'une zone dans des zones plus petites sur la base d'un indice d'abondance.

- le degré d'isolement reproducteur : il est modélisé à travers le recrutement. Soit la connectivité est importante aux jeunes stades et on ne peut associer zones de ponte et productivité d'une sous-population. Le recrutement est alors simulé de façon unique pour l'ensemble des sous-populations. Soit l'isolement reproducteur est important. La connectivité est faible lors de la période de reproduction pour les stades adultes comme pour les jeunes stades (isolation hydrodynamique) et les productivités de chaque sous-population sont indépendantes. Dans ce cas, le recrutement est modélisé de façon indépendant pour chaque sous-unité.
- les mouvements des individus : ceux-ci sont d'autant plus complexes à modéliser qu'ils varient selon les stades de vie. Des modèles individu centré (IBM - individual-based model) associés à des modèles hydrodynamiques permettent de modéliser le phénomène de ponte et la dérive larvaire. Le but de ce type de modèle est de simuler de façon plus réaliste le recrutement dans le temps et l'espace et d'estimer le parcours des œufs et des larves. Aux stades adultes, les mouvements peuvent être modélisés par des modèles lagrangiens. Dans ces modèles, on fait l'hypothèse que les individus se déplacent dans le temps et l'espace en réponse à des variables environnementales (facteurs biotiques comme la nourriture ou abiotiques comme la température). Les mouvements peuvent également être modélisés à l'aide de modèles eulériens. Dans ce cas, les mouvements sont représentés par des flux entre stocks et entre frontières géographiques via des coefficients de transferts (i.e. des probabilités de mouvements entre les différents stocks et les différentes régions).

## B. Quelques cas d'application prenant en compte la structure spatiale des populations

Dans certains cas MSE, la structure spatiale est décrite uniquement par souci de réalisme et elle n'est pas au cœur de la problématique (Dichmont et al., 2008 ; Little et al., 2009 ; Marchal and Vermard, 2013 ; Kuykendall, 2015 ; Smith et al., 2015 ; Punt et al., 2016c). Dans d'autres cas, la dimension spatiale des pêcheries permet de simuler des règles de gestion alternatives comme des AMP (Little et al., 2005 ; Mapstone et al., 2008 ; Bastardie et al., 2009). Dans d'autres cas encore, la dimension spatiale peut être utilisée pour quantifier la performance de mesures de gestion dans un contexte d'incertitude quant à la structure du stock (Fay et al., 2011 ; Ying et al., 2011 ; Hintzen et al., 2014). Les paragraphes qui suivent cherchent à résumer les articles qui correspondent à ce dernier cas de figure.

### 1. L'impact de l'incertitude de la structure spatiale sur la performance de différents HCR pour le rouffe antarctique (Fay et al., 2011)

Le rouffe antarctique (*Hyperoglyphe antarctica* ; Carmichael, 1819) est une espèce à haute valeur marchande exploitée dans le sud-est de l'Australie. Il est géré comme un seul stock malgré des incertitudes sur la structure de la population. D'autre part, la règle de gestion actuelle est basée sur une approche data-poor où une estimation de la mortalité par pêche suffit pour calculer un TAC. Pour autant, cette règle de gestion n'a pas été testée avant implémentation. L'objectif de Fay et al. (2011) est donc d'évaluer différentes HCR pour différentes hypothèses sur la connectivité entre les sous-populations. Fay et al. (2011) ont construit 2 modèles différents : (1) un modèle avec une population occupant une seule région et exploitée par une seule flottille, (2) un modèle avec une population occupant deux régions avec des mouvements entre les sous-populations. La population peut être exploitée par une ou deux flottilles différentes. Pour tester différentes stratégies de gestion dans un contexte spatialisé, les TAC sont calculées :

- (1) soit en ignorant la structure spatiale de la population et en agrégeant les données pour les deux régions.
- (2) soit en estimant une mortalité par pêche pour chaque zone, en pondérant ces estimations par l'inverse de leur variance et en les combinant pour obtenir un F unique pour toute la zone.
- (3) soit en utilisant le F maximal entre les deux zones dans la règle de gestion.

La troisième option est l'approche la plus précautionneuse, toutefois elle peut conduire à des TAC inutilement bas lorsque la connectivité est élevée. Cette étude si elle prend en compte la dimension spatiale de la pêcherie dans le calcul des TAC ne pousse pas l'analyse jusqu'à implémenter des TAC spatialisés. C'est pourtant une stratégie de gestion que les auteurs mentionnent et préconisent.

2. Le risque d'ignorer la structure spatiale des populations dans la gestion des stocks (Ying et al., 2011).

Ying et al. (2011) étudient l'effet de 3 modèles d'évaluation sur la gestion de la métapopulation de *Larimichthys polyactis* en mer de Chine (Figure 3) :

(1) soit le modèle d'évaluation considère qu'il y a des échanges entre les 3 trois sous-populations. L'évaluation est consistante avec la structure de la métapopulation.

(2) soit l'évaluation considère qu'il n'y a pas d'échange entre les 3 sous-populations.

(3) soit l'évaluation considère qu'il n'y a qu'une seule population homogène.

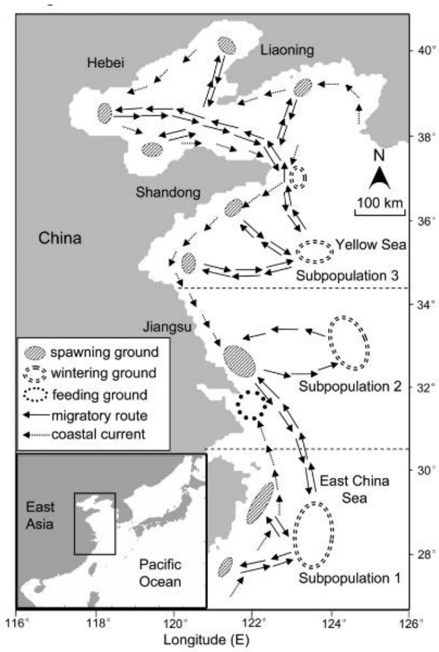



Figure 3 : Dynamique spatiale de la métapopulation de *Larimichthys polyactis* en mer de Chine (Ying et al., 2011)

Dans tous les cas, les modèles d'évaluation de stocks sont des modèles de production ce qui facilite considérablement le calcul des niveaux de référence. Lorsque les échanges sont pris en compte dans l'évaluation, le calcul du TAC est plus complexe, mais les équations admettent une solution analytique et le TAC dépend des échanges entre les sous-populations et de la biomasse dans les zones adjacentes.

Une mauvaise définition de la structure spatiale de la population dans l'évaluation du stock peut mener à l'estimation de paramètres biaisés et donc à un diagnostic d'exploitation erroné. Les niveaux de référence et les niveaux de captures qui en résultent peuvent être eux-mêmes biaisés et peuvent conduire à la surexploitation de certains segments de la population.

3. La gestion d'une population structurée dans l'espace : l'effet d'informations provenant de données indépendantes des pêcheries (Hintzen et al., 2015).

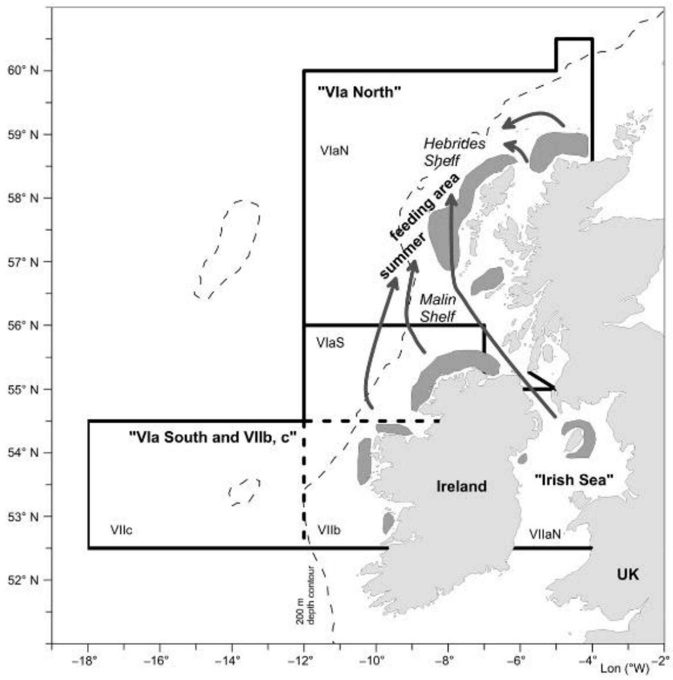



Figure 4 : Migration des stocks de harengs de l'Atlantique des zones VIaN, VIaS/VIIb,c et VIIaN modélisée par Hintzen et al. (2015)

La population de hareng (*Clupea harengus*, Linnaeus 1758) de l'Atlantique des zones VIaN, VIaS/VIIb,c et VIIaN est composée de 3 sous-populations migrant en été et partageant alors la même aire de répartition (Figure 4). Ces trois sous-populations sont gérées comme des stocks distincts par le CIEM. Toutefois, les captures sont constituées d'individus provenant des trois stocks et actuellement les campagnes utilisées pour calculer des indices d'abondance ne réattribuent pas les individus échantillonnés à leurs sous-populations respectives. Le mélange entre les populations n'est donc pas pris en compte dans l'évaluation et dans la gestion des stocks. Toutefois, la campagne 'Malin Shelf' existant depuis 2010 cherche à réattribuer les individus à leur sous-population respective et à fournir des indices d'abondance non biaisés pour chacun des stocks. Hintzen et al. (2015) cherche ainsi à déterminer l'effet que pourraient avoir ces indices d'abondance sur l'évaluation et la gestion du stock sous différentes hypothèses sur le mélange entre les populations, l'erreur de classification des individus et la taille des échantillons. L'évaluation et la gestion du stock ne sont que légèrement améliorées en incluant ces indices d'abondance. En effet, les sorties du modèle d'évaluation sont bien plus dépendantes des captures - qui ne sont pas corrigées - que des indices d'abondance. Hintzen et al. (2015) proposent deux solutions pour débiaiser l'évaluation des stocks :

- soit d'utiliser des modèles reposant uniquement sur des données indépendantes des pêcheries (i.e. les indices d'abondance obtenus via la survey 'Malin Shelf')
- soit de réaliser une évaluation qui soit consistante avec la structure du stock (i.e. en réallouant les captures à chaque sous-unité de la population dans un modèle d'évaluation spatialisé). Cela dans le but d'obtenir des matrices de captures aux âges non biaisés.

## C. Conclusions sur les 3 études de cas et perspectives

**Bilan des articles**

Les 3 études de cas MSE ayant une problématique centrée sur la structure spatiale traitent de 3 problèmes différents :

- L'effet de différentes HCR en fonction de la structure du stock (Cf. B.1). Dans ce cas, Fay et al. (2011) simulent différentes stratégies de gestion pour différentes hypothèses sur la connectivité. Dans ce cas, la gestion n'est pas spatialisée.
- Le risque d'ignorer la structure spatiale du stock dans la gestion (Cf. B.2). Dans ce cas, Ying et al. (2011) simulent un stock pour une seule hypothèse sur la connectivité et ils évaluent trois stratégies de gestion qui diffèrent selon les modèles d'évaluation de stock (un modèle faisant l'hypothèse de trois populations distinctes, un modèle faisant l'hypothèse d'une seule population homogène, et un modèle consistant avec la structure 'réelle' du stock). Dans ce cas, les auteurs gèrent les stocks de façon spatialisée ce qui est facilité par la simplicité du modèle employé.
- L'effet que peuvent avoir des données de campagne sur l'évaluation de plusieurs stocks présentant des échanges entre eux (Cf. B.3). Hintzen et al. (2015) modélisent ainsi plusieurs sous-populations se mélangeant et étudient l'effet d'indices d'abondances débiaisés sur l'évaluation et la gestion des stocks suivant différentes hypothèses sur le taux de mélanges et les caractéristiques des survey.

**L'analyse d'incertitude dans les cas d'étude**

Dans les 3 cas précédents, l'analyse d'incertitude se fait en incorporant du bruit soit au niveau des survey, soit au niveau de processus biologiques et en faisant varier des paramètres précis dans le modèle (i.e. analyse par scénarios). Les paramètres en question sont systématiquement reliés à la problématique d'étude. D'autres paramètres sont très incertains voir sont fixés de façon arbitraire, mais ne sont pas inclus dans l'analyse d'incertitude.

**Perspectives**

Aujourd'hui, à notre connaissance, aucun cas d'application MSE hormis l'étude de Ying et al. (2011) n'a cherché à évaluer de HCR spatialisées. Goethel et al. (2016) font le même constat et montrent qu'il existe des modèles d'évaluation permettant le calcul de niveaux de référence nécessaires à la formulation de ces HCR (Haddon et al., 2005 ; Kerr et al., 2014 ; Plaganyi et al., 2014 ; Goethel et al., 2014 ; Punt et al., 2015 ; Goethel et al., 2016 ; Punt et al., 2016b ; Punt et al., 2018 ; Punt et al., 2019). Ces travaux pourraient servir de base pour construire des HCR spatialisées afin de les utiliser comme stratégie alternative dans notre cas étude.

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Titre français : Évaluation de stratégie de gestion pour la sole de Manche Est : une approche de gestion sous-incertitude.
Titre anglais : Management Strategy Evaluation of the Eastern English Channel Common Sole: Management approach under uncertainty.

Résumé (1600 caractères maximum) :
L'évaluation de stratégie de gestion (MSE) est une approche permettant d'évaluer la performance de stratégies de gestion dans un contexte d'incertitude sur la structure spatiale des stocks. Cette approche a été appliquée au stock de sole commune de Manche Est, un stock pour lequel des indices suggèrent une forte structuration de la population entre trois zones bien qu'il subsiste des incertitudes. Trois modèles ISIS-Fish ont été paramétrés et calibrés pour rendre compte de l'incertitude sur la structure du stock : soit la connectivité au stade adulte est élevée, soit elle est partielle, soit elle est nulle. Ce travail a cherché à évaluer la stratégie de gestion actuelle pour chacune des hypothèses de connectivité. Des projections sur le long terme ont permis de tracer les courbes de captures à l'équilibre et des projections sur le court terme ont visées à évaluer la stratégie de gestion actuelle. Dans les deux cas, les simulations mettent en évidence l'effet de la structure spatiale sur la dynamique d'exploitation de la sole. Malgré le fait que les projections sur le court terme n'ont pas été concluantes, la stratégie de gestion actuelle provoque la surexploitation de la zone UK dans le cas d'une ségrégation partielle et totale et la surexploitation du stock dans le cas d'une ségrégation partielle. Des scénarios alternatifs ont montré que le recrutement ainsi que la structure du stock étaient des sources d'incertitudes importantes et que la distribution des soles devient une source d'incertitude importante à l'échelle locale. Quelques modifications des modèles ainsi qu'une meilleure connaissance de la dynamique spatio-temporelle de la sole rendrait possible une modélisation plus fine de la sole en vue de l'évaluation de la stratégie de gestion actuelle ainsi que d'autres stratégies spatialisées.

Abstract (1600 caractères maximum) :
Management Strategy Evaluation (MSE) provides a rigorous approach for evaluating management strategies in context of uncertainty on stock structure. Such methodology was applied to the common sole of the English Eastern Channel (ICES division: area VIId), a stock where evidences suggest spatial structuration of the population between 3 sub-areas but where uncertainties remain. Three ISIS-Fish models have been parameterized and calibrated to reflect uncertainty on stock structure (1 model with high connectivity among sub-areas at the adult stage, 1 with null connectivity and 1 intermediate case). This study aimed to evaluate the current management strategy under the alternative hypothesis on connectivity. Long-term projections were run for plotting equilibrium curves and short-term simulations were run for evaluating the current management strategy. Both emphasize the effect of spatial structure on exploitation dynamics. However short-term projections weren't conclusive, current management entails local over-exploitation of the UK sub-area in case of intermediate and null connectivity and global overexploitation in case of intermediate connectivity. Uncertainty scenarios point out that recruitment and spatial structure are main sources of uncertainty and that sole distribution become another source of uncertainty at the local scale. Few modifications of ISIS models and a more accurate knowledge of sole spatio-temporal dynamics may allow a finer modelling for further evaluations of the current management strategy and alternative spatial strategies.

Mots-clés : Ecologie halieutique, Modélisation halieutique, Évaluation de stratégies de gestion, Incertitudes.
Key Words: Fishery ecology, fishery modelling, Management strategy evaluation, uncertainty.

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