AGROCAMPUS OUEST

☐ **CFR Angers**

☑ **CFR Rennes**

Année universitaire : 2015 - 2016

Spécialité : **Agronome**

Spécialisation (et option éventuelle) :

Sciences Halieutiques et Aquacoles

Option REA

Mémoire de Fin d'Études

☑ d'Ingénieur de l'Institut Supérieur des Sciences agronomiques, agroalimentaires, horticoles et du paysage

☐ de Master de l'Institut Supérieur des Sciences agronomiques, agroalimentaires, horticoles et du paysage

☐ d'un autre établissement (étudiant arrivé en M2)

Spatio-temporal dynamic of the exploitation of common sole, *Solea solea*, in the Eastern English Channel

Par : Hubert DU PONTAVICE

Soutenu à Rennes, le 14/08/2016

Devant le jury composé de :

Président : Etienne RIVOT

Maître de stage : Marie SAVINA-ROLLAND et Youen VERMARD

Enseignant référent : Etienne RIVOT et Didier GASCUEL

Autres membres du jury :

Marianne ROBERT (Chercheur Ifremer Lorient)

Verena TRENKEL (Chercheur Ifremer Nantes)

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Remerciements

Je tiens, en tout premier lieu, à remercier Marie Savina-Rolland et Youen Vermard, mes encadrants de stage pour leur confiance, leur patience, leurs conseils avisée et leur accompagnement tout au long de ce stage. J'ai pris beaucoup de plaisir à partager ces 6 mois de stage avec vous tant sur le plan scientifique qu'humain. Je tiens également à vous remercier pour votre soutien et vos précieux conseils lors de ma préparation des concours des écoles doctorales.

Je tiens à remercier Paul Marchal et à Bruno Ernande pour leur disponibilité et leurs conseils tout au long de mon stage. Merci à toi Bruno d'avoir pris du temps pour moi et de m'avoir fait bénéficier de tes compétences en statistiques.

Merci également à Etienne Rivot et Didier Gascuel pour le suivi de ce stage et leurs conseils.

Un grand merci aux membres du centre Ifremer de Boulogne-sur-Mer pour m'avoir si bien accueilli et intégré. Je tiens à remercier particulièrement : Charles, Jérémy, Pierre, Khaled, Rémi, Clémence, Cyrielle et Cecilia pour leur bonne humeur, les très bons moments partagés et pour m'avoir prouvé que la vie à Boulogne n'était pas aussi terrible que je l'imaginais. Un grand merci à toi Cecilia (« Miss Rome » pour les intimes) de m'avoir supporté dans ton bureau pendant ces 6 mois de stage. Je vous suis, également, à tous, très reconnaissant de m'avoir soutenu, encouragé et conseillé dans la recherche d'une thèse puis lors de la préparation des concours des écoles doctorales.

Merci aux copains de l'agro, de prépa et d'enfance pour leur soutien et leur amitié.

Je tiens à remercier ma famille et en particulier mes parents et sœurs pour leur soutien perpétuel ; Et enfin merci à Anne qui me supporte et me soutient depuis de nombreuses années.

Abstract

The Eastern English Channel (EEC) common sole (Solea solea) stock is one of the most important stocks for the French fisheries in the EEC. Low recruitments in 2012 and 2013, coupled with a fishing mortality well above Fmsy led to repeated cuts in TAC over the last years. This master thesis aimed to study the spatiotemporal dynamics of the French fisheries exploiting sole in the EEC and their impact on this stock; it also allowed drawing assumptions on populations' dynamics. We first showed a spatial structuration of the French fisheries (mainly trammel net and bottom otter trawl). A focus on trammel netters which represent the main share of the landings and which are highly dependent on common sole showed spatial differences on the length structures of the catches. Regression trees on mean lengths of catches and a multinomial logistic regression on the length structures of the catches revealed that these differences can be explained by the mesh size used, fishing period and the fishing area (including nursery area). The impact of potential subpopulations with different biological parameters in the EEC was tested focusing on growth parameters in these subareas, using a non-linear mixed effect model. It showed differences in growth rates and asymptotic lengths between the Northeast and the Southwest of the EEC. Finally, differences in the landings were checked through exploitation patterns to describe links and differences between catches and landings in the different regions and areas.

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List of Acronyms

AIC: Akaike Information Criterion

BN: Basse-Normandie

CC: Commercial Categories

HF: Hauts-de-France

HN: Haute-Normandie

EEC: Eastern English Channel

FO: Fishing Operation

MLR: Multinomial Logistic Regression

MLS: Minimum Landing Size

NE: Northeast

RT: Regression Tree

SW: Southwest

UK: United Kingdom

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1. Introduction & context

1.1. Biology & ecology

Common sole, *Solea solea*, is a benthic species living on fine sand and muddy substrates between 0 and 150 metres deep. The biogeographical range of common sole extends, in eastern Atlantic, from southern Norway down to Senegal, and the Mediterranean Sea including the Marmara and Black Seas (Carpentier et al., 2009). Sole feeds on annelid worms, small molluscs and crustaceans (Carpentier et al., 2009). Sole life cycle includes a pelagic larvae stage followed by a benthic juvenile stage in the estuarine and coastal nurseries grounds (Riou et al., 2001). At maturity, young soles (aged 2 and 3-years) move away from coastal area toward deeper grounds and breed every year (Le Pape, 2005). In the Eastern English Channel (EEC), breeding takes place from February to June with a maximum intensity in April/May (Carpentier et al., 2009; Ifremer, 1993).

ICES (ICES, 2015) assumes a single population in the area VIId (ie: the EEC) and sole is assessed and managed as such. However, Rochette et al. (2012) suggested the existence of 3 isolated sub-population at the scale of the EEC. This hypothesis is mainly based on larval dispersion analyses which showed limited dispersion between spawning areas and coastal and estuarine nursery ground (Rochette et al., 2012). In addition, previous analyses showed that sole juveniles stay in their nursery grounds during their 2 first years of life (Coggan and Dando, 1988; Le Pape and Cognez, 2016; Anon, 1989) and remain close to their nursery area even after seasonal spawning migration (Kotthaus, 1963; Anon, 1965). A mark-recapture survey suggested the low mobility of adult soles (Burt and Millner, 2008).

1.2. Exploitation, assessment and management

The EEC stock is mainly exploited by three countries, France, Belgium and the United Kingdom. Between 2010 and 2013, UK fleets operated only along the English coast, while Belgian fleet was spread over the Northwest of the (**Figure 1, a**). They represented, respectively, 15% and 25% of landings of common soles in the EEC (**Figure 1, b**). French fleets, which gathered 60% of the landings of common soles, were concentrated along the French coast.

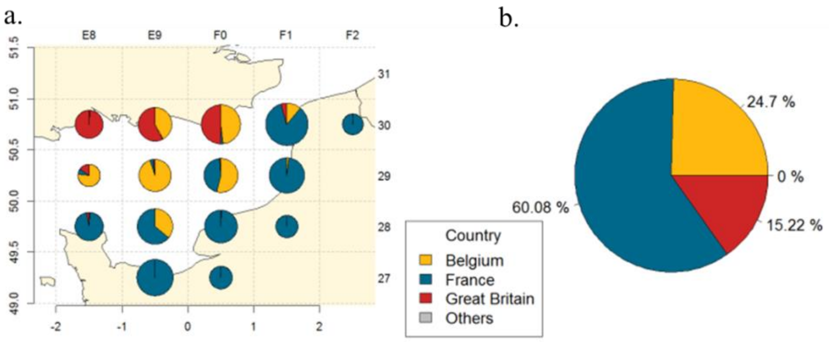

Figure 1: a) spatial landings distribution by country exploiting common sole in the EEC between 2010 and 2013; **b)** Proportion of landing by country exploiting common sole in the EEC between 2010 and 2013. (From CSTEP data)

French fleets exploiting the common sole stock in the EEC is dominated by trammel netters and trawlers. Globally netters exploiting common sole in the EEC are small vessel that fish close to the French coast. The others French fleets exploiting common sole in the EEC are small bottom trawl fleet and polyvalent fishing vessels seasonally targeting sole (pers. comm.).

This stock is considered overfished. From 1980, fishing mortality on this stock has fluctuated at levels higher than Fmsy (ICES, 2016) (**Figure 2, b**). Low recruitments in 2012 and 2013 (**Figure 2, c**) and high fishing mortality have led to a deterioration of the stock condition with a declining biomass from 2013. This decrease in biomass induced management measures and TAC cuts since 2014 (ICES, 2016). In 2015, the estimated SSB (Stock Spawning Biomass) was close to MSY Btrigger (8143 tonnes) and fishing mortality close to the Flim. The aim set by the CFP in 2011 was to achieve Fmsy by 2015, or as soon as possible thereafter. In 2016 ICES advice is therefore based on the MSY approach and recommend to further reduce the TAC by 24% to achieve Fmsy in 2017 (ICES, 2016).

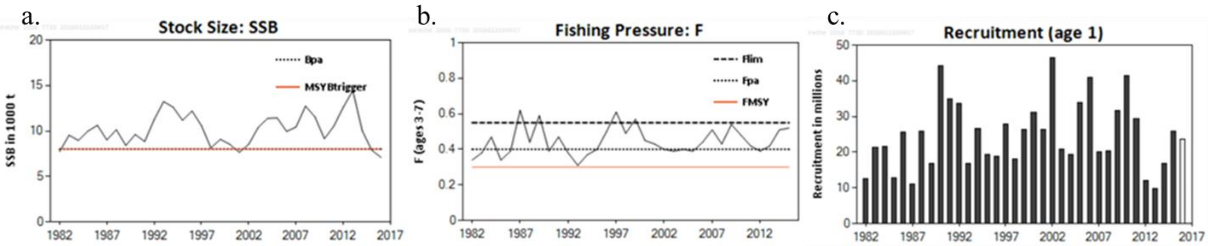

Figure 2: Sole in Division 7.d. Summary of stock assessment. **a)** Stock Size: Spawning Stock Biomass; **b)** Fishing Pressure; **c)** Recruitment for age 1 (ICES, 2016), the white bar represents the predicted recruitment in 2017.

In 2016, a multi-annual management plan was proposed by the NWWAC (North Western Waters Advisory Council) aiming at maintaining the TAC at 3,000 tonnes until 2020 provided that the biomass is maintained above Bmsy-trigger (NWWAC, 2015). Unfortunately, ICES could not consider this plan in the last stock assessment as it had not been officially endorsed by EU.

1.3. Anthropic impacts

The main anthropogenic disturbance is due to overfishing. The direct effects of fishing causes declines of biomass and indirect effects can affect sole populations. Selection pressure by fishing has an impact on growth and, length and age at of exploited species. Mollet et al. (2007) showed, in the North Sea, a decrease in the size of female at age 3 from 286 mm (and 251 g) to 246 mm (and 128 g) between 1960 and 2002. In addition, low mobility might render the quality of the habitat even more important for Sole than for more mobile species. Habitat degradation is one of the most serious threats for the recovery of fish stocks (Jennings and Kaiser, 1998). Nursery habitats, which are an essential habitat for juvenile common sole (Riou et al., 2001), sustain anthropogenic disturbance through pollution and habitat destruction. This degradation was notably showed by Rochette et al. (2010) for the Seine Estuary. In this area the loss in habitat surface combined with habitat degradation led to an important loss in the contribution of the Seine estuary nursery to the whole sole population in the EEC.

1.4. Scientific and socio-economic issues, and problematic

Common sole stock in EEC is one of the most commercially important species in this area with commercial catch between 4,000 and 5,000 tonnes. Repeated cuts in TAC are hard to overcome by fishing fleets, particularly when they cannot diversify their activity and mostly rely on a given species. In the last years, the main fleets involved in the sole fishery became very dependent on the sole due to several management measures on historical target species (i.e. the cod recovery plan limited cod exploitation and its targeting and restrictive TAC on rays were set). In 2014, French EEC sole fishery made a turnover of more than €13 000 00 and more than 340 fishing vessels were involved in sole fishery.

In this context, a project funded by France Filière Pêche and led in partnership with, DPMA, CRPM Nord Pas de Calais Picardie, Haute and Basse Normandie, the producer's organisations FromNord, CME and OPBN, the Hauts-de-France and Normandie regions and the scientific organisations Ifremer, Agrocampus Ouest and UMR BOREA was initiated at the end of 2015. Its aim is to improve the biological and ecological knowledge on sole and to integrate it into stock assessment models in the ICES context. The project focuses on three areas of research: (i) spatial population structure and connectivity, (ii) recruitment and (iii) fishing practice and selectivity. The master internship was integrated in this project and aimed at improving knowledge on the third axis (fishing practice and selectivity).

This master thesis will, firstly, focus on French fleet exploiting alone the area along the French coast and which represent the main share of landings in the EEC. Then, we will focus on trammel netters for two main reasons: (1) they represent more than 65% of total French landings and their activity is highly dependent on sole; (2) Selectivity: Even if nets seem quite selective with a discard rate lower than 5% (1.8% in 2014 (Isabelle et al., 2015)), a question arised regarding the commercial valorisation of the smallest commercial category.

The master thesis aimed to study the spatiotemporal dynamics of the French exploitation of common sole in the EEC and draw assumptions on populations' dynamics.

It will be divided in 4 chapters. We will first focus on describing the spatiotemporal dynamics of landings, then focus on the length structure of the catches from French fishery in the EEC. In a light of the results on the length structure of the caches, we will search for spatial variability of growth in the population of common sole in the EEC. Finally, we will come back to exploitation patterns and describe links between catches and landings in the different regions.

2. Spatiotemporal dynamics of common sole French landings in the Eastern English Channel

In this chapter, spatiotemporal dynamics of common sole French landings in the EEC was explored from exhaustive French landings data. It aimed to understand how are distributed the landings across the EEC and what were the changes since the early 2000s in terms of volumes of common soles landings, fishing gears and mesh size used, and, commercial categories of common soles landed. Volumes landed in the EEC by the French fleet permit to explore the spatial repartition of fishing effort while fishing gears and mesh sizes used can indicate what the impact of the population is. Discussions with fishermen suggest that fishing strategies and, consequently, the catches are different depending on the region they operate from. In order to test this hypothesis we studied regional variability of landings.

2.1. Materials & Methods

- SACROIS data

The French landing data (2000 to 2015) were extracted from SACROIS, a database produced by an algorithm coupling fish market sales, logbooks and VMS (Vessel Monitoring System) data to get an "exhaustive" estimate of the landings and their geographical distribution (SIH Ifremer, 2016). Sole landings in the EEC are provided per "fishing operation" (as defined in a logbook, i.e. aggregating all landings realised in a given day, in an ICES square with a given gear) and include the landing weight, the date of the fishing operation, the statistical rectangle, the vessel, the landing harbour and the fishing gear category.

The fishing gear category provides relevant information on the fishing gear type (technical description in **Appendix I**), the target assemblages and the mesh size range. For the trammel net, the mesh size ranges is the mesh size of the inner panel. Mesh size should be informed in "stretched mesh". However, preliminary analysis of the data showed a significant number of mesh size between 40 and 50 mm for the trammel nets, mesh size ranges which are not relevant for this gear when targeting sole, indicating that mesh sizes might have been filled in using half of the mesh and not the stretched mesh as requested. Therefore, irrelevant mesh sizes were doubled for mesh size between 40-50mm for trammel nets, allowing more consistency in the database. Mesh size data was gathered exhaustively from 2009 so the spatial repartition of mesh size was studied between 2009 and 2015.

Another output of SACROIS algorithm is the spatio-temporal (dates and ICES statistical rectangles) reallocation of the landings by commercial categories (CC) (SIH Ifremer, 2016) sold in fish markets. Fishes are sold by Commercial Category according to their weight (**Table 1**). This allows a rough approximation of the size structure of the landings.

Table 1: Description of Soles commercial categories

Commercial Category	Weight (in g)	French local name
10	500/+	Extra Grosse
20	330/500	Moyenne à grosse
30	250/330	Moyenne
40	200/250	Solette et Belle
51 (50)	140/200	Solette
52 (50)	120/140	Petite Solette

- Landings from SACROIS vs. vessels' home region

Discussions with fishermen suggest that fishing strategies are different depending on the region they operate from. In order to test this hypothesis we first added regional information in the dataset. Regions are assigned to the landings harbour for each landings data, assuming that catches were realized close to the landing harbour.

This dataset was used to first explore spatial and temporal trends in landings volumes and their variability based on statistic rectangles (the finest spatial information available), gear category and home region.

2.2. Results

2.2.1. **Spatial distribution of total landings**

EEC sole landed by French fleets are concentrated near the coast (**Figure 3**). Most of the soles landed in the EEC were caught in the statistical rectangle 30F1 (more than one third of the French landings), just in front of Boulogne-Sur-Mer harbour, and, to a lesser extent, in the bay of Seine. Landings from statistical rectangles 29F1 and 28F0, near the coast of Haute-Normandie (HN), used to contribute significantly to the landings but their contribution reduced gradually from 2004. Since 2012, landings in 28F0 remain below 200 tons.

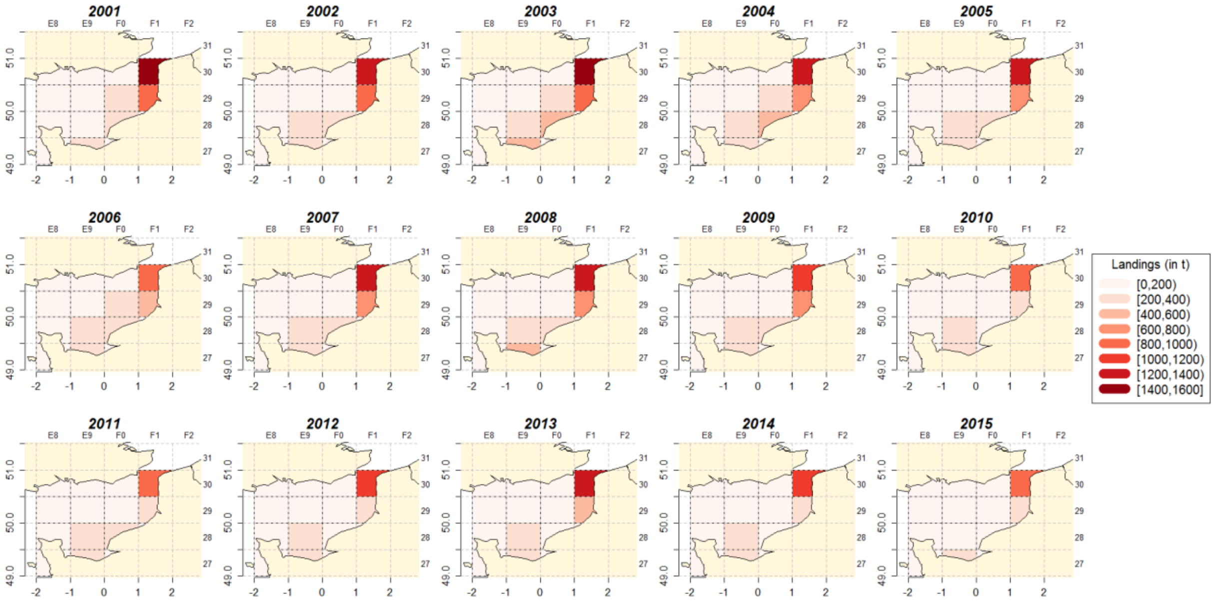

Figure 3: French landings (in t) of Common Sole in EC by statistics rectangle between 2001 and 2015.

2.2.2. **Regional landings**

In these three regions, Haut-de-France (HF), Haute-Normandie (HN) and Basse-Normandie (BN), sole landings have been decreasing since 2002/2003 (**Figure 4**). This decrease is particularly important in HN (reduction of 68% in 2015 compared to the maximum observed landings). The French quota increased in volume (not in proportion) between 2000 and 2008, it decreased until 2010 and dropped between 2013 and 2015 after a peak in 2013.

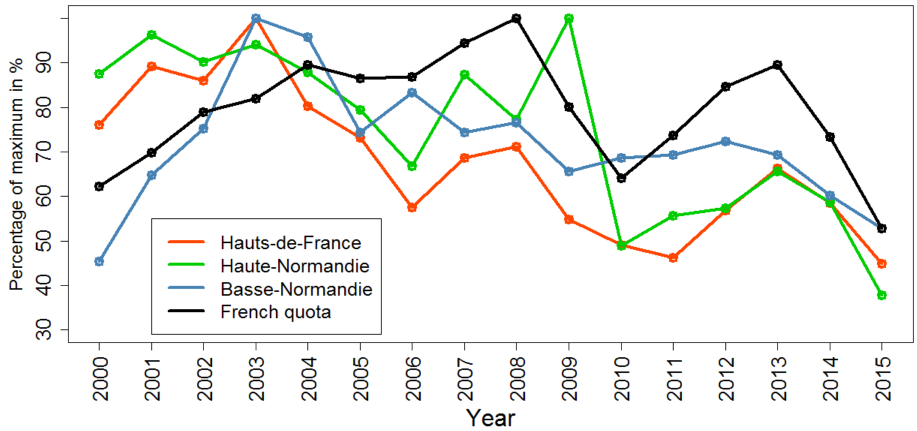

Figure 4: French landings of common sole in the EEC and quota (before the exchanges between EU countries) between 2000 and 2015

2.2.3. **Spatial distribution of landings by fishing gear**

In the EEC, the French sole fishery is dominated by trammel nets which landed 65% of the sole landings in 2015. Then, bottom otter trawls contributed 21% of landings and fishing dredges and beam trawl to 9% and 3% respectively (**Figure 5**).

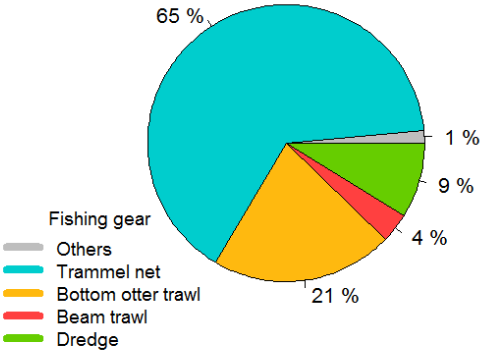

Figure 5: Contribution of the different gears to the French common sole landings in the EEC in 2015

However, the contribution to the landings by gear varies greatly according to regions and geographical areas (**Figure 6, a.**). In HF, trammel netters are responsible for the majority of the landings (**Figure 6, a.**) while a very small proportion of the landings is made by trawlers (**Figure 6, a.**). In HN, from the early 2000s, the landings of trawlers (Otter Bottom Trawlers and Beam Trawlers) and trammel netters have gradually decreased whereas the volumes landed by dredgers remains (**Figure 6, a.**). Globally landings in HN have decreased more significantly than others regions (from nearly half of the observed landings in 2002 to less than 25% in 2015). In BN, except in 2000, the landings of bottom otter trawlers are always higher than trammels landings (**Figure 6, a.**). Overall, landings are subject to inter-annual variations following similar patterns in all regions. These landings peaked in 2002-2004 and are decreasing since.

Spatial landing distribution shows a decrease of trammel netters contribution in the Southwest (SW) of the EEC in favour of trawlers between 2000 and 2015 (**Figure 6, b.)**. On the contrary, trammel netters contribution increased in the Northeast (NE). Fishing gear distribution is intermediate in the middle of the EEC (**Figure 6, b.)**. Finally, local fishing practices stand out, particularly in two statistical rectangles, in the South-East with a high contribution of beam trawls and in the statistical rectangles 29F1 with an important contribution of dredge (**Figure 6, b.)**. This spatial variability of the fishing gear is partly due to the inter-regional variability (**Figure 6, a.)** but there is also an important intra-regional variability (**Appendix II**).

In terms of regional distribution, two specific areas can be identified: one in the North (30F0 and 30F1) where only vessels from the HF area are operating and another in the South (28E8, 28E9, 27E9), only visited by the BN fishery. Other statistical rectangles cannot be allocated to a region because they are shared among regions. Landings in HN come from statistical rectangles shared with BN to the south and HF to the north (**Appendix II)**.

Spatial and regional structuration of sole fisheries in the EEC is characterized by i) a fishing fleet in the NE dominated by netters from HF, ii) trawlers in the SW coming from BN and iii) an intermediate area in the middle of the EEC mixing trawlers and netters.

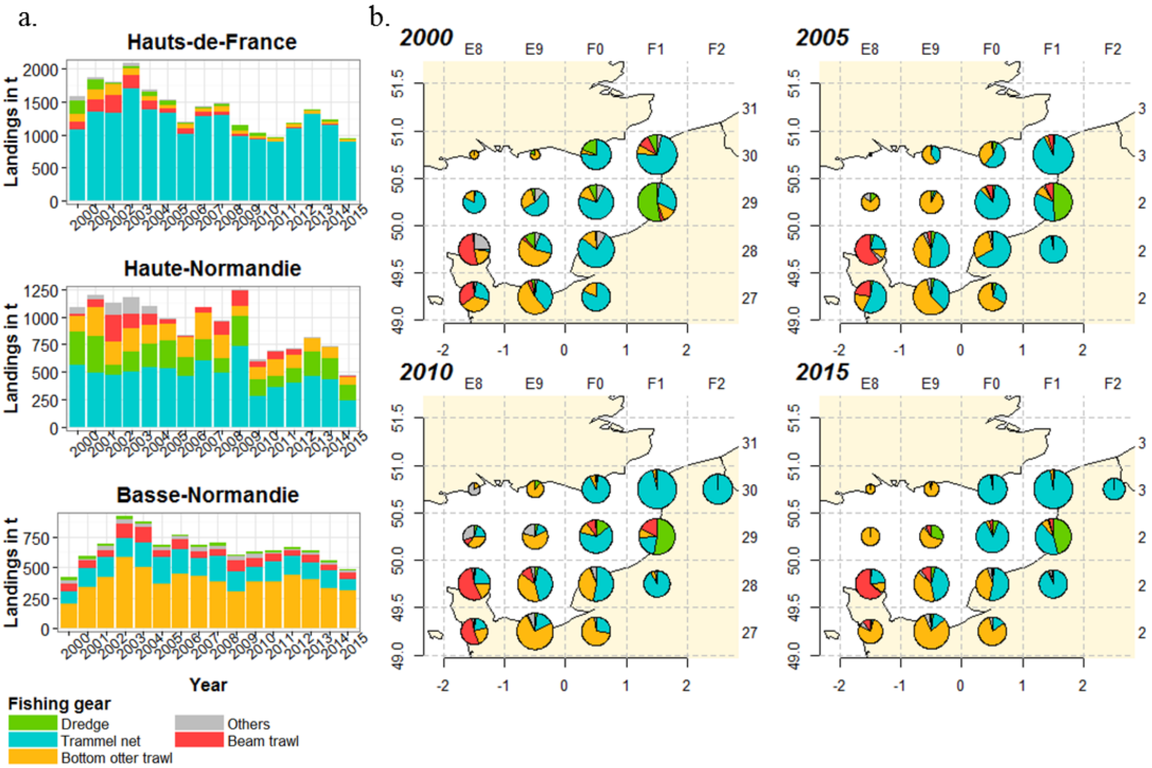

Figure 6: a) Landings by region and by fishing gear from 2000 to 2015, **b)** spatial landings distribution by fishing gear. Pies are proportional to the volume landed in the statistical rectangles.

2.2.4. Spatial distribution of landings by mesh size used in the trammel net fishery

Trammel net is the main gear used by the French fleets to catch sole (65% of the French landings in 2015), whereas bottom trawls or dredges in the EEC will mostly use a unique mesh size range to target sole. Trammel netters used mainly 2 mesh size ranges to catch common soles in the EEC (**Figure 7**): (1) 90-99mm - 82%; (2) 100-119mm - 12%.

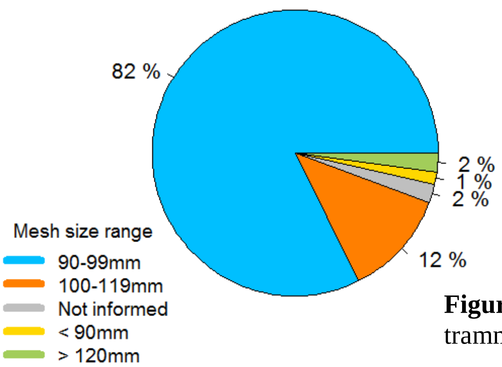

Figure 7: Contribution of the different mesh size range for the trammel net to the French common sole landings in the EEC in 2015.

In the NE of the EEC, landings of trammel netters are dominated by 90-99mm mesh size range over the whole studied period. On the other hand, in the SW, landings of trammel netters are dominated by 100-119mm mesh size in 2015 whereas the share of mesh size 90-99mm were more important in 2011 and 2013 (**Figure 8**). In the middle of the EEC, the situation is intermediate: Before 2010, there were 3 mesh sizes used, "< 90", "90-99" and "100-119". Since 2010, the main mesh size has mostly been 100-119m and 90-99mm.

Finally, local fishing practices stand out, particularly in the statistical rectangles 28E8, with an important contribution of bigger mesh size range (>120mm).

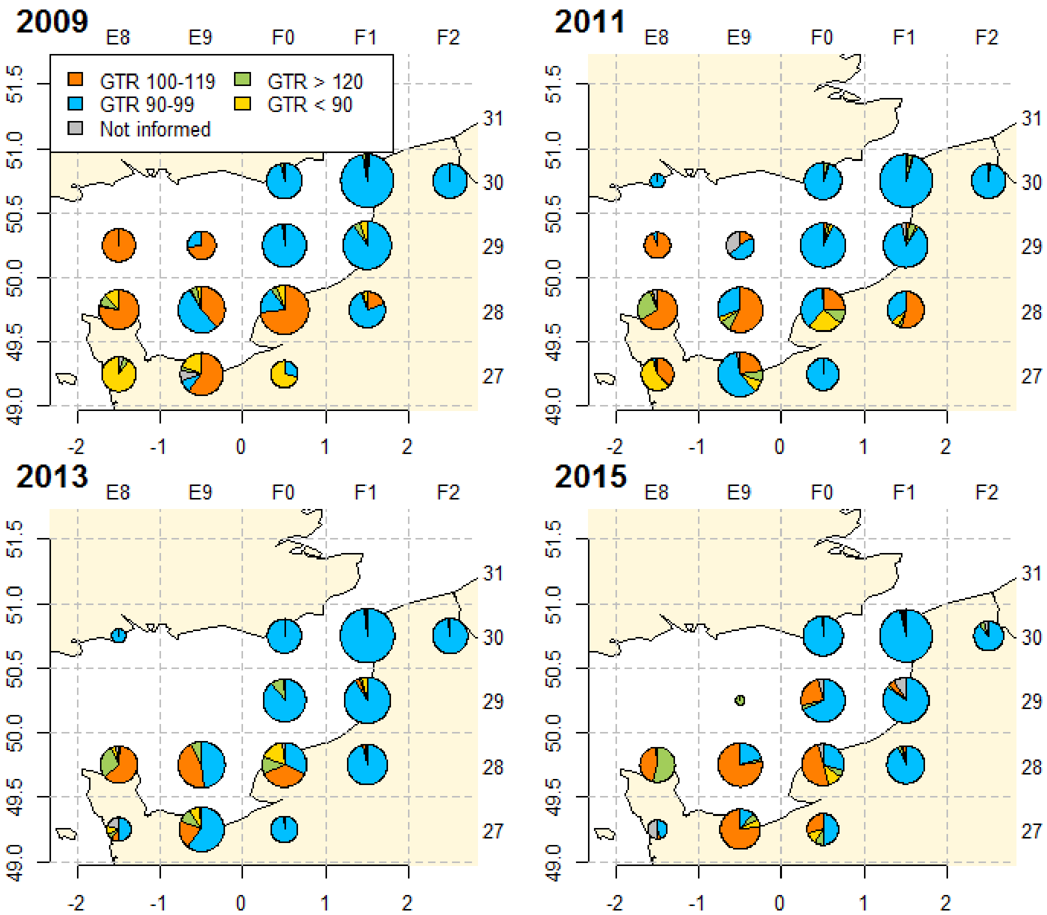

Figure 8: Mesh size range proportion in common sole landing in Eastern Channel for 2009, 2011, 2013 and 2015 from the SACROIS database.

2.2.5. Spatial distribution of landings by commercial category

In 2015, common sole commercial categories (CC) are highly variable depending on the season and the area (**Figure 9,** please refer to **table 1** for CC definitions). Sole landed are globally bigger in the 1st quarter and smaller in the 3rd quarter in all the EEC. Moreover, for each quarter, the weight of landed soles increases gradually from the north of the EEC to the south. In the north of the ECC under the latitude 50°, the weight of landed soles is particularly low.

Studying CC for trammel netters only shows again a gap between structure of CC between the NE of the EEC and the SW (**Figure 10**). Sole caught in in the North of the EEC are bigger than in the south with the limit at latitude 50°. Soles landed are particularly small in the NE in the 3rd and the 4th quarter and the CC shift toward small length over the years. The soles weight caught in the 1st quarter in SW is particularly important and decrease slightly until the 3rd quarter.

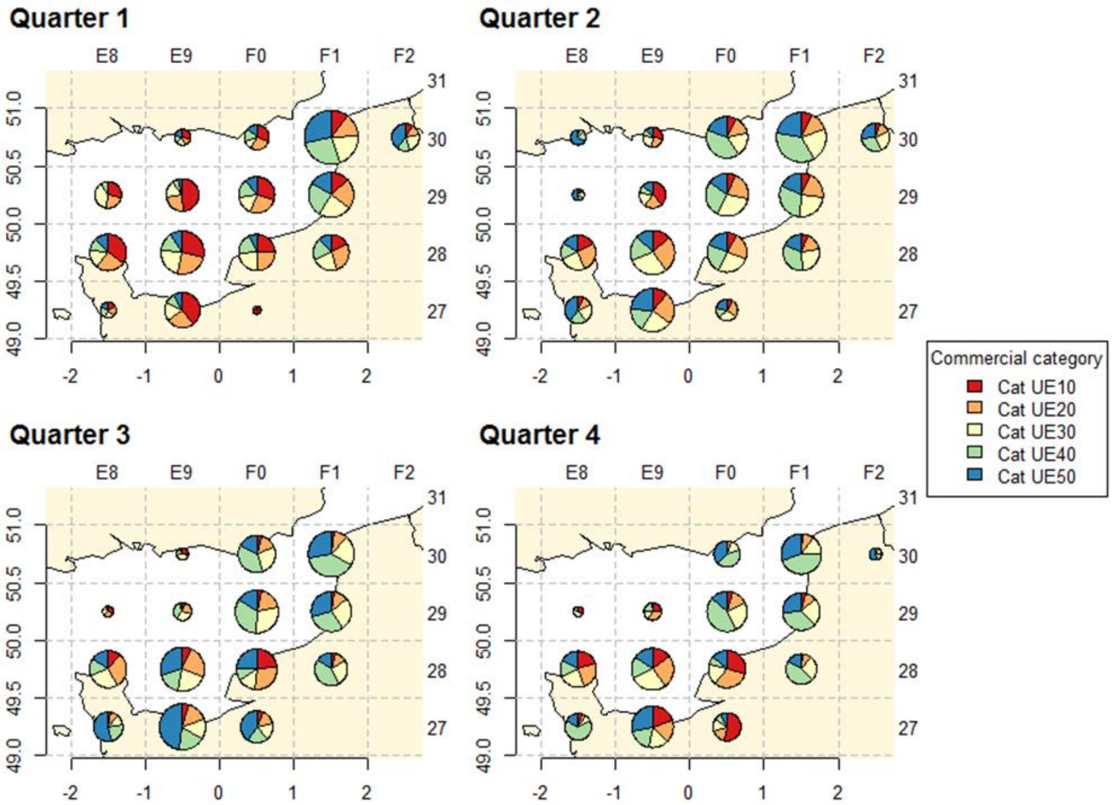

Figure 9: Common sole total landing in the EEC by statistical rectangle and by commercial category. Pies are proportional to the volume landed in each quarter in the given statistical rectangles.

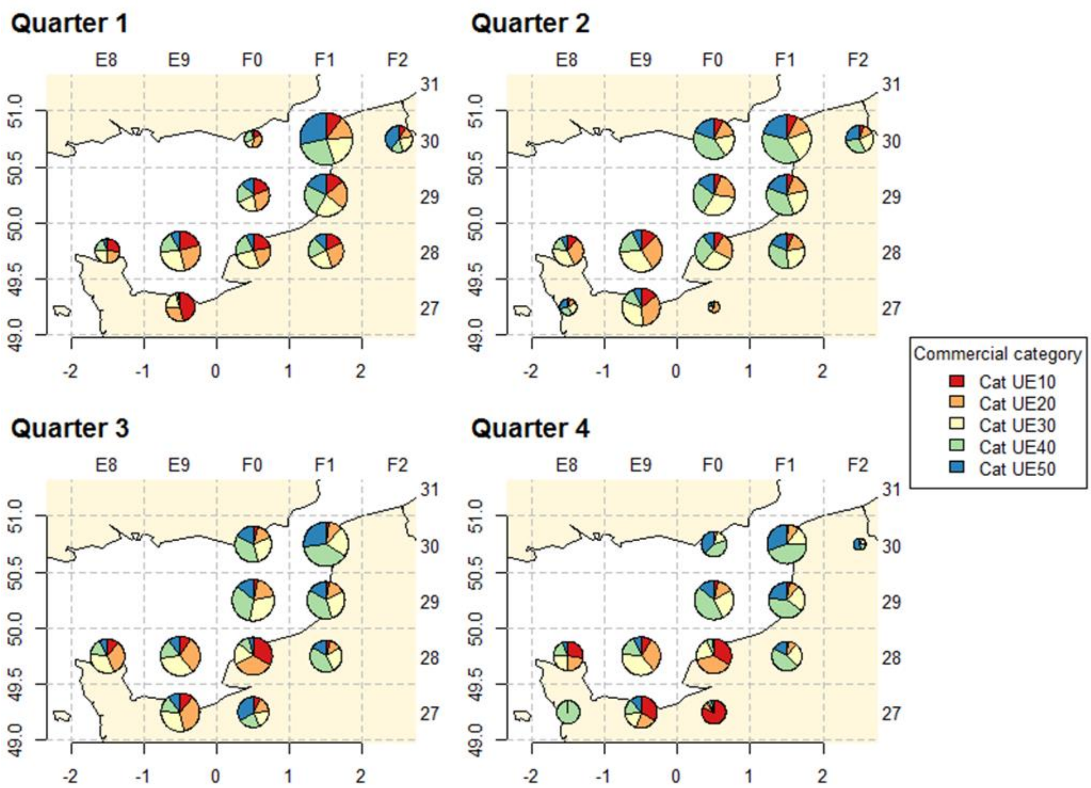

Figure 10: Common sole total landing of **the trammel netters** in the EEC by statistical rectangle and by commercial category. Pies are proportional to the volume landed in each quarter in the given statistical rectangles.

2.3. Discussion

Most of soles landed were caught in the NE of the EEC and in the SW, and globally close to the coast. In the NE, the important landings close to the coast could be due to the trammel netters which are small vessels that cannot travel away from the coast. This could be linked with the spatial distribution of adult sole in the EEC and notably, the increase of concentration of adults common sole which come in coastal zones (Carpentier et al., 2009) during the spawning period. In addition, the results show that the SW of the EEC is mainly exploited by the BN fleets while the NE is exclusively exploited by the HN fleet. The intermediary area exploited by HN fleets but also partly by BN and HN fleets.

The great decrease of landing since 2004 cannot be imputed to quotas given that they were not a limiting factor until 2014 (with two exceptions in 2009 and 2010) (ICES, 2016). Several hypotheses may be proposed to explain this decrease: (1) Spatial distribution of the population changed since the early 2000s, (2) A decrease of biomass of common sole in the EEC, (3) the decrease of prices of common soles due to market fluctuations (in particular in North of France) coupled with a decrease of catches could speed a decrease of fishing effort up and, thus a decrease of landings. This last hypothesis is partly checked by the ICES common soles assessment (ICES, 2016). Indeed, peak of spawning biomass (**Figure 2, b.**) matched with peak of landings and the peak of recruitment at age 1 (**Figure 2, c.**) was followed by increased landing. For instance in 2002, the peak of recruitment at age 1 was followed by increased landing in HF and in BN, in 2003 and 2004 (**Figure 6, a.)**.

This decrease of landings is found for each region exploiting common sole in the EEC. Note however an unexplained peak of landings in HN in 2009, it could be a data acquisition error because, in 2009, the data acquisition procedure and the database of logbook changed.

The method to affect regions at each landing can imply a bias because landings are affected at the landing regions based on landing harbour and not at the home port regions. So regions are not strictly representatives of regional fishing's practices. However, for trammel netters, landing port is usually the fishing home port because they are small vessels fishing close to the coast.

Trammel netters used mainly 2 mesh size ranges of the inner panel to catch common sole in the EEC: 90-99mm and 100-119mm with a spatial structuration. In the NE, since 2009, netters used only the 90-99mm range and in the SW in 2015 netters used mainly the 100-119mm range. The use of the 100-119mm range was expanded in 2014 and 2015 mainly to increase the length structure of the catch to improve the valorisation of the landings. That increase was partly induced by the OPBN (a producer's organisations in BN) that encouraged fishermen to improve the selectivity by increasing the minimum size of landing from 24cm (the official minimum landing size) to 26cm.

Finally, for the global landings and for the trammel netter, the individual weight of common soles landed in the NE in the EEC is lower than in the SW with a limit in the latitude 50°. This suggests that the length structure of the catches varies depending on the fishing area or/and the fishing practise given the spatial structuration in terms of fishing gear and mesh size ranges. In addition, the decrease of sole weight in the second semester could, partly, due to recruitment (small fish entering the stock) in the 3rd quarter which brings out a higher proportion of sole caught coupled with the adult dispersal after the spawning period. In the following part, this hypothesis was tested for the trammels netters.

3. Length structure of common sole captures by trammel nets in the EEC

3.1. Introduction

In the previous section, commercial categories of soles landed in the EEC show a high spatial variability with soles landed in the north of the EEC smaller than in the south. In parallel, fishing practises in terms of fishing gears and mesh sizes used by trammel netters show spatial structuration in the EEC with, notably, a majority of 90-99mm mesh size range used by trammels netters in the North and a majority of 100-119mm mesh size range in the South. This suggests a link between the fishing gear selectivity and the variability in the length distribution. Fishing gear selectivity was analysed from fishing gear mesh size which is the main (but not the only) parameter influencing the selectivity. Few authors showed that the fish size selectivity of trammel nets depends primarily on the mesh size of inner net (**Figure 11**) (Erzini et al., 2006, Kitahara, 1968; Losanes et al., 1992b; Purbayanto et al., 2000; Salvanes, 1991).

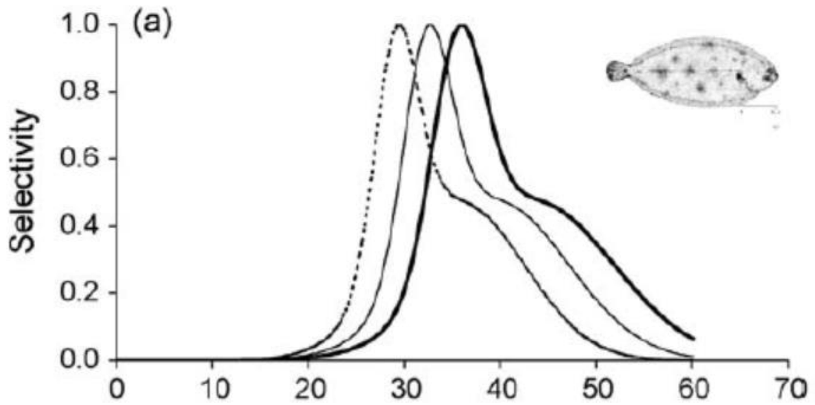

Figure 11: Selectivity curves for *Solea solea* in Basque country using SELECT models; dashed line: 90mm inner panel mesh, continuous line: 100mm inner panel mesh, bold line: 110mm inner panel mesh (Erzini et al., 2006).

However, the length distribution in catch is also directly linked to the length distribution of the underlying population. It is then important to take into account the structure of the population and test the hypothesis of the existence of 3 isolated sub-populations in the EEC (potential variation in population structure, in growth, in length and age at maturity…). In addition, changes in the population structure over the years due to recruitment fluctuations could also influence the catch-at-length.

In this section, we will focus on the length structure of the catches to assess the impact of (i) nets selectivity, (ii) length structure of population and (iii) the interaction of these two parameters from catch-at-length data of a fraction of commercial catches.

3.2. Materials & Methods

3.2.1. **Data**

➢ OBSMER

The OSMER program aims at observing, in situ, French fishing activities and their catches. During a trip, for a fraction of fishing operations, the observer identifies the species caught; records the weight by species and catch category (landings/discards), and measures all individuals from commercial species. For each commercial species, the number per length (1 cm group) and per haul is recorded. The commercial fishery database OBSMER was used for the length data analysis of the catches from 2009-2015 in the EEC. The haul by haul data from trammel netter includes the fishing date, the exact fishing position (latitude and longitude), the statistical rectangle, the fishing gear category, the home port of the fishing vessel, the catch category (landings or discard) and the catch in numbers at length. As for SACROIS, the mesh sizes between 40 and 50mm were doubled for the trammel net.

➢ Nurseries

The nurseries area is an essential habitat for juvenile stages of common sole. Therefore, fishing operation made in nursery area were identified using Age 1 sole distribution as identified by Rochette et al., 2010 (**Figure 12, a**).

➢ Subareas

The hypothesis of low connectivity between 3 sub-populations, described in the introduction, can potentially affect the length structure of catches. The 3 subareas UK, Southwest (SW) and Northeast (NE), consistent with the suggested existence of 3 isolated subs-population in the EEC (Rochette et al., 2012) were introduced in this study (**Figure 12, a**).

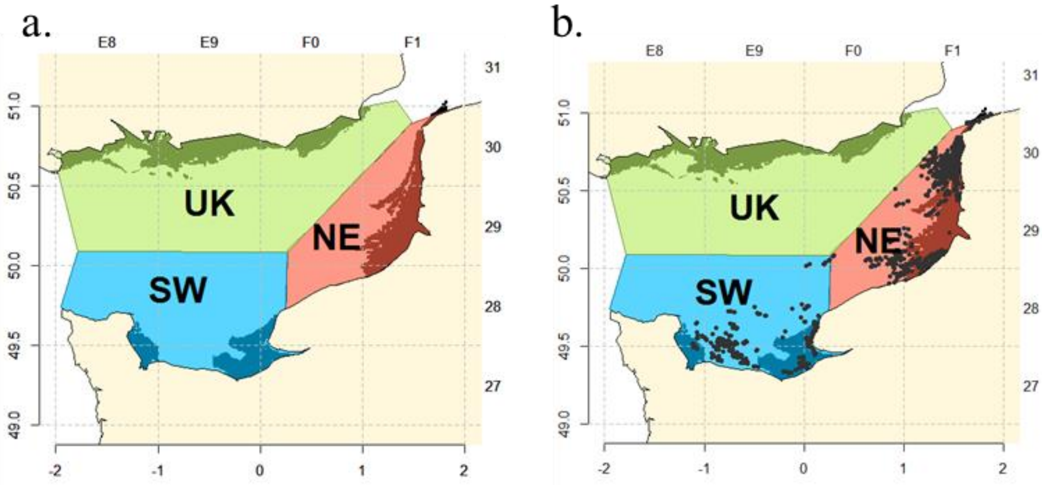

Figure 12: a) 3 subareas colored in blue, red, and green and the darker areas along the coast representing the nurseries area; **b)** Position of trammel net hauls with common sole in the EEC from Obsmer between 2009 and 2015

3.2.2. **Analytical Methods**

Mean length Cartography

In each statistical rectangle, the mean length is computed by statistical rectangle and by mesh sizes range (with more than 50 individuals gathered).

This first descriptive method allows for a visual description of the spatial distribution of mean length of sole catches in the EEC.

Statistical analyses

In order to assess the spatio-temporal variability of catches length structure and the impact of fishing practises, 5 variables were selected (**Table 2**).

Table 2: Description of variables used in the statistical analyses: 2 regression trees (RT) and 1 multinomial logistic regression (MLR)

Variables	**Mesh size range**	**Latitude/Longitude**	**Subarea**	**Quarter**	**Year**	**Nursery**
Type	factor	Numeric	factor	factor	factor	Factor
Values taken	90-99 mm 100-119 mm	[49 ; 51.5] [-2 ; 2]	Southwest (SW) Northeast (NE)	1/2/3/4	2009-2015	IN OUT
Statistical analyses	1st RT 2nd RT MLR	1st RT MLR	2nd RT MLR	1st RT 2nd RT MLR	MLR	2nd RT MLR

In the analysis the mesh sizes were restricted to two main mesh size ranges used (90-99mm and 100-119mm) as they were responsible for most of the landings (87%) during the period 2000-2014 (94% in 2015).

Spatial features of the landings length structure were explored using either haul by haul latitudinal or longitudinal information provided by Obsmer data (c.f. section 3.2.2), or the 3 subareas defined in **(Figure 12**, **b**). Data for the UK subarea are hardly available because French netters do not fish in these grounds, so the UK subarea was removed from this analysis. The OBSMER geolocation allows to locate each haul station inside or outside nurseries grounds in order to create an IN/OUT variable. Location of nursery grounds is defined in section 3.2.1.

Regression tree

Spatio-temporal variability of mean length was first assessed using regression trees. This method allows to class variables affecting the mean length of captures according to mean length variability given their importance during the classification. Interaction effects were also suggested thanks to the partitioning construction of the trees. The analysis by mean length approach requires an aggregation of the individual fish information contained in OBSMER (the two levels of aggregation tested are presented later in this section) but provides an initial understanding on the determinants of the mean length of the captures.

The Regression tree approach based on CART (Classification and Regression trees) uses recursive partitioning to determine a series of binary rules that divide the data into smaller more homogeneous subgroups. The splitting criterion, which is used to decide which variable gives the best split is: $SS_T - (SS_L + SS_R)$ where $SS_T = \sum(y_i - \bar{y})^2$ is the sum of squares for the node, and SS_L and SS_R are the sums of squares for the right and left son, respectively. The aim is to maximize the between group sum of squares.

First of all, the best level of simplification is determined thanks to the “complexity parameter” setting a complexity threshold (default value 0.01). Then, pruning, i.e. the level of simplification of the tree, is validated or tightened using cross validation in checking the number of splits from which the cross validation error increases. Finally, pruning has been further improved by taking into account the error bars (1-SE rule). Residuals were also checked to compare observed mean lengths and predicted values.

The CART algorithm uses a surrogate split process to overcome the missing data. It can classify, a posteriori, an individual with no modality for a constitutive variable of the tree. Moreover a regression tree constructed with the CART algorithm can work with all types of variables: qualitative, ordinal and continuous quantitative (Santos, 2015).

Observed haul level data were aggregated into combinations of factors. Two different groups of factors are studied separately, by changing only the spatial variable:

- 1st group: **Latitude, Longitude**, Mesh size range, Quarter, Nurseries, Year
- 2nd group : **Subarea**, Mesh size range, Quarter, Nurseries, Year

For the 2 regressions, only combinations with more than 20 individuals were kept (1st group: 85% of individuals, 2nd group: 83%) using the following explanatory variables:

- 1st group: **Latitude, Longitude**, Mesh size range, Quarter, Nurseries
- 2nd group : **Subarea**, Mesh size range, Quarter, Nurseries

Therefore, the statistical individual is the average individual for each variable combination (including year) with more than 20 individuals. The year effect was not used in the analysis but used to realise cross-validation RT By not including the "year" effect in the RT it was possible to get a variable combination **for each year** (7 between 2009 and 52015) that were used to perform cross-validation.

To pool individual data into latitude and longitude, these two variables were aggregated in small group of 1/8° for latitude and 1/4° for longitude. Latitude and longitude were then considered as numeric variables in the regression procedure.

Multinomial logistic regression

A Multinomial logistic regression aims to model the probability of a given sole to belong to a length class. Therefore, it allows exploring length distribution variability.

Individual total lengths were aggregated into 12 length classes (**Table 3**). The first and last percentiles of the sole length distribution were aggregated into two length classes between 0mm and 200mm (0-200), and 410mm and 490mm (410+), respectively. In between 210mm and 400mm, lengths were aggregated by 20 mm length class. This discretization of the length structure allows the thorough description of the largest share of the distribution without increasing too much the number of classes.

Table 3: Length classes used for the multinomial logistic regression with the number of individuals in each class and the corresponding percentage.

Length class (in mm)	**0-200**	**210-220**	**230-240**	**250-260**	**270-280**	**290-300**
Number of individuals	352	896	1546	3261	7048	6589
Percentage	1.2	3.1	5.3	11.2	24.3	22.7
Length class (in mm)	**310-320**	**330-340**	**350-360**	**370-380**	**390-400**	**410+**
Number of individuals	4183	2489	1367	713	353	254
Percentage	14.4	8.6	4.7	2.5	1.2	0.09

The probability that a sole $\boldsymbol{\omega}$ belongs to a length class $\boldsymbol{y_k}$ (k=12) was defined as

$$\boldsymbol{\pi_k} = \boldsymbol{P}[\boldsymbol{Y}(\boldsymbol{\omega}) = \boldsymbol{y_k} | \boldsymbol{X}(\boldsymbol{\omega})] \quad (1)$$

where Y was the dependant variable and X were the exploratory variables with the constraint

$$\sum_{k} \boldsymbol{\pi_k(\omega) = 1}$$

Therefore the likelihood is given by

$$\boldsymbol{L} = \prod_{k} [\boldsymbol{\pi_1(\omega)}]^{y_1(\omega)} \times \ldots \times [\boldsymbol{\pi_K(\omega)}]^{y_K(\omega)} \qquad (2)$$

Where

$$\boldsymbol{y_k(\omega)} = \begin{cases} \boldsymbol{1\ if\ Y(\omega) = y_k} \\ \boldsymbol{0\ otherwise} \end{cases}$$

The principle of the multinomial logistic regression is to model K-1 (here 12-1) ratio of probability ($\boldsymbol{\pi_k}$). One category (length class) is set as the base line. In our case the reference category was defined as the first length class [0; 200]. Logit for $\boldsymbol{y_k}$ is then computed as:

$$\boldsymbol{C_k = ln\frac{\pi_k}{\pi_{0-230}} = a_{0,k} + a_{1,k}X_1 + \cdots + a_{J,k}X_J} \qquad (3)$$

And, therefore, probabilities at posteriori are

$$\boldsymbol{\pi_k = \frac{e^{C_k}}{1 + \sum_{k=1}^{K-1} e^{C_k}}} \qquad (4)$$

Finally, the log-likelihood was maximized

$$\boldsymbol{LL} = \sum_{k} \boldsymbol{y_1(\omega)} \ln \boldsymbol{\pi_1(\omega)} + \cdots + \boldsymbol{y_K(\omega)} \ln \boldsymbol{\pi_K(\omega)} \qquad (5)$$

Multinomial regression was implemented in R (R Core Team , 2014) using the package ‘nnet’ and the ‘multinom’ function (Ripley and Venables, 2016). Multinomial model were fitted using neural networks allowing the definition of a large number of parameters and length classes.

The model selection was selected through minimization of the Akaike’s Information Criterion (AIC). The fitting quality of the regression was assessed via the McFadden Pseudo-R^2 and the global significance was assessed with a likelihood-ratio test comparing the selected model and the null model. Then, prediction quality was evaluated by comparing the residuals of the observed and predicted length distribution of all combination of variables kept in the model. To compare predicted distribution and observed distribution for a particular variable, the mean of the predicted length distribution for this variable was computed. In addition, the dataset from Obsmer was segregated into two groups: (1) a learning sample, and (2) a validation sample to perform a cross-validation. The validation sample was selected extracting randomly 10% of each combination of the 5 variables (Subarea, Mesh size range, Quarter, Year, and Nursery). The reclassification quality of the data of the validation sample was studied using a Model build from the learning sample.

3.3. Results

3.3.1. **Mean length variability**

Mean length Cartography

Only a few statistical rectangles are fished with 100-119 mm mesh size trammel nets. Therefore only the mean lengths for all trammels nets (all mesh sizes merged, subsequently named “all trammels”) and for 90-99 mm mesh size trammels (subsequently named “90_99 trammels) are shown. The mean lengths of the “all trammels” show a gradient with bigger average sizes in the south of the EEC and smaller ones in the north (**Figure 13**). These differences could be explained by differences in the mesh sizes used in the different regions but this gradient is also found for the “90-99 trammels” meaning that differences are therefore not only due to mesh size. These differences can be found each year since 2009 (**Appendix III**).

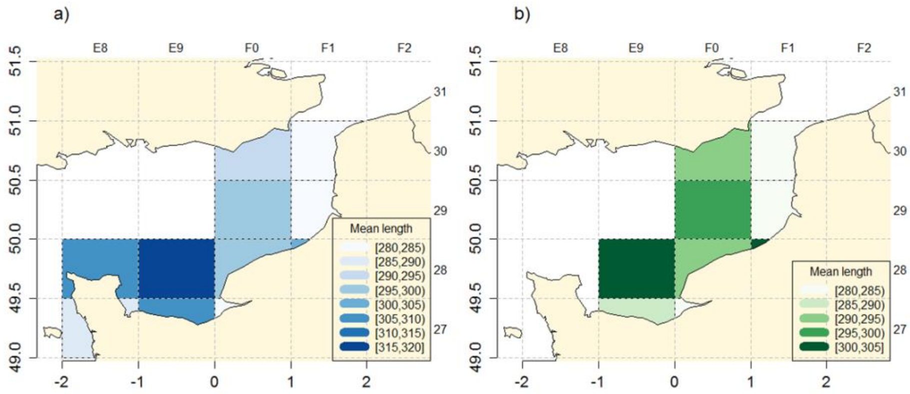

Figure 13: Mean length by statistical rectangles of catches between 2009 and 2015: **a**) for all mesh size range, **b)** only for 90-99mm mesh size range

Throughout the year, the mean lengths show a gradient with an increase from the NE to the SW**, (Figure 14, a**). In the South of EEC, for all mesh sizes, there is a peak in the mean length of catches during the 2nd and 3rd quarter. In the North of EC, the mean lengths gradually decrease between the 1st and 4th quarter. A similar gradient can be observed for catches with the 90-99 mm mesh size range (**Figure 14, b**). Moreover, for this mesh size range, mean lengths are bigger the first two quarters of the year.

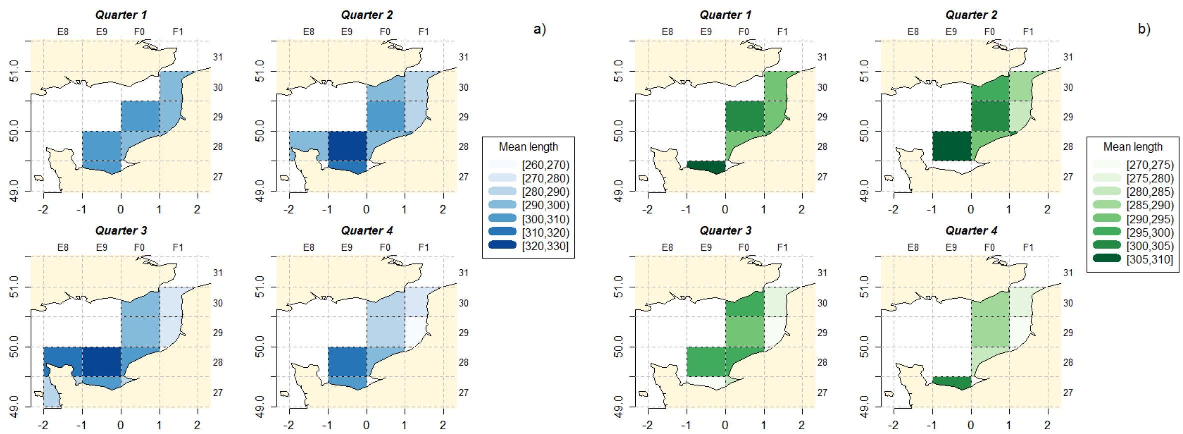

Figure 14: Mean length by statistical rectangle and by quarter of catches between 2009 and 2015: **a)** for all mesh size range, **b)** only for 90-99mm mesh size range

Regression tree

The 1st RT was pruned keeping 7 splits **(Figure 15**). The quality of the residuals is correct with 90% of them below 20 mm and 59% of residuals below 10 mm (**Appendix III**). In the 1st RT, the mesh size range is the variable that has the most impact on the means. The quarter effect then stands out for both mesh size ranges (100-119 mm and 90-99 mm). Overall, the soles caught in the 2nd quarter are, on average, larger than in the 3rd quarter. We can notice that the quarter effect for 90-99 mm mesh size is consistent with the observations made previously (**Figure 14, b**). In the 90-99 mm mesh size branch, two areas are identified in terms of longitude. There is a lag of 0.45° between the two different longitudinal limits highlighted (0.75°E in the two first quarters and 1.2°E in the two last quarters) in the first RT depending on the time of the year, but in both cases soles are on average smaller East of the EEC. Finally, fishing on nursery areas affects mean lengths with bigger soles caught out of the nursery grounds.

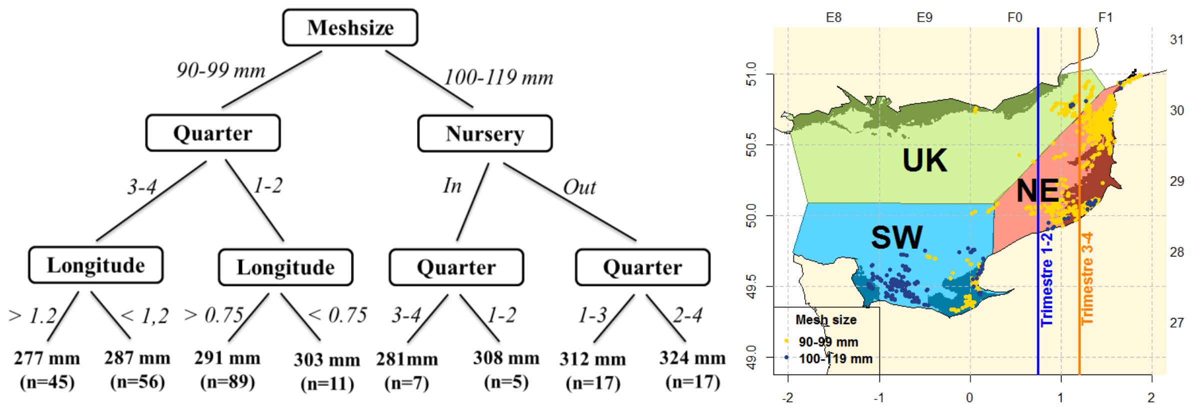

Figure 15: a) Regression tree developed from mesh size, quarter, nursery, and latitude and longitude. Choosing cuts are indicated on each branch in italics. The mean lengths and the numbers of individuals (combination in our case) are indicated in bold at each leaf at the base of the tree. **b)** Map of the Eastern Channel, where points represent trammel net hauls for both mesh size ranges and lines represent longitudes highlighted in the 1st regression tree.

The 2nd RT was pruned keeping 6 splits (**Figure 16**). The quality of the residuals is correct with 94% of residuals below 20 mm and 62% below 10 mm (**Appendix IV**). This RT shows the same effects, the subarea is highlighted as a significant variable. The soles caught in the NE of the EEC are smaller than those in the SW and in the UK subarea. However, this difference in the mean lengths is tenuous.

Differences in the variables affecting mean lengths depending on the mesh size ranges suggest the existence of interactions between variables. Indeed, without interaction, variables would affect mean lengths in the same proportion whatever the mesh size used. Therefore, 3 interactions could exist between: Mesh size and Quarter, Mesh size and Nursery and Mesh size and Subarea.

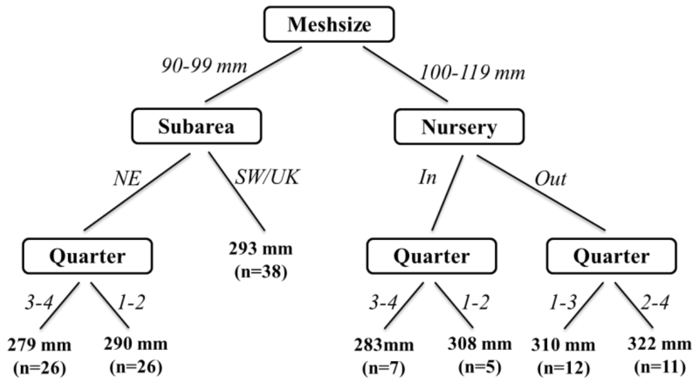

Figure 16: Regression tree developed from mesh size, quarter, nursery and subarea. Choosing splits are indicated on each branch in italics. The mean lengths and the numbers of individuals (combination in our case) are indicated in bold at each leaf at the base of the tree.

3.3.1. **Length class distribution**

The model selection procedure using the AIC criterion led to select a complete model with 5 variables and 7 interactions:

Single effect: **mesh size range**, **year**, **quarter**, **nursery** and **subarea**

Interaction effect: **mesh size** x **subarea**, **mesh size** x **nursery**, **subarea** x **nursery**, **subarea** x **quarter**, **nursery** x **year**, **nursery** x **quarter** and **mesh size** x **quarter**

The McFadden Pseudo-R² is fairly low: 0.062. However, the likelihood-ratio test is clearly significant ($p<2.2.10^{-16}$). Residuals (**Figure 17**) show a globally homogeneous distribution but the residuals structure is quite peculiar with a global underprediction for the smallest and the biggest length classes and an overprediction for the average length class. The model tends to underpredict the probability of belonging to the length classes 240-250, 320-330 and 340-350 and to underpredict the probability of belonging to length classes 270-280 and 290-300. Moreover for the last two length class, the residuals variability is higher. Finally, the analysis of variance indicates (**Appendix V**) that all variables and interactions kept in the model contribute significantly to explain the model variability. The cross validation shows that the model predicts only 4 length classes between 270mm and 340mm (**Appendix VI, a.).** It is coherent results given these are the main length classes. And from either side of these predicted length classes, the observed length classes are homogeneously distributed (**Appendix VI, b.**).

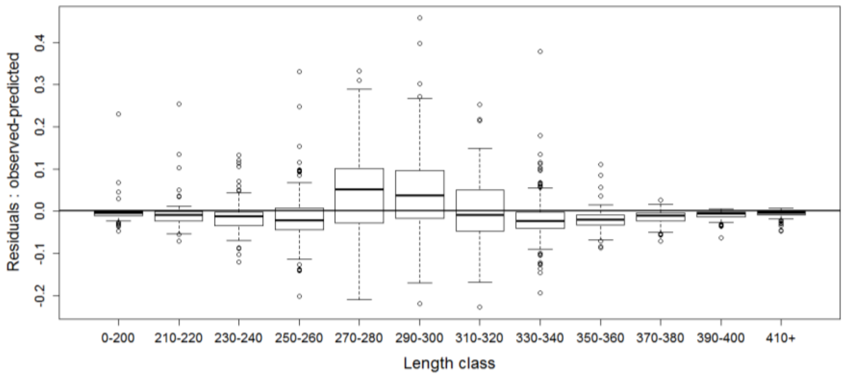

Figure 17: Residuals of the multinomial regression: observed length distribution - predicted length

In the following section, the means of predicted probabilities of belonging to each length class for each explanatory variable were plotted against length distributions of capture in order to judge the predictive quality of the Model.

Fishing gear

The observed length distribution (**Figure 18**) shows a shift toward the biggest length class for the captures with a mesh size in the 100-119mm range compared to the 90-99 range. The shape of the distribution of the 90-99mm mesh size range is narrower than 100-119mm one.

The multinomial regression model confirms a mesh size effect on the length distribution of the catch (**Appendix V**). The superposition of predicted values and observed values shows a mismatch (**Figure 18**). The mismatch is particularly important for the 100-119 mesh size range with overprediction on the small length and underprediction on the large length. However, the predicted distributions follow the main distribution patterns: (1) the distribution shift between the two mesh size ranges is predicted but slightly underestimated; (2) The difference in shape of the two respective distributions is well predicted.

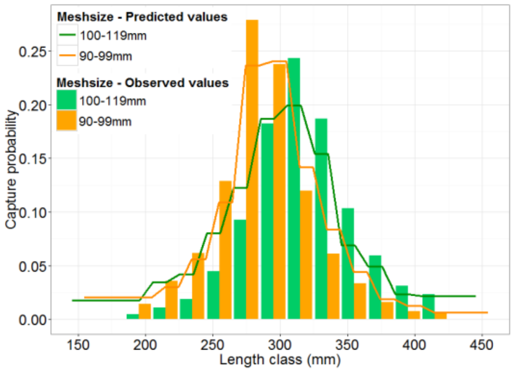

Figure 18: Predicted and observed length distributions of capture of common sole for two mesh size ranges 100-119mm and 90-99mm

Subarea

Observed length distributions show a great shift depending on the 2 subareas with a maximum around the length class 290-300 mm (**Figure 19, a.**). The shape of the distribution in the NE of the EEC is narrower than in the SW. In SW, frequencies of captures of small soles (smaller than 260mm) are very low and much lower than in NE. Furthermore, frequencies of captures of large soles (bigger than 300mm) are much higher.

Doing the analysis with the 2 mesh size ranges leads to the same observation (**Figure 19, b. and c.**). The shape of the distribution in the NE of the EEC is narrower than in the SW. With the 100-119mm mesh size range, the distributions show difference in mode and in shape (**Figure 19, c.**). In the SW, the distribution is wider than in the NE.

The multinomial regression model confirms a subarea effect on the length distribution of the catch and an interaction effect between the subarea and the mesh size range (**Appendix V**). But the model tends to underpredict the difference between the two subareas as shown the predicted probabilities (**Figure 19, a.**). On the large length, the length frequencies are overpredicted in the NE and underpredicted in the SW. In addition, the predicted frequencies are not very well predicted for the 100-119mm mesh size range, while the predicted frequencies are well predicted for the 90-99mm mesh size range.

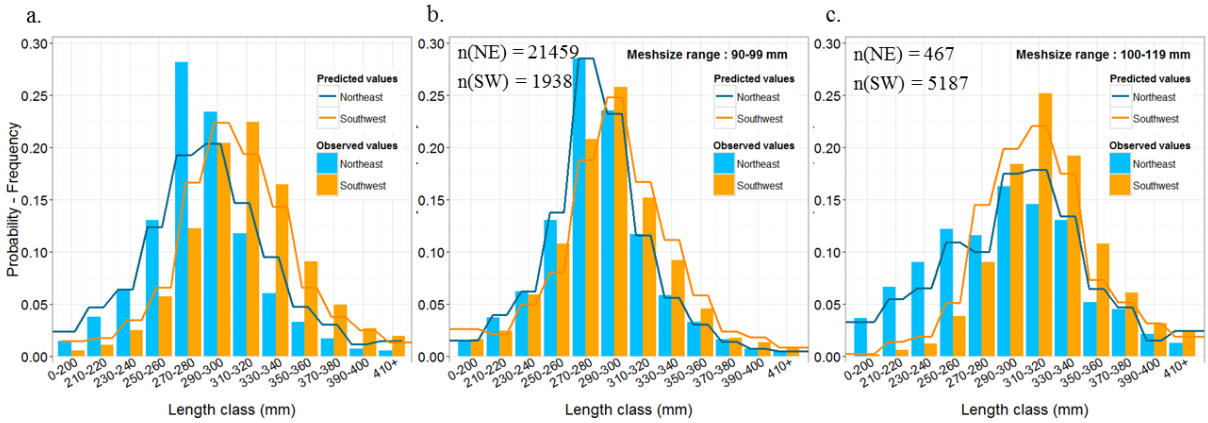

Figure 19: Predicted and observed length distribution of capture of common sole for the two subareas Northeast and Southwest (respectively in blue and in orange) for **a)** global catch, **b)** catches with mesh size in the range 90-99mm, and **c)** catches with mesh size in the range 100-119mm

Nurseries

A global view of length distributions in the nursery (**Figure 20, a.**) show a tenuous difference in catch at length between soles caught in and out nursery areas, except a slight shift toward the biggest length class outside the nursery area. However, length distribution of captures in and out of the nursery areas is very different depending on the mesh size range used (**Figure 20, b. and c.**); there is no significant difference in the distributions associated with the mesh size range 90-99m, whereas the difference (a shift and a difference in shape) is particularly important in the case of the range 100-119mm (**Figure 20, c.**).

The multinomial regression model confirms a nursery effect on the length distribution of the catch and an interaction effect between the nursery and the mesh size range (**Appendix V**). But the model tends to underpredict the length frequencies of captures of small soles and to overpredict the length frequencies of captures of large soles (**Figure 20, a.**).

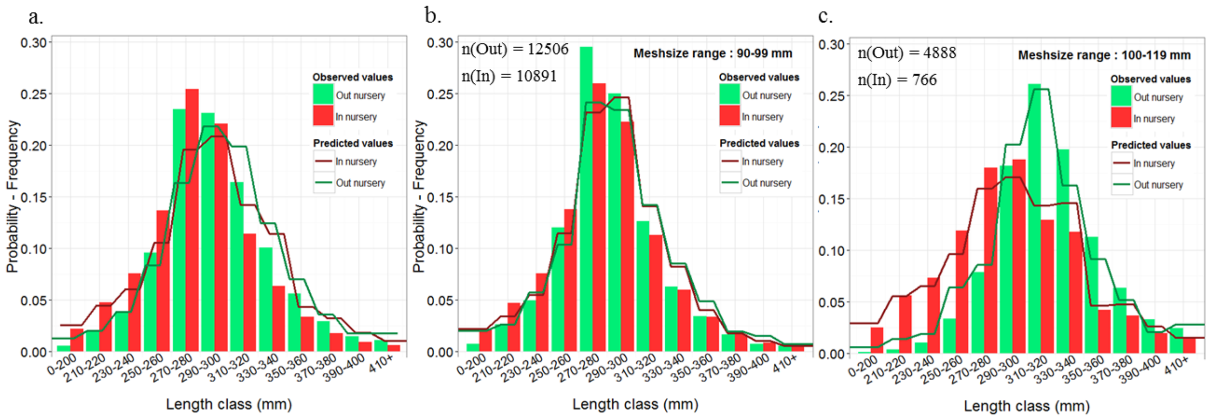

Figure 20: Predicted and observed length distributions of capture of common sole in or out the nursery areas (respectively in red and in green) for **a)** global catch, **b)** catches with mesh size range 90-99mm, and **c)** catches with mesh size range 100-119m

The multinomial regression model indicates that the interaction effect between the quarter and the nursery is significant (**Appendix V**). This is particularly interesting to take into account this interaction given the seasonal spawning migration.

With the mesh size range 90-99mm (**Figure 21, a**.), length distributions of soles caught outside and inside the nursery areas vary throughout the year. The proportion of small soles (between 220 and 240 mm) caught in and out the nursery area is lower in the 1st and the 4th quarter. Then, the proportion of small soles (220-240mm) increases in the 2nd and the 3rd quarter in the nursery areas and, to a lesser extent, in the 3rd quarter outside the nursery area. In the 2nd and the 3rd quarter, the difference in the length distributions of captures inside and outside the nursery area is the highest. In the 4th quarter, the length distributions retighten and, in the nursery areas the distribution is slightly shifted toward the large length in comparison with the catches out the nursery area.

In the case of the mesh size range 100-119mm (**Figure 21, b**.), the results are harder to interpret given the low numbers of individuals, particularly for the nursery grounds. Outside the nurseries, the length distributions are wider in the 2nd and the 3rd quarter and narrower in the 4th quarter. The results for 3rd quarter (which is the quarter with the most data for the 100-119mm) indicate a much more important difference in length distribution between in and out the nursery grounds.

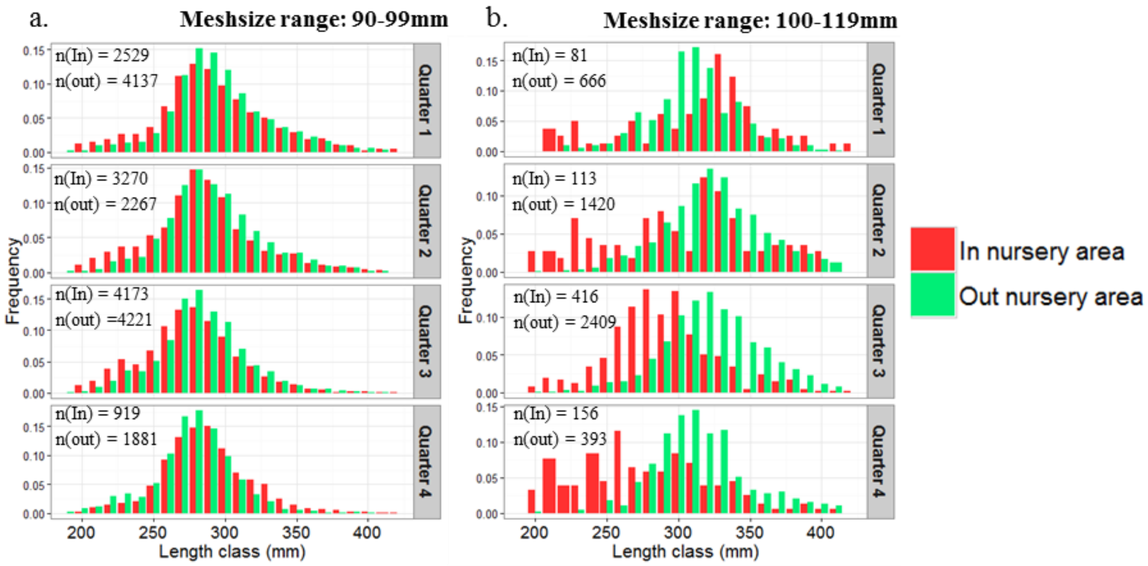

Figure 21: Length distribution of capture of common sole in or out the nursery areas (respectively in red and in green) by quarter and by a mesh size range: **a)** 90-99mm and **b)** 100-119mm. n(In) and n(out) indicate the number of individual in each length distribution

Quarter

Length distributions of the soles caught with the mesh size range 90-99mm (**Figure 22, a.**) vary with the season of catch, the distribution is shifted toward bigger length classes for the soles caught in the 1st quarter and to a less extent in the 2nd quarter. In the 3rd and the 4th quarter, length distributions are narrower and shifted toward the small length classes.

The length distributions of soles caught with a mesh size in the range 100-119mm (**Figure 22, a.**) follow a different pattern. Firstly, the length distribution for the range 100-119mm is globally wider than the range 90-99mm. During the 1st quarter and the 4th quarter soles caught are shifted toward the small lengths but the distribution in the 1st quarter is much narrower than in 4th quarter. Length distributions of the soles caught in the 2nd and the 3rd quarter are very similar and shifted toward the large lengths.

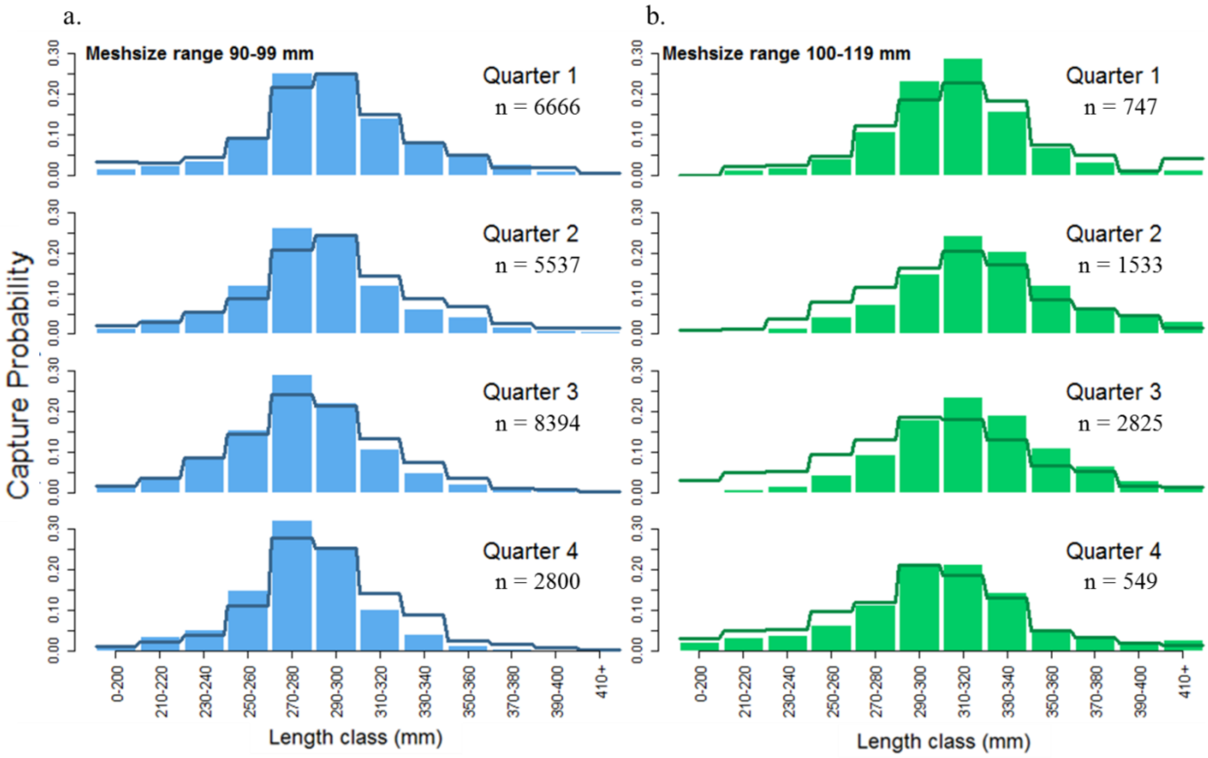

Figure 22: Predicted and observed length distribution of capture of common soles by quarter and by a mesh size range 90-99mm **(a)** and 100-119mm **(b)**.

The multinomial model indicates the significant effect of the quarter on the length distribution and the interaction effect between quarter and mesh size (**Appendix V**).

Except for the 4th quarter, the predicted length frequencies for the mesh size range 90-99mm are well fitted with the observed distribution. In the other hand, the predicted length frequencies are for the mesh size range 100-119mm are badly fitted, in particular for the 2nd and the 3rd quarter.

Year

The year effect also show some dissimilarities in length distributions depending on mesh size ranges used. For the mesh size range 90-99mm (**Figure 23, a.**), the length distributions were shifted toward small length class between 2011 and 2013 in comparison with the others years. In comparison with the other mesh size range (**Figure 23, b.**), distributions are narrower, except in 2015 in which the distribution is spreader. For the mesh size range 100-199mm, the distributions were shifted toward small length class in 2014 and 2015 whereas 2009 was shifted toward the big length class.

The multinomial model indicates the significant effect of the year on the length distribution (**Appendix V**). However, the predicted length frequencies show an important mismatch with the observed distributions for the two mesh size ranges (**Figure 23, a. and b.**).

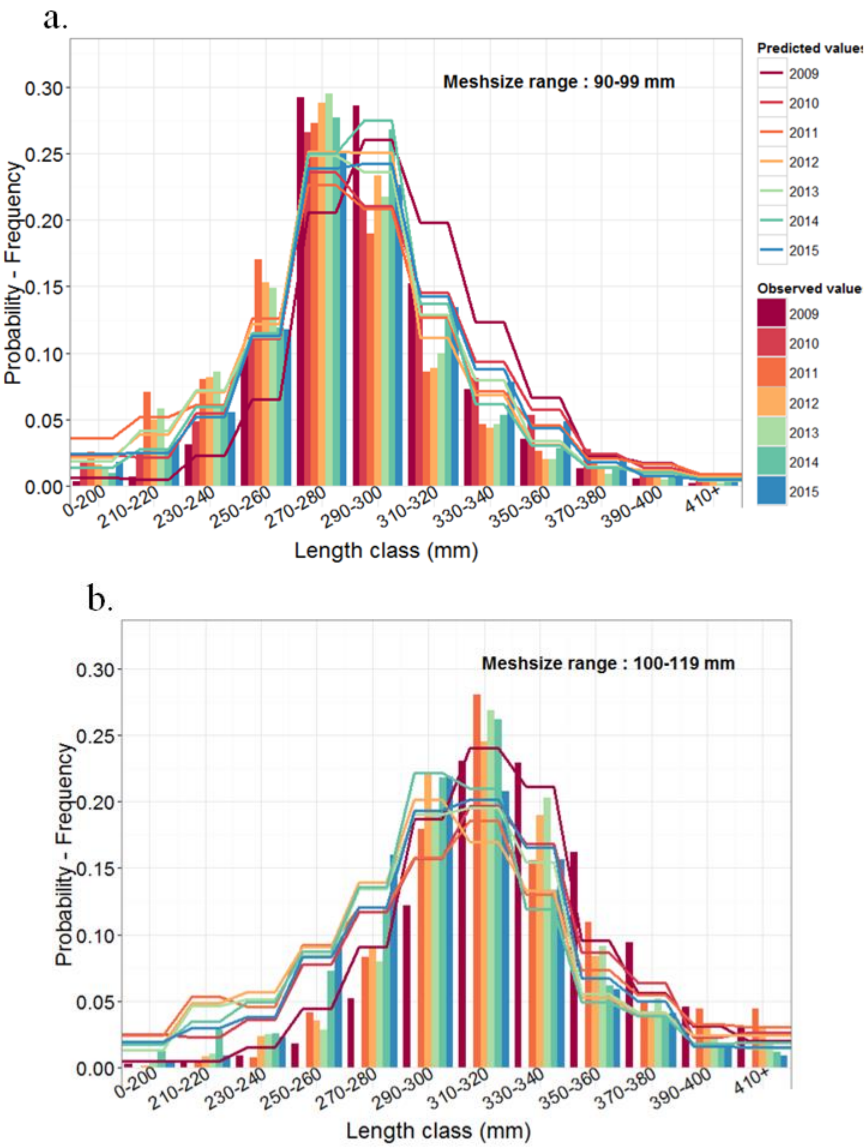

Figure 23: Predicted and observed length distribution of capture of common soles by year and by a mesh size range 90-99mm **(a)** and 100-119mm **(b)**.

3.4. Discussion

3.4.1. Fishing impact – Selectivity

In a first approach, the mesh size range used affects catch-at-length given that it is the first variable in the two regression trees and a significant variable in the multinomial model. The mesh size range of the inner panel in trammel net gear appears to determine not only the mean length but also the shape of the length distribution. Indeed, increasing the mesh size range, the length distributions are shifted toward the biggest lengths but distributions are flatter. In addition, the trammel nets with 100-119mm mesh size ranges show a high sensibility depending on catches area. Differences in length structure are really important depending on the subarea and on the nursery areas. It might suggest that fishing areas in which go the trammel netter using 100-119mm range determine a lot (much more than for the trammel netters using 90-99mm range) the length structure of the captures.

In Obsmer dataset, meshes of trammel nets in which we focused (90-99mm and 100-119mm) were aggregated in size ranges. In consequences, the diversity of mesh sizes in trammel net fisheries targeting common sole in the EEC was not included. It may have biased our understanding of the effect of mesh size on the length composition and notably the differential mesh size effect depending on subarea. Indeed, the shift between the NE and the SW is less important for the mesh size range 90-99mm. It could be partly due to the diversity into the 90-99mm range reported by fishermen and fishermen committees. In the SW of the EEC, fishermen using a mesh size in the 90-99mm range are equipped with 94mm mesh size whereas in the NE they use, mostly, 90mm mesh size. In addition, information concerning the type of materials of the net is not provided in the Obsmer dataset. But, fishermen and fishermen committees report that different materials are used to catch common soles in the EEC: monofilament and multifilament. It can influence the selectivity of the fishing gear and, so the length structure of the catch. The wide shape of the length structure of the catches for the 100-119mm mesh size range could be influenced by the type of line used to build the nets.

Furthermore, Matsuoka (1991) expressed size selectivity for the trammel net in function of two main components: wedging and entangling. This could explain the bimodality of selectivity curves as assumed by Losanes et al. (1992a): while the first mode could be correspond to fish that are essentially gilled or wedged, the second one could be attributed to entangling or trammelling/pocketing (particularly due to the outer panel) . The difference in shape between mesh size ranges could be influenced by the relative importance of these two components. The narrow length distribution of the catches for the 90-99mm range could be explained by selectivity due to only one component wedging **or** entangling whereas the selectivity of 100-119mm range might be influenced by wedging **and** entangling.

Others parameters could change the efficiency of the fishing gears like the orientation of the trammel net relative to tidal current and the type of material of the fishing gears. Indeed, fishermen in the south of the EEC tend to use multifilament trammel nets positioned perpendicularly to tidal current. On the contrary, in the north part of the EEC, they tend to use monofilament trammel nets positioned parallel to tidal current.

3.4.2. **Impact of structure of population**

One of the assumptions is based on the fact that length structure of the population affects directly length structure of the catches. Consequently, the variability in length structure of the catch can suggest variability in length structure of the population. To detect it, it is necessary to take into account a part of variability in length structure induced by fishing. The shift of length distribution between the subarea in the SW of the EEC and the subarea in the NE found for catches of the two mesh size ranges studied could be a sign of a difference of structure of population. This difference between the subareas is found also quarterly (**Appendix VII**) and yearly (**Appendix VIII**) for the two mesh size ranges. However, Subarea variability in the EEC is harder to interpret given spatial structuration in terms of mesh size range used. Obsmer dataset provide little data for trammel net with 90-99mm mesh size ranges in the SW and very little data for trammel net with 100-119mm mesh size ranges in the NE.

3.4.3. **Nursery ground**

Length distributions in the nursery ground show that globally length distributions in these areas are shifted toward the small length. For the mesh size range 90-99m, the increase of proportion of small length (between 220 and 240mm) in the 2nd and in the 3rd quarter, lead to an increase of discards given a minimum landings size (MLS) of 240mm.

3.4.4. Temporal variability

The length distributions of captures show a quarterly variability with higher distribution of proportion of small soles caught in the 2nd and the 3rd quarter by the 90-99mm range and from the 3rd quarter by the 100-119mm range (**Figure 22**). It could explain by the recruitment (the arrival of young soles in the stock) and then the decrease of proportion of small soles could be due to weighted gain of these small soles. But, the shift of the increase of proportion of small soles between the two meshsize ranges could indicate a shift in the arrival of recruitment between the two subareas (knowing that almost all of 90-99 mm is concentrated in the NE of the EEC and that all of 100-119mm is concentrated in the SW). In parallel, fishermen report a shift in fishing period; it starts sooner in the NE than in the SW thanks to the increase of concentration of big soles close to the coast from the 1st quarter. It might suggest a shift in the spawning period.

In the other hand, the annual variability in the catches of small soles can be linked with the recruitment. Between 2009 and 2015, the highest catches of small soles are correlated with a good recruitment 2 years before, and inversely, the lowest catches of small soles are correlated with bad recruitment (**Figure 23**). This catches of small soles are particularly important in the nursery areas and the size of catches are under the MLS. This raises questions in terms of management because it is damaging to the stock of the impact that these small soles from good recruitment are caught and discarded because below the MLS.

Figure 24: At right, the observed length distribution of common soles capture of trammel netters (90-99mm and 100-119mm) by year between 2009 and 2015 in and out nursery areas (in red and in green, respectively). At left, the recruitment for age 1 (ICES, 2016). The red arrows indicate the good recruitments and the blue arrows the bad recruitment

4. Spatial analysis of growth parameters of common sole in the Eastern English Channel

In the previous section, the catch at length study, suggested differences in length structure between two regions: the Southwest (SW) of the EEC and the Northeast (NE) of the Eastern English Channel (EEC). These differences in length could be due to differences in growth between the 2 subareas. Therefore, this section aims to test the existence of differences in the growth parameters of soles caught in the SW and the NE of the EEC. Available length-at-age data were used to fit Von Bertalanffy relations with non-linear mixed effects model in order to take into account not only the subareas but also the variability linked to the quarter, the sexual dimorphism and the year.

4.1. Materials & Methods

4.1.1. Data

All French individual data collected during French survey or commercial sampling are stored in the database BARGEO. For common sole in the EEC, most of the samples come from commercial samplings and to a less extent surveys. BARGEO provides individual information on age, length and weight, sampling date, fishing ICES division (or position in case of a scientific survey), fishing gear and vessel ID.

To undertake spatial analysis, it is necessary to obtain the fishing location of each sampling, or an approximate of it. SACROIS provides spatial information at the scale of the statistical rectangle. In order to refine the spatial information of the commercial landings (from ICES division to ICES squares), SACROIS database was merged with BARGEO database using vessel ID and sampling/landing keys. The main assumption made during the merging is that soles sampled were coming from the statistical rectangle where the fishing vessel caught the biggest volume of sole during the trip.

4.1.2. Estimation of growth parameters

The most studied and commonly applied model among all the length–age models is the von Bertalanffy growth model: The process of individual growth in fish is rooted in physiological processes and is the net result of two opposing processes, catabolism and anabolism (Von Bertalanffy, 1957). The growth curve was fitted from age 2 because there were no age 0 and too few individuals at age 1 sampled.

$$\boldsymbol{Lt} = \boldsymbol{Linf} - (\boldsymbol{Linf} - \boldsymbol{L2}) \times \boldsymbol{exp}(-\boldsymbol{K} \times (\boldsymbol{t} - \mathbf{2})) \quad (6)$$

Where, ***Lt*** is the length at time ***t***, ***L2*** the length at age 2, ***Linf*** the asymptotic maximum length and ***K*** the growth rate i.e. the speed at which the asymptotic length is reached (in year-1).

Growth parameters were fitted for 4520 individual caught between 2010 and 2015 considering the subarea to detect potential growth variability between the NE of the EEC and the SW. In addition, the quarter sampling was integrated to take into account the continuous growth over the year. Indeed, the sampling was not conducted uniformly over the year, so growth parameter could vary depending on the sampling period given the continuous growth of fishes over the year. Sex of common sole was also integrated in the model, to take into account the sexual dimorphism and heterogeneous distribution of the sex of individuals in the sampling (64% of females in the SW and 87% of female in the NE). Finally, the sampling year was integrated as a random effect to take into account the inter-annual growth variability which could be, for instance, due to changes in food availability or intraspecific competition.

4.1.3. **Analytical Method**

The growth curve was fitted thanks to a nonlinear mixed-effects model.

The nonlinear mixed-effects model aims to test the subarea and quarter effects on growth parameters while accounting for the noise related to the year. The subarea and the quarter were the fixed effects and the year was the random effect.

The nonlinear mixed-effects model for repeated measures proposed by Lindstrom and Bates (1990) can be thought of as a hierarchical model (Pinheiro and Bates, 2000). At one level the j^{th} individual of the i^{th} year is modelled as:

$$\boldsymbol{y_{i,j} = Linf_i - (Linf_i - L2_i) \times exp\left(-K_i \times \left(t_j - 2\right)\right) + \varepsilon_{i,j}} \quad (7)$$

i =2000, …, 2015 **and** ***j = 1,..., n_i*** and $\boldsymbol{\varepsilon_{i,j} \sim N(0, \Psi)}$

Where n_i is the number of individuals in the i^{th} year.

$$\begin{aligned} \boldsymbol{K_i} &= (\boldsymbol{\beta_1} + \boldsymbol{b_{1,i}}) + \boldsymbol{\beta_2\, x_{1,i}} + \boldsymbol{\beta_3\, y_{1,i}} + \boldsymbol{\beta_4 z_{1,2,i}} + \boldsymbol{\beta_5 z_{1,3,i}} + \boldsymbol{\beta_6 z_{1,4,i}} \\ \boldsymbol{Linf_i} &= (\boldsymbol{\beta_7} + \boldsymbol{b_{2,i}}) + \boldsymbol{\beta_8\, x_{2,i}} + \boldsymbol{\beta_8\, y_{2,i}} + \boldsymbol{\beta_9 z_{2,2,i}} + \boldsymbol{\beta_{10} z_{2,3,i}} + \boldsymbol{\beta_{11} z_{2,4,i}} \\ \boldsymbol{L2_i} &= (\boldsymbol{\beta_{12}} + \boldsymbol{b_{3,i}}) + \boldsymbol{\beta_{13}\, x_{3,i}} + \boldsymbol{\beta_{14}\, y_{3,i}} + \boldsymbol{\beta_{15} z_{3,2,i}} + \boldsymbol{\beta_{16} z_{3,3,i}} + \boldsymbol{\beta_{17} z_{3,4,i}} \end{aligned} \quad (8)$$

Where

$$\boldsymbol{x_{k,i}(\omega) = \begin{cases} 1, & Subarea\ of\ individual\ i = Northeast \\ 0, & Subarea\ of\ individual\ i = Southwest \end{cases}}$$

$\boldsymbol{k} \in [\boldsymbol{K_i}, \boldsymbol{Linf_i}, \boldsymbol{L2_i}]$ **and** ***i =2000, … , 2015***

$$\boldsymbol{y_{k,i}(\omega) = \begin{cases} 1, & Sex\ of\ individual\ i = Male \\ 0, & Sex\ of\ individual\ i = Female \end{cases}}$$

$\boldsymbol{k} \in [\boldsymbol{K_i}, \boldsymbol{Linf_i}, \boldsymbol{L2_i}]$ **and** ***i =2000, … , 2015***

$$\boldsymbol{z_{k,q,i}(\omega) = \begin{cases} 1, & Quarter\ of\ individual\ i = q \\ 0, & Quarter\ of\ individual\ i \neq q \end{cases}}$$

$\boldsymbol{k} \in [\boldsymbol{K_i}, \boldsymbol{Linf_i}, \boldsymbol{L2_i}]$, ***i =2000, … , 2015,*** **and** ***q=1, … , 4***

And $\boldsymbol{b_i}$ is the random effect vector associated with the i^{th} year

$$\boldsymbol{b_i} = \begin{bmatrix} \boldsymbol{b_{1,i}} \\ \boldsymbol{b_{2,i}} \\ \boldsymbol{b_{3,i}} \end{bmatrix} \sim \boldsymbol{N(0, \Psi)} \quad (9)$$

Where $\boldsymbol{\Psi}$ is the variance-covariance matrix: $\boldsymbol{\Psi} = \begin{bmatrix} \boldsymbol{\Psi_{1,1}} & \boldsymbol{\Psi_{2,1}} & \boldsymbol{\Psi_{3,1}} \\ \boldsymbol{\Psi_{2,1}} & \boldsymbol{\Psi_{2,2}} & \boldsymbol{\Psi_{3,1}} \\ \boldsymbol{\Psi_{3,1}} & \boldsymbol{\Psi_{3,2}} & \boldsymbol{\Psi_{3,3}} \end{bmatrix}$ **(10)**

Model selection aimed to determine whether the three parameters improved significantly the significance of the model for each effect: the *random effect* and the 3 *fixed effects*. The mixed-effects model was fitted based on maximal likelihood. The likelihood ratio tests was used to test the random effect structures (Pinheiro and Bates, 2000), even if they can be somewhat conservative (Pinheiro and Bates, 2000). In consequence, the AIC was also taken in consideration to compare the random effect structures. According to Pinheiro and Bates, (2000), simple likelihood ratio tests for testing the significance of parameter for the *fixed effect* can be somewhat "anti-conservative" in that they tend to suggest more significant parameters than the actual number of significant parameters. For this reason, the Akaike Information Criterion (AIC) was used to determine whether parameters are significant or not.

The selection was performed using a backward stepwise procedure. The first step aimed to compare a random effect with a block-diagonal variance-covariance matrix ($\boldsymbol{\Psi_{1,1}}, \boldsymbol{\Psi_{2,2}}, \boldsymbol{\Psi_{3,3}}, \boldsymbol{\Psi_{2,1}}, \boldsymbol{\Psi_{2,3}}, \boldsymbol{\Psi_{3,1}}$) and with only the variances ($\boldsymbol{\Psi_{1,1}}, \boldsymbol{\Psi_{2,2}}, \boldsymbol{\Psi_{3,3}}$) using the likelihood ratio tests and the AIC. Then, the significance of each parameter of the random effect was tested using the likelihood ratio tests and the AIC. The significance of each parameter for the fixed effect was finally tested, using the AIC. The starting model was the full model and we tested the deletion of each parameter using AIC (and the likelihood ratio tests for the random effect), deleting the variable that improved the model (by reducing the AIC) or that did not changed the models quality (AIC ~ 0 or p-value of the likelihood ratio tests < 0.05) by being deleted. The process was repeated until no further improvement was possible.

4.2. Results

The model selected with the backward procedure **(Appendix IX)** is composed of:

- The random effect :
  - *Year effect:* **variances** on the 3 growth parameters
- 3 fixed effects :
  - *Subarea effect* : **K** and **Linf**
  - *Sex effect* **: K, Linf** and **L2**
  - *Quarter effect* **: K** and **L2**

The quarter effect on the Linf was removed from the model in the preliminary analysis due a systematically wrong estimation of the Linf for the 4th quarter. It might be due to the low number of individuals in the 4th quarter, in particular from the SW area, as shown in the factorial design **(Appendix X).**

The residuals are distributed symmetrically around zero but the variance decreases toward the small fitted value and the residuals seems more positive (**Figure 25, a.**). The tails of distribution on the normal plot of the standardized residuals, shown in **Figure 25, b.**, confirms that the overestimation on the small length and show a slight underestimation on the large length. However, it does not indicate any important violation of the normality assumption.

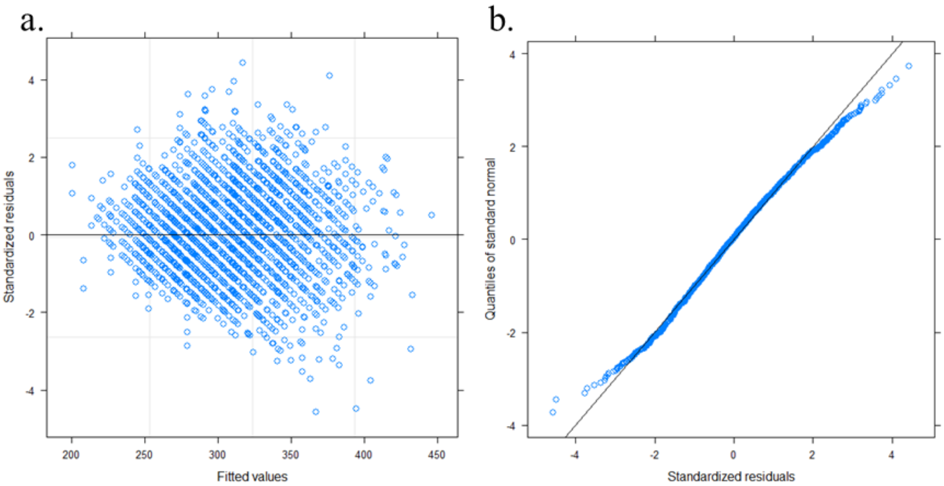

Figure 25: Residuals of the non-linear mixed model; a) Fitted values vs Standardized residuas; b) QQ plot

The *Subarea effect* induces a variation of the **K** parameter, the growth rate, the **Linf** parameter, the asymptotic length. The analysis of variance (**Appendix XI**) shows the significance (t-test < 0.0001) of the coefficients associated to **K** and **Linf** for this effect. The mean values of **K** are between 5% and 15% (depending on the quarter) higher in the NE of the EEC than in the SW of the EEC (**Table 4**). The mean values of **Linf** are 12% and 16% (for the female and the male, respectively) lower in the NE of the EEC than in the SW of the EEC (**Table 4**).

The *Sex effect* induces a variation of the **K** parameter, the **Linf** parameter and the **L2 (**length at age 2) parameter. The analysis of variance (**Appendix XI**) shows the significance (t-test < 0.0001) of the coefficients associated to **K, Linf** and **L2** for this effect. The mean values of **K** are 10% and 26% (depending on the quarter and the subarea) higher for the female than for the male (**Table 4**). The mean values of **Linf** are 12% and 16% (for the SW and the NE, respectively) higher for the female than for the male (**Table 4**). The mean values of **L2** are between 3.5% and 4.2% (depending on the quarter) lower for the male (**Table 4**).

The *quarter effect* induces a variation of the **K** parameter and the **L2** parameter. The analysis of variance (**Appendix XI**) shows the significance (t-test < 0.0001) of the coefficients associated to **K** and **L2** for this effect. The mean values of **K** increase from the 1st quarter to the 4th quarter for all quarters and in the 2 subareas (**Table 4**). The mean values of **L2** drop between the 1st and 2nd quarter for male and female. In the 3rd quarter, it still decreases slightly and, in the 4th quarter, it remains equal to the 3rd quarter (**Table 4**).

Finally, the growth curve for each combination of year, quarter and subarea for female and male common sole are displayed in **Appendix XIII** and **Appendix XIV.**

Table 4: Mean value of the growth parameters from the non-linear mixed model between 2010 and 2015 for each combination of *Quarter*, *Subarea* and *Sex* kept in model. In the last column, the percentage of difference was computed between two subareas in the EEC: the Northeast (NE) and the Southwest (SW).

Growth Parameters	Quarter	Subarea	Sex	Value	% var NE/SW
K (in year-1)	1	NE	F	0.19	11
	1	SW	F	0.17	
	1	NE	M	0.15	15
	1	SW	M	0.12	
	2	NE	F	0.28	7
	2	SW	F	0.26	
	2	NE	M	0.24	9
	2	SW	M	0.22	
	3	NE	F	0.38	6
	3	SW	F	0.36	
	3	NE	M	0.34	6
	3	SW	M	0.32	
	4	NE	F	0.44	5
	4	SW	F	0.42	
	4	NE	M	0.40	5
	4	SW	M	0.38	
Linf (in mm)	1, 2, 3, 4	NE	F	382.65	12
		SW	F	435.73	
	1, 2, 3, 4	NE	M	322.72	16
		SW	M	382.65	
L2 (in mm)	1	NE, SW	F	263.34	
	1	NE, SW	M	254.24	
	2	NE, SW	F	230.06	
	2	NE, SW	M	220.96	
	3	NE, SW	F	219.08	
	3	NE, SW	M	209.98	
	4	NE, SW	F	221.06	
	4	NE, SW	M	211.96	

4.3. Discussion

Firstly, the analysis of the growth parameters confirms common sole dimorphism in the EEC showing a differential growth between male and female. The growth rate, the asymptotic length and the length at age 2 are higher for the female in the two subarea.

In addition, the quarter effect on the growths parameters is hard to interpret because quarterly changes in mean length at each age are not consistent as shown in appendix from the age 2 to the age 6 **(Appendix XV**). We cannot observe a progressive and continuous growth and a similar pattern over the years. However, we can attribute the drop of the L2 between the 1st and the 2nd quarter to the changes in age class of individuals from the age 2 to age 3.

The hypothesis of heterogeneity in the growth parameters between the NE and the SW of the EEC is validated for Linf, the asymptotic length and, the growth rate. L2 does not vary significantly depending on the subarea of the EEC.

Overall, the significant differences in growth parameters between subareas suggest a low mobility of soles, or even the existence of two sub populations. This corroborates the results of the mark-recapture survey investigated by Burt and Millner (2008) which show a low mobility of adult sole in the EEC : sole of the NE could only migrate to the English coasts and sole of the SW made only short migrations. The growth differences between the SW and the NE of the EEC might be due to phenotypic differences in response to different environnemental conditions (for example difference in food availability or abiotic conditions). This variability in growth parameters could also due to the existence of 2 subpopulations in the NE and in the SW of the ECC with each its own growth characterics. Fish growth is subject to a high degree of genetically-based variation and therefore has the potential to evolve rapidly in response to harvesting or environnemental changes (Lorenzen, 2016). Evolutionary effects of fishing on growth may arise from multiple mechanisms including size selective fishing (Enberg et al., 2012). Differences in size selective haversting between the NE and the SW of the EEC (c.f. section 2.2.1) could have created or increased differences in growth rate (Conover and Munch, 2002) and in the size-at-age. It could, notably, be due to the selection of mature individuals earlier in the NE (as shown by Mollet et al. (2007) for the common sole in the North Sea).

Given that the K parameter is lower in the NE, it might suggest that the growth rate is lower in the NE of the EEC. However, in the Von Bertalanffy relation, K is not strictly the growth but it is the speed at which the asymptotic length is reached.

The lower asymptotic length in the NE of the EEC might suggest that maturation age and length occurs sooner than in the SW (Roff, 1983). Indeed, after maturation, the available energy is not fully allocated to growth anymore; a significant portion being used for breeding. The individual grows less quickly after the maturation.

The subarea effect on the length at age 2 was not selected in the final model, so the estimated length at age 2 is the same for the two subareas.

This analysis from Bargeo data is partly biased because the soles sampled come mainly from commercial fisheries; they have been caught with different selective fishing gears and might not be representative of the actual population(s).The analysis of additional survey data (e.g. Data from the English survey UK-BTS) could confirm or refute the results of this study. In this study, the year has been considered as a random effect to account for the inter-annual variability, but in fish population, it could exist also inter-cohort growth variability (Feltrim Marcelo and Ernst, 2010; Whitten et al., 2013). So, a cohort effect could be considered as a random effect in the model.

5. From catches to landings

In the previous sections, the spatio-temporal structuration of sole landings in the EEC was highlighted, and the variability of length structures for the trammel netters was described for trammel netters. The results obtained on the landings per CC are consistent with those obtained on the catch size structures: Thus, the higher proportion of smaller commercial categories in the NE sole landings are at least partly due to the higher proportion of smaller soles in the catch. Another reason might be different discard practices. Therefore, we came back to exploitation patterns and focused in this section on the links between catches and landings in the different regions focusing on the trammel netter.

5.1. Materials & Methods

5.1.1. **Data**

Data used in this section are extracted from the OBSMER database (cf section 3.2.1) and identical to the ones used in chapter 3, except that in this section we focus on another variable not used previously: the catch category (discards or landings).

5.1.2. **Discarded fraction estimate**

The discarded fraction was computed using the OBMER procedure (Isabelle et al., 2015): by averaging the discarded proportions of common soles of each sampled fishing operation (FO), weighted by the weight of the catch of common soles of the FO. Estimates of discarded fractions are calculated under the assumption of independence of each FO.

5.2. Results

The discard rate of common soles in the EEC was globally low for trammel netters between 2010 and 2015. In the NE of the EEC, it was twice as high, on average, as in the SW between 2009 and 2015 (1.4% in the NE and 0.7% in the SW). But, in this period the rate of discard was higher in SW in 2010 and 2014 (**Figure 26, a.**). In SW, the mean discard length fluctuated a lot (270mm in 2009, 180mm in 2010) over the years between 2009 and 2015 but it was on average (236mm) higher than in the NE where the mean length of discard of sole remained stable around 220mm (**Figure 26, b.**).

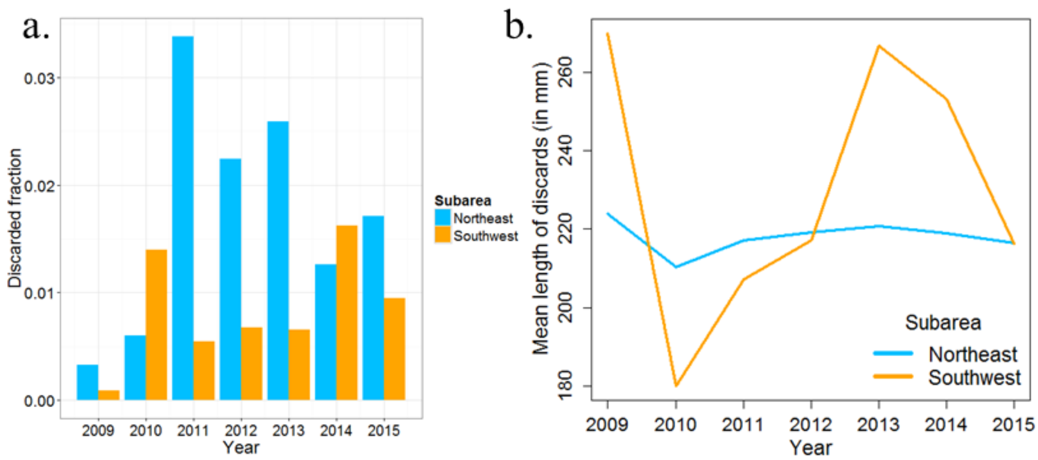

Figure 26: a) Discarded fraction and **b)** Mean length of the discards of common sole captures by trammel netters in the EEC by subarea and by year, between 2010 and 2015.

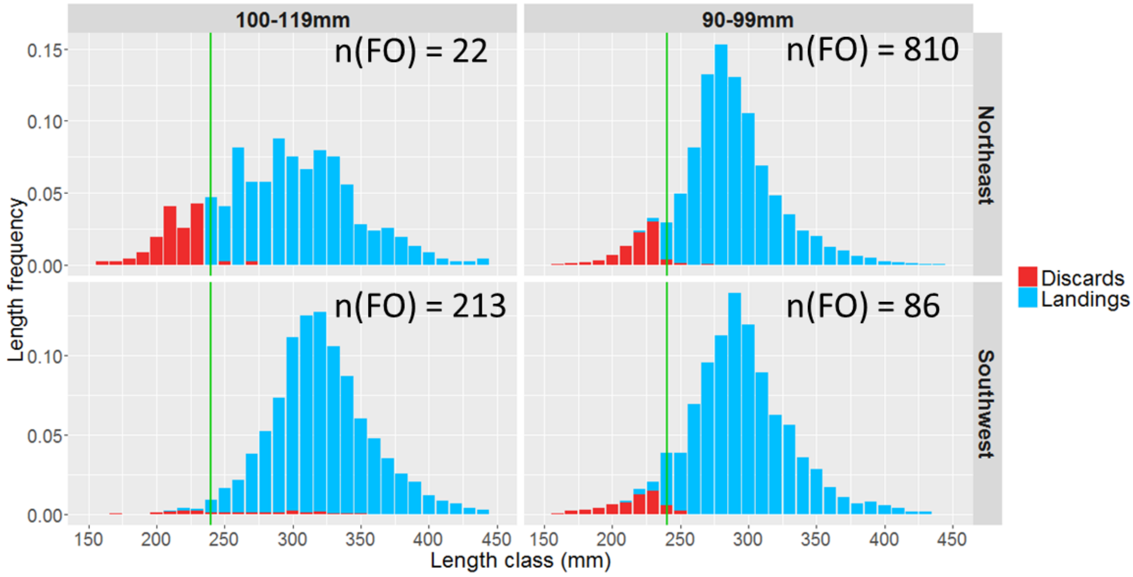

Figure 27: Sole discards and landings length distribution between 2009 and 2015 in the NE and in the SW of the EEC for the mesh size ranges 90-99mm and 100-119mm; n(FO) indicate the number of fishing operations used to produce each length distribution and the green line indicates the MLS before 2015 (240mm).

The length structures of discards by subarea show that almost all the soles discarded in the NE of the EEC are smaller than the minimum landing size (MLS) (240mm) with the 90-99mm and 100-119mm mesh size range, while the soles discarded in the SW with the 100-119mm mesh size range are widely distributed and can reach 350mm (but they represent a very low proportion of catches) (**Figure 27**). In the case of the 90-99mm mesh size range in the SW of the EEC, the discard volumes are lower than in the NE because catches of soles below the MLS are lower; however the discards are concentrated below the MLS.

Between 2009 and 2015, the discard rate is, on average, higher in Haute-Normandie (HN) (2.6%) than in Hauts-de-France (HF) (1%) and in Basse-Normandie (BN) (0.5%) (**Figure 28, a).** Except in 2014, the discard rate in BN remained very low compared to the two others regions. The mean length of the discards was higher (staying over the MLS) but more variable over the years in BN than in HF and in HN where the mean length was around 220mm (**Figure 28, b**).

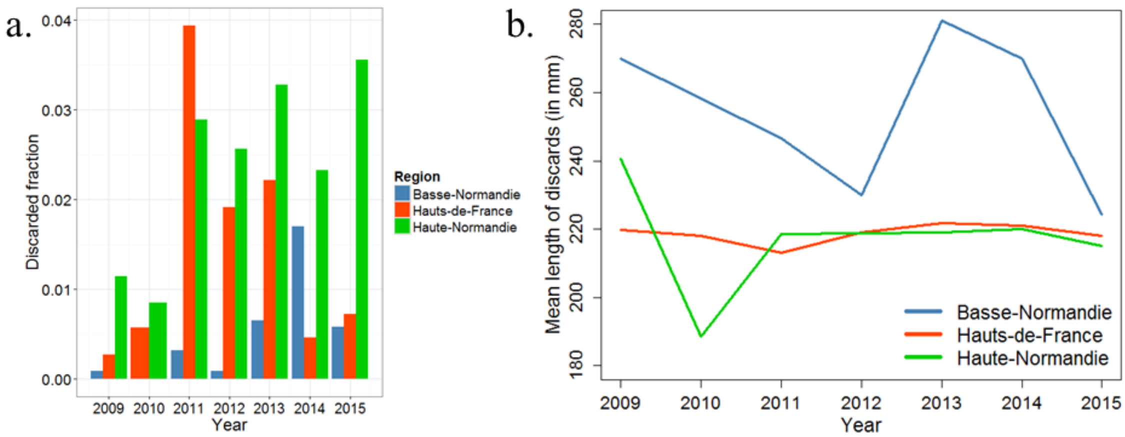

Figure 28: a) Discarded fraction and **b)** Mean length of the discards of common sole captures by trammel netters in the EEC by region and by year, between 2010 and 2015

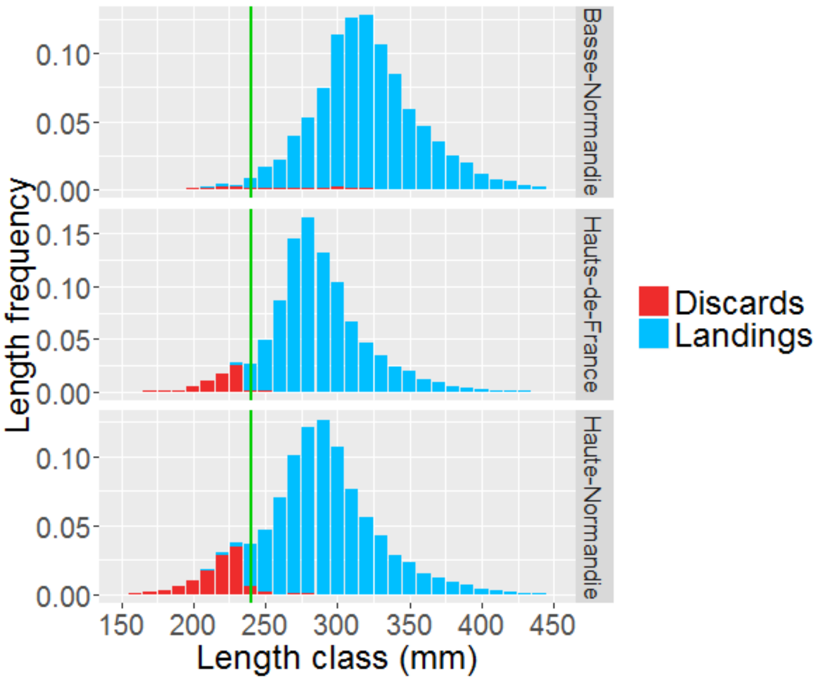

Figure 29: Sole landings and discards length distributions between 2009 and 2015 in Basse-Normandie, Hauts-de-France and Haute-Normandie; the green line indicates the MLS before 2015 (240mm).

The length structures of the discards are the same in HF and in HN with almost all of the soles discarded below the MLS while the length structure of the sole discarded in the BN is wider (**Figure 29**).

Nursery area

Between 2009 and 2015, the discard rate was higher inside the nurseries (2.21% in average) than outside (0.8% in average) (**Figure 30, a.**). The mean length of discards was higher over the years (except in 2011) outside nurseries than inside (**Figure 30, b.**). The discards length structures in and out of the nursery areas show that the soles discarded inside the nursery areas represent a significant proportion of the catches (**Figure 31**). They were smaller than the MLS with the 90-99mm mesh size range and, with the 100-119mm range a small proportion of discards was higher than the MLS. Outside nurseries, in the case of the 100-119mm mesh size range, almost all the soles caught were above the MLS and the discards were widely distributed whereas, in the case of the 90-99mm range, almost all the discards were concentrated below the MLS.

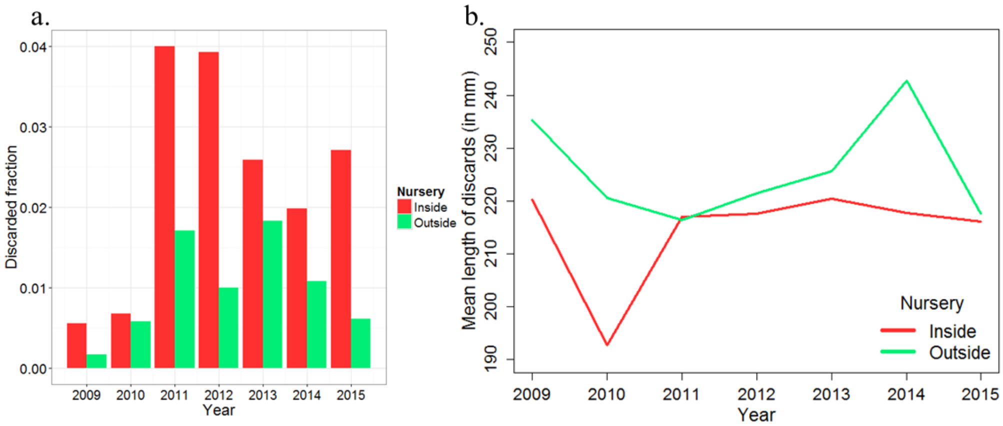

Figure 30: a) Discarded fraction and **b)** Mean length of the discards of common sole captures by trammel netters in the EEC by region and by year, between 2010 and 2015.

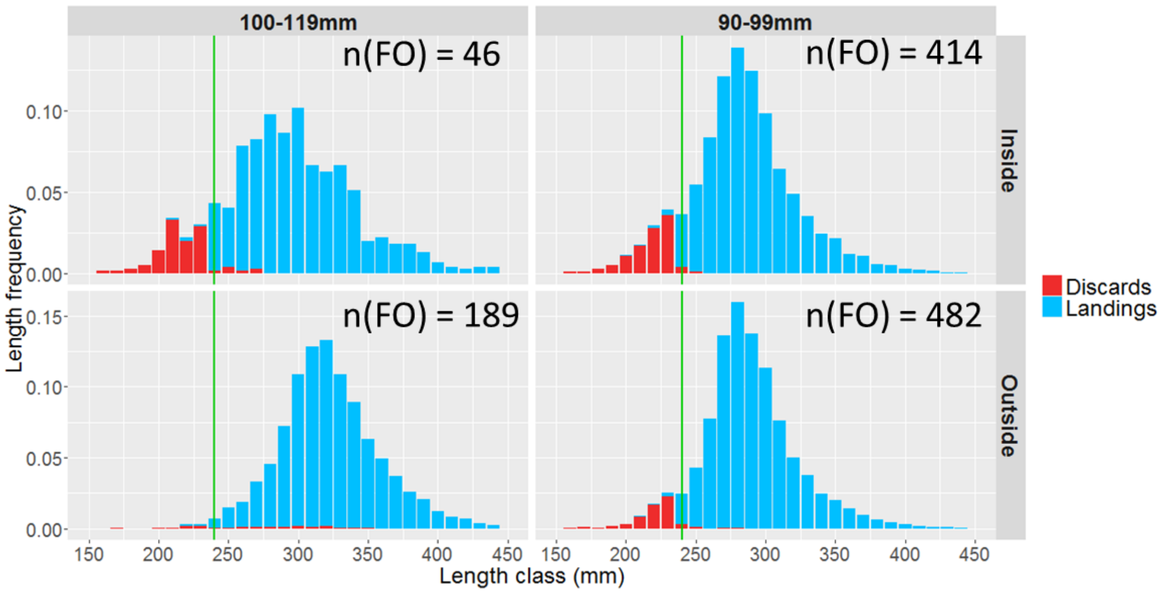

Figure 31: Length distribution of captures of common sole between 2009 and 2015 inside and outside the nursery area for the mesh size range 90-99mm and 100-119mm with the catch category (Discard or landings); n(FO) indicate the number of fishing operation used produce each length distribution and the green line indicates the MLS before 2015 (240mm).

5.3. Discussion

The results show a subarea effect and a mesh size effect on the discard rate. These suggest that the discard rate is directly linked to the structure of catches. The discard rates are lower (and almost null) when the catches are above the MLS. This is the reason why the discard rates in the SW and outside the nursery with the 100-119mm mesh size range are very low. In opposition, with the 90-99mm meshsize range in the NE of the EEC, the catches are shifted toward the small sizes and the discard rates are higher. The discard rate seems important for the mesh size range 100-119mm in the NE but the length structure is built from only 22 fishing operations including 17 in nursery area. The results for the nursery areas suggest that there were more discards inside nursery areas for the two mesh size ranges. The difference in and out of the nursery area in terms of discard rate is particularly important for the 100-119mm mesh size range (but the number of fishing operations is less important inside the nursery areas).

The region effect is harder to interpret because it cannot be distinguished from the subarea and meshsize effects:

- In BN, the mesh size range 100-119 is used in 97% of fishing operations and 96% of fishing operation are in the SW of the ECC
- In HF, the mesh size range 90-99 is used in 99.5% of fishing operations and 100% of fishing operations are in the NE of the ECC
- In HN, the mesh size range 90-99 is used in 87% of fishing operations and 68% of fishing operations are in the NE of the ECC.

With the 100-119m mesh size range used mainly by the fishermen from BN, the discards are widely distributed below and above the MLS. However, the proportion of discard above the MLS is too low to consider this practise as highgrading. It could be due to damaged sole that fishermen cannot valorise. It is surprising that this practice is observed only in the SW of the EEC and not also in the NE. Discussions with fishermen could provide part of the answer.

The higher proportion of soles discarded with the 90-99mm mesh size range in the NE could impact fishermen activities under the landing obligation which took effect in January 2016. For now the netters have been given a de minimis exemption, but if they loose it, the share of soles currently discarded would have to be landed and count against their sole quota. This could worsen the already difficult economic situation of trammel netters in the HF. In this context, the selectivity should be improved in the north to limit discards while maintaining sufficient catch volumes. Tests with 100mm mesh sizes will be conducted in the North of the EEC in the SMAC project. Moreover, whatever the mesh size, the rates of discards inside nursery areas are much higher than outside. Therefore, finer analyses could help defining periods and areas in nursery grounds where discard rates are be particularly high in order to implement temporary closures.

Conclusions and perspectives

The differences observed in the spatio-temporal distribution of the landings allowed structuring the French fisheries fishing on common sole in terms of fishery practices. These results, which are already relevant and important to describe the EEC sole exploitation, need to be extended by analyses on the two others countries exploiting common sole in the EEC (Belgium and UK) in order to have a complete overview of all fisheries combined.

Once the different practices identified, we focused on the outputs of these practices, namely the catch at length to assess the impact of each practice on the stock. As trammel nets are responsible for the majority of the landings, we focused in the manuscript on this gear, and looked at the different mesh size ranges used. All analyses (regression trees and multinomial logistic regression) suggested differences in the catch at length composition of the different mesh size ranges. Differences were explained by the gear used but also by the areas, highlighting some hypotheses already formulated by (Rochette et al., 2012) about the existence of subpopulations in the EEC. These results drove us to the analysis of growth parameters, comparing the Northeast and the Southwest of the EEC. This raises the question of the management of the common sole fishery at the scale of the EEC as a single stock.

Finally, discard rates of the different fleets were checked to assess the impact of discarding practices on the observed landings structures shown in the first part of the manuscript. Differences were observed but could not explain the differences in the landings composition observed, confirming a real difference in catches and not differences in landings induced by different discards practices.

The master thesis was part of the SMAC project. Results on differences in catch at length structure will be used during discussion with fishermen to assess the feasibility and advantages of changing fishing practices to improve the EEC sole exploitation and eventually its biological status.

Results showed that the range of sizes caught by the 100-119 mm size trammel nets is wider than the size rang caught by the 90-99 mm mesh size. However some questions are still on-going, in fact, the material used in these nets are also different and might also impact selectivity. Moreover, these gears are used in different areas where currents strength is different, thus impacting the way gears are used. All these factors have to be tested and will be tested soon by running at sea experiments. The results can also be used in the context of Management Strategy Evaluation to see the biological and economic impact of changing part (or all) the fishery from on gear type to another.

The differences in catch at length also fuels some hypotheses already mentioned by other authors about the existence of distinct subpopulations of sole in the EEC. Growth analysis ran on commercial data in this report will soon be repeated on survey data (much more standardized) and covering the whole area to check if these results are confirmed and validated. If this hypothesis was confirmed, it would then change the stock definition and the way it is assessed and managed. Archambault et al. (2016) already tried to assess that kind of hypotheses on the stock assessment based on a discretization of this stock in three units. This work will have to be pushed further if some more information comes to validate this hypothesis, and even more in a context of overfishing of that stock.

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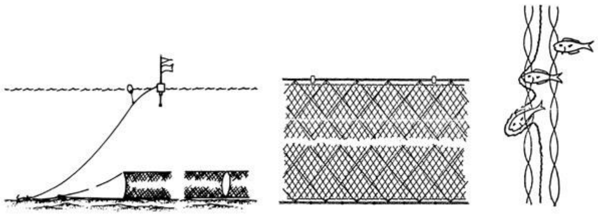
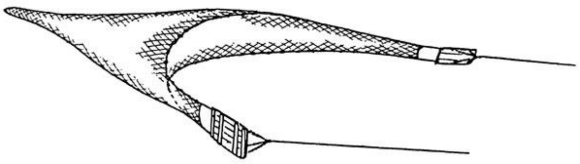
Appendix

Appendix I : Technical description of the main gear exploiting common sole in the Eastern English Channel

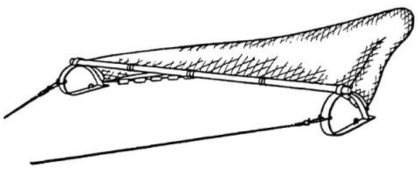
- **Trammel net** consists of three walls of multifilament or monofilament netting, with a loosely hung, small mesh inner net between larger mesh netting.
- 

Source: FAO-Fish.Tech.Pap.222, p. 4

- **Bottom otter trawl** is a cone-shaped net consisting of a body, normally made from two, four and sometimes more panels, closed by one or two codends and with lateral wings extending forward from the opening. A bottom trawl is kept open horizontally by two otter boards (FAO Fisheries & Aquaculture).



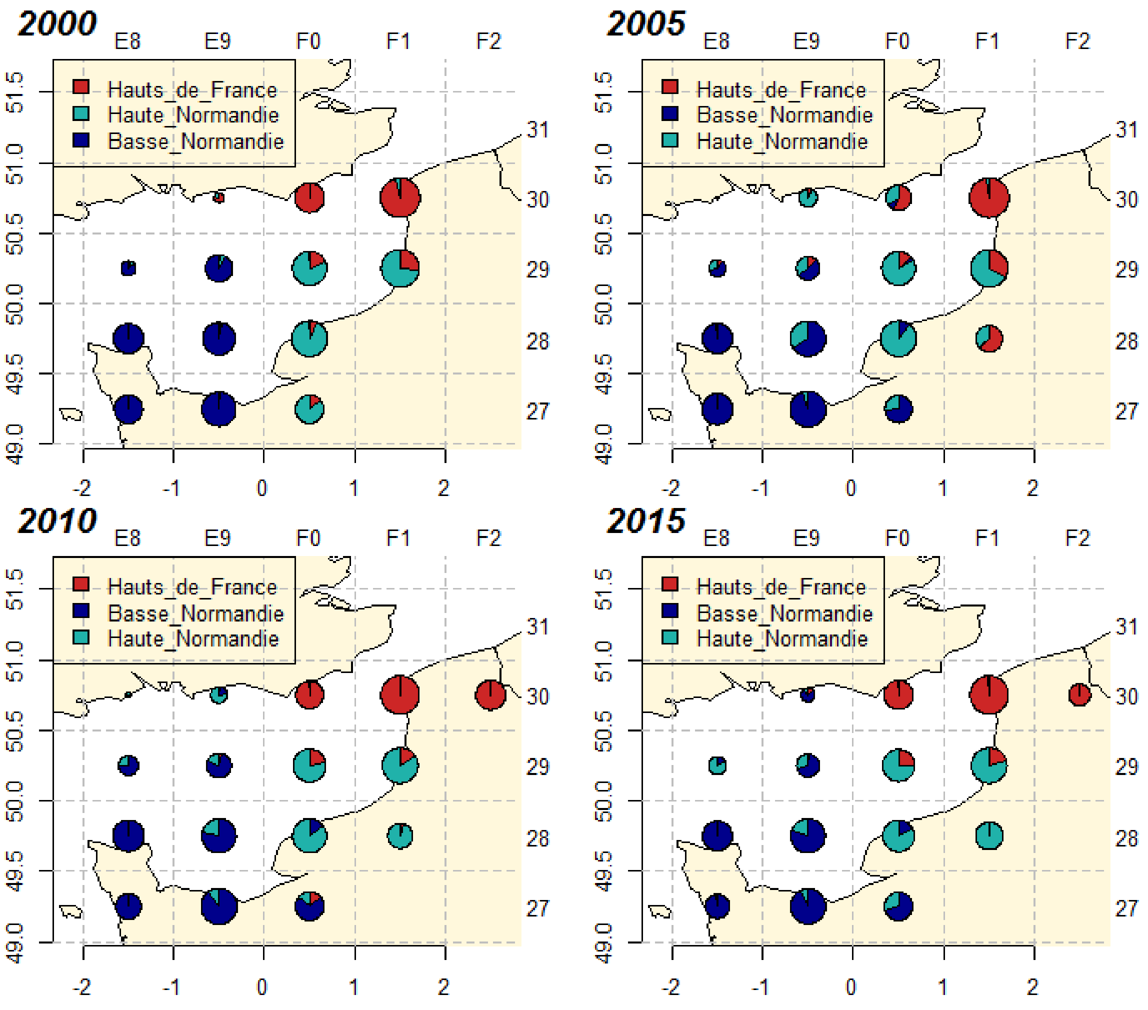
- **Beam trawl consists** of a cone-shaped body ending in a bag or codend, which retains the catch. In these trawls the horizontal opening of the net is provided by a beam, made of wood or metal. The vertically opening is provided by two hoop-like trawl mostly made from steel (FAO Fisheries & Aquaculture).



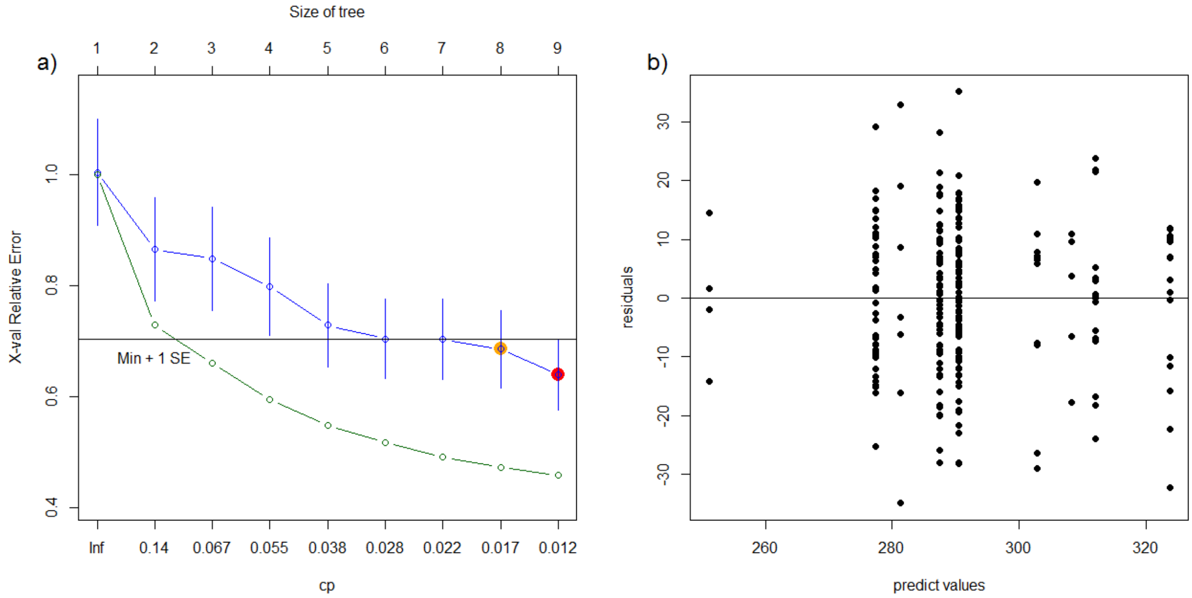
Source: FAO-Fish.Tech.Pap.222, p. 26

Source: FAO Fisheries & Aquaculture - Home [WWW Document], n.d. URL http://www.fao.org/fishery/en

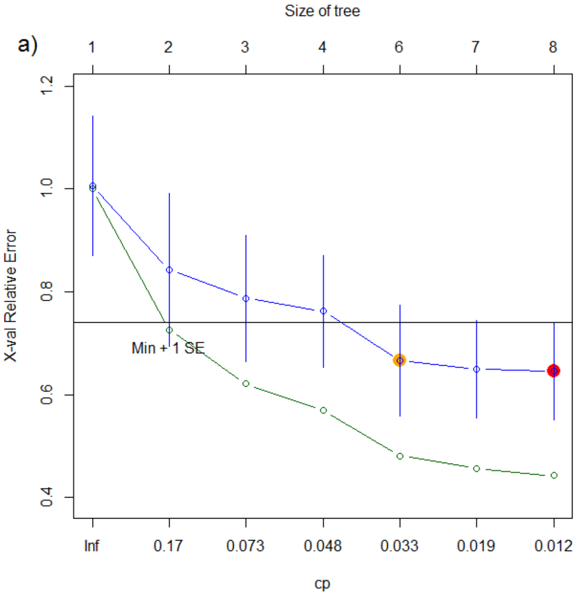
Appendix II : Spatial distribution of common sole landings in the EEC by region in 2015.

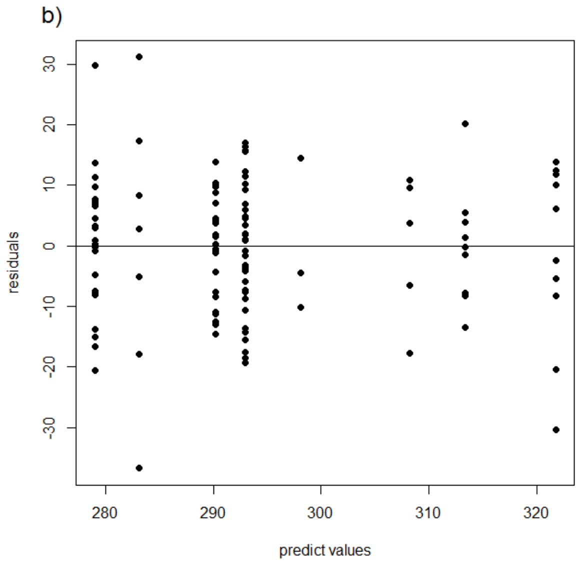


Appendix III : **a)** Relative error and 1-R² as a function of complexity parameter and the size of the tree; **b)** Residuals of the 1st regression tree (observed vs. predict values)



Appendix IV : a) Relative error and 1-R² as a function of complexity parameter and the size of the tree; **b)** Residuals of the 1st regression tree (observed vs. predict values)





Appendix V : analysis of variance of the multinomial logistic regression model

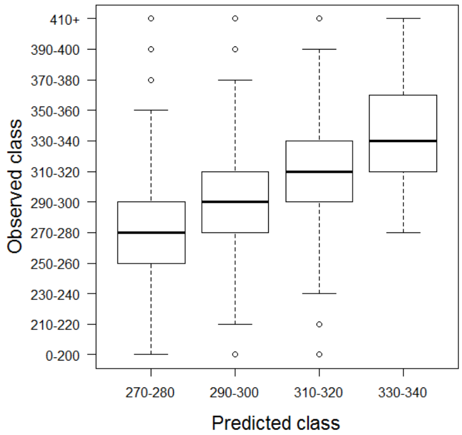
```
> Anova(modAI, type='III')
Analysis of Deviance Table (Type III tests)

Response: classup
                  LR Chisq Df Pr(>Chisq)
meshsize            911.27 11  < 2.2e-16 ***
subarea             159.70 11  < 2.2e-16 ***
nursery             169.98 11  < 2.2e-16 ***
quarter             228.12 33  < 2.2e-16 ***
year                868.69 66  < 2.2e-16 ***
meshsize:subarea    164.79 11  < 2.2e-16 ***
meshsize:nursery    190.14 11  < 2.2e-16 ***
subarea:nursery     182.27 11  < 2.2e-16 ***
subarea:quarter     279.73 33  < 2.2e-16 ***
nursery:year        371.24 66  < 2.2e-16 ***
nursery:quarter     324.86 33  < 2.2e-16 ***
meshsize:quarter    167.07 33  < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Appendix VI : a) Confusion matrix from the cross-validation of the multinomial logistic regression model, "Prediction" is the predicted length class computed from the model build with the learning sample and "Reference" is the observed value of the validation sample. **b)** Distribution of the observed length class depending on predicted length class from the cross validation.

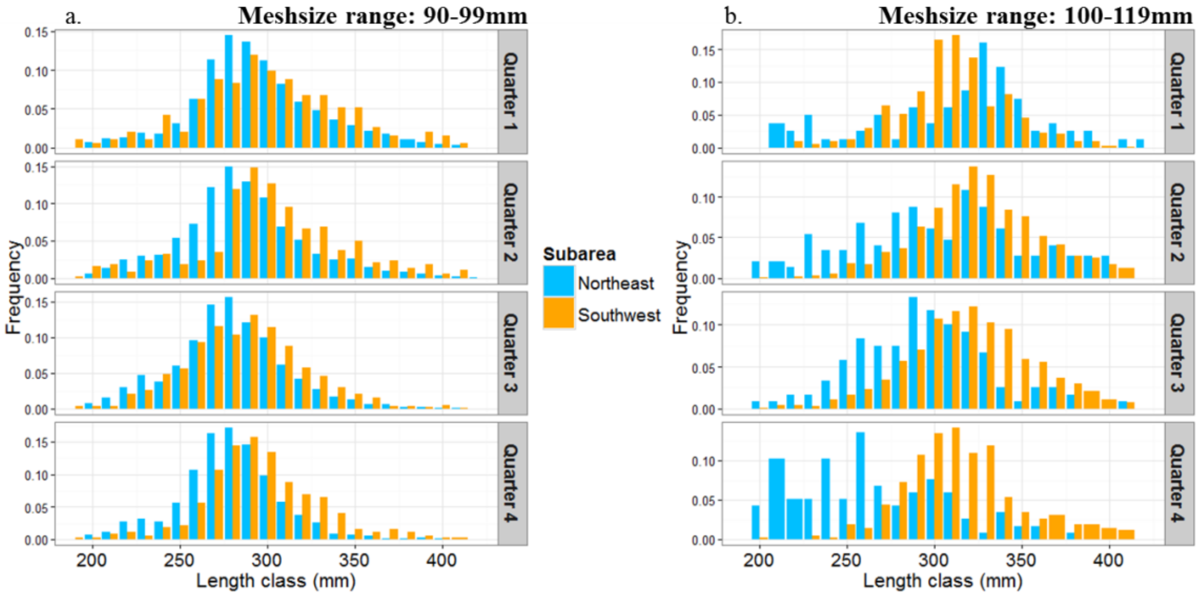
a)

	Prediction											
Reference	**0-200**	**210-220**	**230-240**	**250-260**	**270-280**	**290-300**	**310-320**	**330-340**	**350-360**	**370-380**	**390-400**	**410+**
0-200	0	0	0	0	20	2	1	0	0	0	0	0
210-220	0	0	0	0	71	13	2	0	0	0	0	0
230-240	0	0	0	0	123	16	3	0	0	0	0	0
250-260	0	0	0	0	263	31	8	0	0	0	0	0
270-280	0	0	0	0	**509**	95	29	2	0	0	0	0
290-300	0	0	0	0	388	**135**	68	1	0	0	0	0
310-320	0	0	0	0	196	69	**102**	6	0	0	0	0
330-340	0	0	0	0	90	35	87	**6**	0	0	0	0
350-360	0	0	0	0	50	23	33	3	0	0	0	0
370-380	0	0	0	0	24	12	25	4	0	0	0	0
390-400	0	0	0	0	8	11	15	1	0	0	0	0
410+	0	0	0	0	5	5	12	1	0	0	0	0

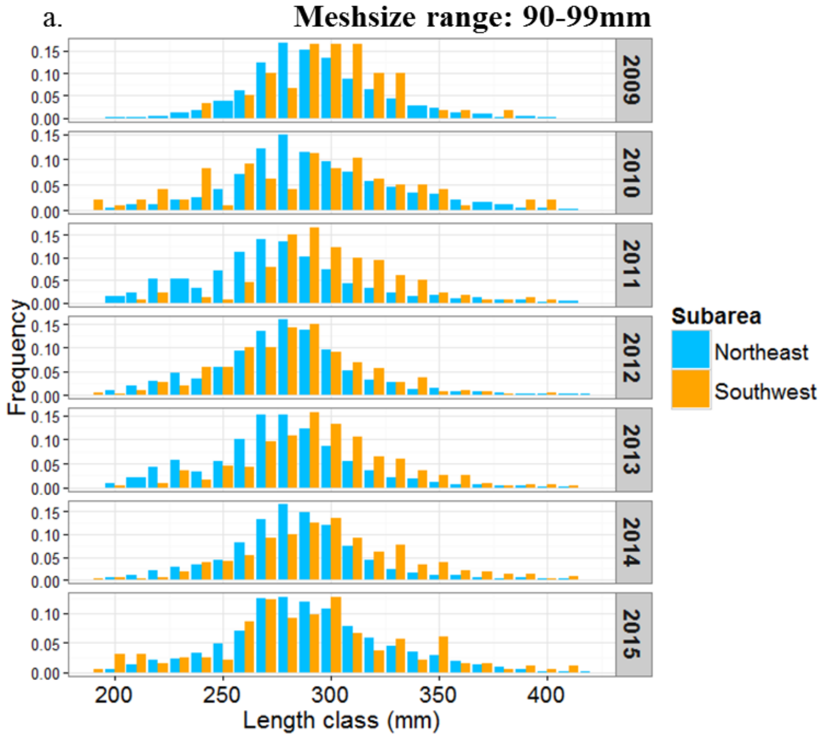
b)

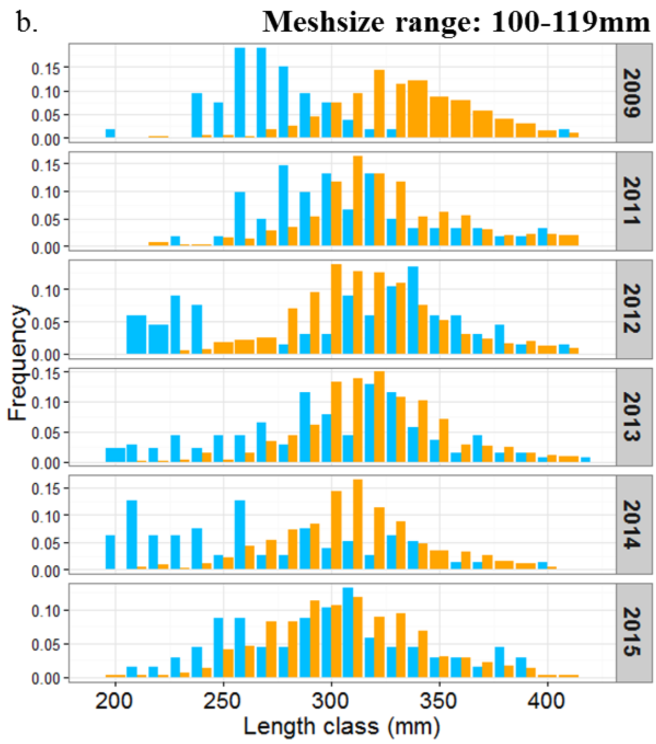


Appendix VII : Length distribution of capture of common sole in SW or NE in the EEC by quarter and by a mesh size range: **a)** 90-99mm and **b)** 100-119mm.



Appendix VIII : Length distribution of capture of common sole in SW or NE in the EEC by year and by a mesh size range: **a)** 90-99mm and **b)** 100-119mm.





Appendix IX : Summary of the final model selection with the different models tested. The procedure began with select random effects and, then fixed effects; the complete model is highlighted in blue and the final model in green. For each effect in the model, 1 is assigned to the growth parameters taken into account in the model and 0 otherwise. P-value is the result of loglikelihood ratio.

	Fixed effects									Random effects									
	Subarea			Sex			Quarter			Year						AIC	ΔAIC	LogLik	P-value
										Var			Var + Cov						
	K	Linf	L2	K	Linf	L2	K	Linf	L2	K	Linf	L2	K	Linf	L2				
Random effects selection																			
Model 1	1	1	1	1	1	1	1	0	1	0	0	0	1	1	1	51431.9		-25693.95	
Model 2	1	1	1	1	1	1	1	0	1	1	1	1	0	0	0	51416.53	-15.37	-25689.27	0.0248
Model 3	1	1	1	1	1	1	1	0	1	1	1	1	0	0	0	51439.5	22.97	-25701.75	<0,0000
Model 4	1	1	1	1	1	1	1	0	1	1	0	1	0	0	0	51462.82	46.29	-25713.41	<0,0001
Model 5	1	1	1	1	1	1	1	0	1	0	1	1	0	0	0	51456.8	40.27	-25710.4	<0,0001
Fixed effects selection																			
	1st step																		
Model 6	0	1	1	1	1	1	1	0	1	1	1	1	0	0	0	51449.68	33.15	-25697.65	0.0065
Model 7	1	0	1	1	1	1	1	0	1	1	1	1	0	0	0	51484.5	67.97	-25722.15	<0,0001
Model 8	1	1	0	1	1	1	1	0	1	1	1	1	0	0	0	51416.62	0.09	-25695.75	0.0576
Model 9	1	1	1	0	1	1	1	0	1	1	1	1	0	0	0	51431.43	14.9	-25692	0.0486
Model 10	1	1	1	1	0	1	1	0	1	1	1	1	0	0	0	51468.4	51.87	-25713.46	<0,0000
Model 11	1	1	1	1	1	0	1	0	1	1	1	1	0	0	0	51470.09	53.56	-25705.28	<0,0001
Model 12	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	51482.9	66.37	-25722.91	<0,0000
Model 13	1	1	1	1	1	1	1	0	0	1	1	1	0	0	0	51614.58	198.05	-25778.22	<0,0001
	2nd step																		
Model 14	0	1	0	1	1	1	1	0	1	0	0	0	1	1	1	51421.86	5.24	-25693.93	0.0071
Model 15	1	0	0	1	1	1	1	0	1	0	0	0	1	1	1	51484.08	67.46	25725.04	<0,0001
Model 16	1	1	0	0	1	1	1	0	1	0	0	0	1	1	1	51431.41	14.79	-25698.7	<0,0001
Model 17	1	1	0	1	0	1	1	0	1	0	0	0	1	1	1	51467.09	50.47	-25716.55	<0,0001
Model 18	1	1	0	1	1	0	0	0	1	0	0	0	1	1	1	51468.94	52.32	-25717.47	<0,0001
Model 19	1	1	0	1	1	1	0	0	0	0	0	0	1	1	1	51510.76	94.14	-25740.92	<0,0001
Model 20	1	1	0	1	1	1	1	0	0	0	0	0	1	1	1	51613.49	196.87	-25791.74	<0,0001

Appendix X : Factorial design on the *Year*, the *Quarter* and the S*ubarea* of the Bargeo data

Female	Southwest					Northeast			
Year/Quarter	**1**	**2**	**3**	**4**		**1**	**2**	**3**	**4**
2010	36	61	124	0		96	0	182	111
2011	0	111	80	7		108	203	252	127
2012	34	138	98	0		90	0	160	194
2013	0	128	95	42		93	278	199	54
2014	42	88	127	0		137	205	0	93
2015	0	31	99	36		182	0	0	142

Male	Southwest					Northeast			
Year/Quarter	**1**	**2**	**3**	**4**		**1**	**2**	**3**	**4**
2010	66	39	75	0		12	0	27	19
2011	0	45	23	0		14	64	15	2
2012	43	71	62	0		4	0	36	27
2013	0	115	13	9		16	20	23	6
2014	32	64	36	0		14	66	0	2
2015	0	20	25	11		22	0	0	52

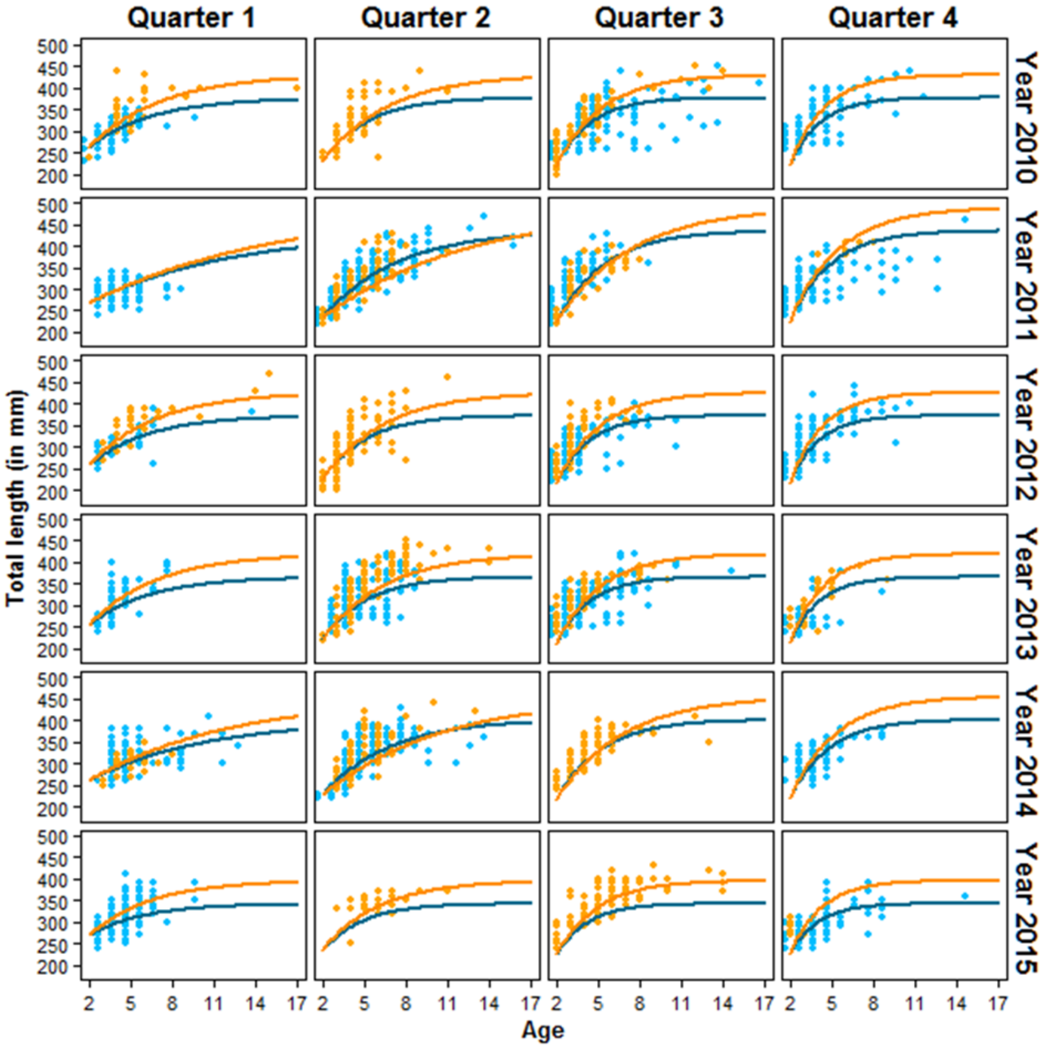
Appendix XI : Analysis of variance of the non-linear fixed effect model

```
> anova(model8)
                     numDF denDF   F-value p-value
L2.(Intercept)           1  5394 12497.468  <.0001
L2.Trimestre             3  5394   199.088  <.0001
L2.Sexe                  1  5394   547.502  <.0001
K.(Intercept)            1  5394   211.982  <.0001
K.subarea                1  5394    84.261  <.0001
K.Trimestre              3  5394    61.816  <.0001
K.Sexe                   1  5394   397.869  <.0001
Linf.(Intercept)         1  5394   899.381  <.0001
Linf.subarea             1  5394   144.921  <.0001
Linf.Sexe                1  5394   225.071  <.0001
```

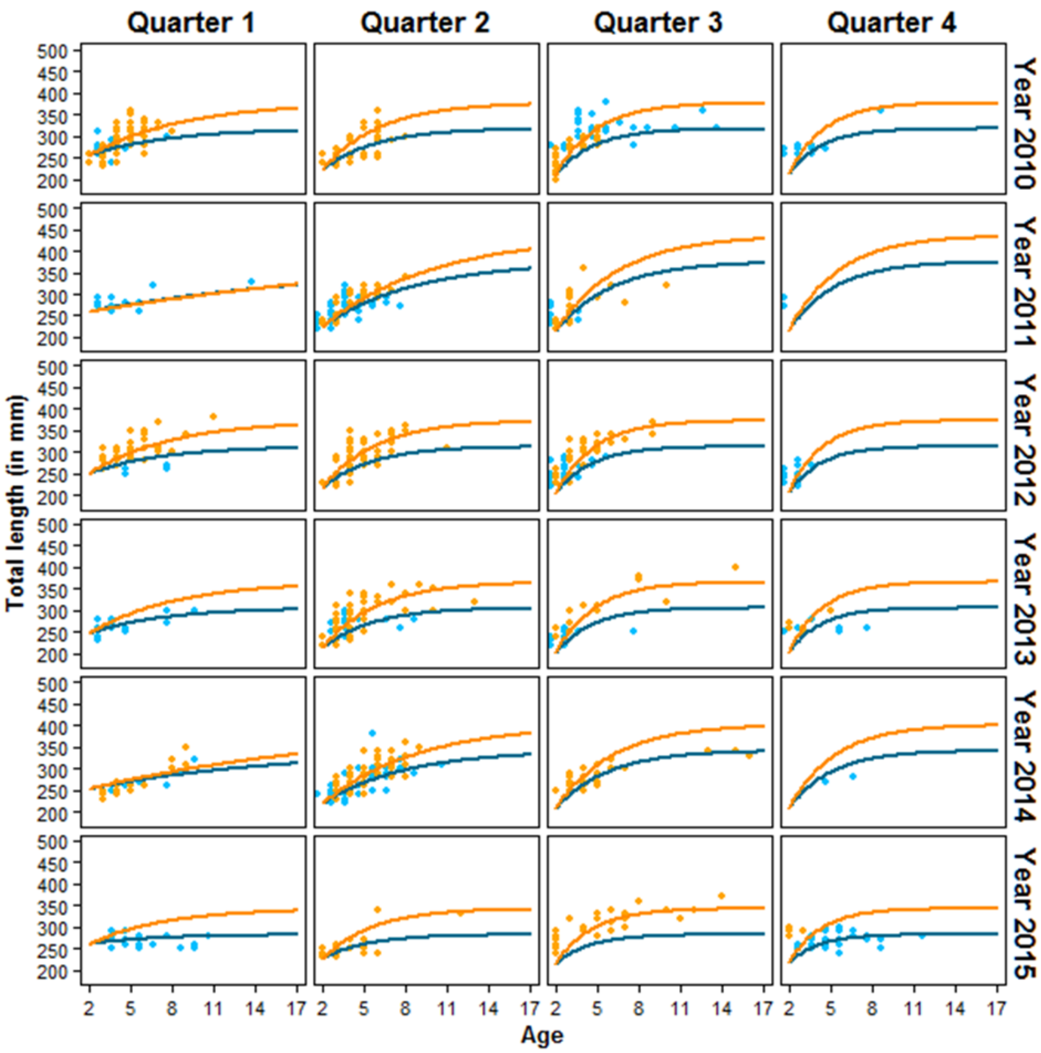
Appendix XII : Summary of the non-linear mixed effects model with the parameters for the random effects and for the fixed effects.

```
> summary(model8)
Nonlinear mixed-effects model fit by maximum likelihood
  Model: Taille ~ Von_Berta(Age, K, Linf, L2)
 Data: data_bio_sexe
       AIC      BIC    logLik
  51416.62 51535.36 -25690.31

Random effects:
 Formula: list(K ~ 1, Linf ~ 1, L2 ~ 1)
 Level: annee
 Structure: Diagonal
        K.(Intercept) Linf.(Intercept) L2.(Intercept) Residual
StdDev:    0.06177781          29.6529       4.953434 27.70038

Fixed effects: list(K ~ subarea + Trimestre + Sexe, L2 ~ Trimestre + Sexe, Linf ~      subarea + Sexe)
                    Value Std.Error   DF   t-value p-value
K.(Intercept)      0.1679  0.028288 5394   5.93712  0.0000
K.subareane        0.0211  0.008074 5394   2.61528  0.0089
K.Trimestre2       0.0948  0.010098 5394   9.38828  0.0000
K.Trimestre3       0.0998  0.010537 5394   9.46812  0.0000
K.Trimestre4       0.0570  0.012245 5394   4.65569  0.0000
K.SexeM           -0.0440  0.008952 5394  -4.92008  0.0000
L2.(Intercept)   263.3353  3.325931 5394  79.17644  0.0000
L2.Trimestre2    -33.2758  3.108578 5394 -10.70451  0.0000
L2.Trimestre3    -10.9792  2.791291 5394  -3.93337  0.0001
L2.Trimestre4      1.9769  3.057184 5394   0.64663  0.5179
L2.SexeM          -9.0974  1.798053 5394  -5.05958  0.0000
Linf.(Intercept) 435.7310 12.993562 5394  33.53438  0.0000
Linf.subareane   -53.0773  3.591627 5394 -14.77806  0.0000
Linf.SexeM       -59.9303  3.994721 5394 -15.00237  0.0000
```

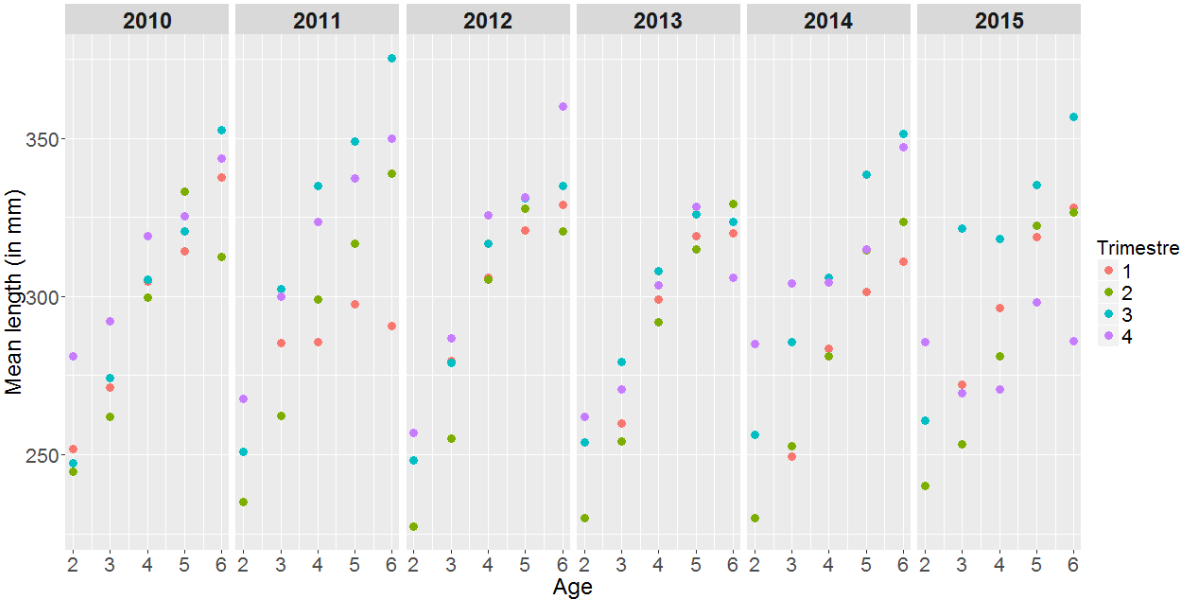
Appendix XIII : Growth curves for computed from K, Linf and L2 estimated in the non-linear mixed model for **female** common sole in the EEC depending on the quarter, the year and the subarea: SW in orange and NE in blue The points represent the observed length-at-age from Bargeo data in the SW (orange) and in the NE (blue)



Appendix XIV : Growth curves for computed from K, Linf and L estimated in the non-linear mixed model for **male** common sole in the EEC depending on the quarter, the year and the subarea: SW in orange and NE in blue The points represent the observed length-at-age from Bargeo data in the SW (orange) and in the NE (blue)



Appendix XV : Mean length of common sole in the EEC at each quarter from the age 2 to the age 6 between 2010 and 2015 computed from Bargeo data.



AGRO CAMPUS OUEST	Diplôme : Ingénieur Spécialité : Agronome Spécialisation / option : Sciences Halieutiques et Aquacoles – option REA Enseignant référent : Etienne RIVOT

Auteur(s) : Hubert DU PONTAVICE

Date de naissance* : 06/10/1992

Organisme d'accueil :
Ifremer – Centre Manche Mer du Nord
Adresse : 150 Quai Gambetta,
62200 Boulogne-sur-Mer

Maître de stage : Marie SAVINA-ROLLAND ; Youen VERMARD

Nb pages : 40 Annexe(s) : 15

Année de soutenance : 2016

Titre français : Dynamique spatio-temporelle de l'exploitation de la Sole commune, Solea solea, en Manche Est

Titre anglais : Spatio-temporal dynamics of the exploitation of common sole, *Solea solea*, in the Eastern English Channel

Résumé : Le stock de sole commune (*Solea solea*) de Manche Est (ME) est d'une grande importance économique. La conjonction de faibles recrutements en 2012 et 2013 et d'une mortalité par pêche au-dessus du Frmd a conduit à des diminutions répétées du TAC. Ce mémoire a pour objectif d'étudier la dynamique spatio-temporelle de l'exploitation française de la sole commune en ME et d'en tirer des hypothèses sur la dynamique de la population. En premier lieu, nous avons mis en évidence la structuration spatiale de la pêcherie française de sole commune dominée par les filets type trémail et les chaluts de fond à panneaux. Dans un second temps, en se concentrant sur les fileyeurs qui représentent la majeure partie des débarquements (65%) et qui sont fortement tributaires de la sole commune, nous avons montré l'existence d'une variabilité spatiale des structures en taille des captures. L'analyse, basée sur deux arbres de régression (longueurs moyennes) et sur une régression logistique multinomiale (distributions en tailles), a révélé que ces différences peuvent être expliquées par le maillage utilisé, la période de pêche et la zone de pêche. L'impact de potentielles sous-populations présentant des différences de paramètres biologiques a, ensuite, été testé à partir des paramètres de croissance en utilisant un modèle non linéaire à effets mixtes. Nous avons ainsi montré des différences de taux de croissance et de longueur asymptotique entre le Nord-est et le Sud-Ouest de la ME. Dans une dernière partie, les liens entre les captures et les débarquements ont été analysés dans les différentes régions et zones.

Abstract: The Eastern English Channel (EEC) common sole (Solea solea) stock is one of the most important stocks for the French fisheries in the EEC. Low recruitments in 2012 and 2013, coupled with a fishing mortality well above Fmsy led to repeated cuts in TAC over the last years. This master thesis aimed to study the spatiotemporal dynamics of the French fisheries exploiting sole in the EEC and their impact on this stock; it also allowed drawing assumptions on populations' dynamics. We first showed a spatial structuration of the French fisheries (mainly trammel net and bottom otter trawl). A focus on trammel netters which represent the main share of the landings and which are highly dependent on common sole showed spatial differences on the length structures of the catches. Regression trees on mean lengths of catches and a multinomial logistic regression on the length structures of the catches revealed that these differences can be explained by the mesh size used, fishing period and the fishing area (including nursery area). The impact of potential subpopulations with different biological parameters in the EEC was tested focusing on growth parameters in these subareas, using a non-linear mixed effect model. It showed differences in growth rates and asymptotic lengths between the Northeast and the Southwest of the EEC. Finally, differences in the landings were checked through exploitation patterns to describe links and differences between catches and landings in the different regions and areas.

Mots-clés : *Solea solea*, Manche Est, Exploitation, Structure en taille, Paramètres de Croissance, Sélectivité

Key Words: *Solea solea*, Eastern English Channel, Exploitation, Length structure, Growth parameters, Selectivity

* *Elément qui permet d'enregistrer les notices auteurs dans le catalogue des bibliothèques universitaires*