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Original Article

Species targeting and discarding in mixed fisheries

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This study examined some of the spatial patterns and temporal dynamics of species targeting and discarding, for the French bottom trawlers operating in the eastern English Channel, building on spatial overlaps (or mismatches) between fishing effort, survey-based biomass or abundance indices and discard rates. We first identified that cuttlefish (*Sepia officinalis*), squids (*Loligo* sp.) and, to a lesser degree, striped red mullet (*Mullus surmuletus*), and seabass (*Dicentrarchus labrax*) were the main targets, while fishing for historically important species was less attractive. This result was broadly in accord with catch compositions, although mackerel (*Scomber scombrus*) targeting was possibly underestimated. We also showed that the distributions of fishing effort and of undersized herring, plaice, and whiting did not overlap. Although fishing effort covered fishing grounds populated with undersized horse mackerel, the proportion of undersized individuals in the discards was small. Plaice and whiting discard rates overlapped in space with undersized abundance indices. Fishing effort may have avoided spatial units with potentially high plaice discard rates, which may have been driven by large proportions of undersized fish, but also by restricted access to coastal area. Overall, the EU Landing Obligation had limited effects on fishing effort allocation relative to either undersized abundance or discard rates distributions.

Keywords: discard rates, eastern English Channel, fishing effort, mixed fisheries, spatial overlap, target species, undersized fish.

Introduction

Efficient fisheries management requires to anticipate the dynamics of exploited ecosystems, but also of the fishing fleets harvesting them (Branch *et al.*, 2006; Nielsen *et al.*, 2018). Fleet dynamics research has considered decisions made by fishers in the long term, e.g. capacity investment/disinvestment (Clark, 1990) and in the short term. Short-term fleet dynamics, which is the focus of this study, have often been investigated from two different angles: spatial allocation of fishing effort and discarding, with the objectives of identifying, quantifying, and possibly forecasting the drivers of fishers' behaviour.

Discrete choice models building in a random utility function (Holland, 2000; Van Putten *et al.*, 2011; Girardin *et al.*, 2017), but also conceptual modelling approaches (Gillis *et al.*, 1993; Marchal *et al.*, 2013; Van der Lee *et al.*, 2014; Dolder *et al.*, 2020) have been pursued to identify the determinants of spatial effort allocation and possibly run short-term forecast. In an extensive review of fishing effort allocation drivers applicable to worldwide fishery case studies, Girardin *et al.* (2017) identified in particular expected revenue, but also traditions and species targeting as the main drivers of fishers' short-term decisions-making. Following the increasing accessibility of high resolution satellite-based information on fishing vessels' positioning, the linkages between fishers' area choices and the spatial distribution of the resources have been subject to detailed investigations (Gillis *et al.*, 1993; Rijnsdorp *et al.*, 2011; van der Lee *et al.*, 2014; Hintzen *et al.*, 2019).

A large volume of fisheries science literature has also been dedicated to analysing the main drivers of and/or simulating discarding behaviour (Sampson, 1994; Gillis *et al.*, 1995; Rochet and Trenkel, 2005; Poos *et al.*, 2010). Applications to EU fisheries have particularly increased (Uhlmann *et al.*, 2014; Paradinas *et al.*, 2016; Mortensen *et al.*, 2017; Catchpole *et al.*, 2018; Mytilineou *et al.*, 2018; Robert *et al.*, 2019), as a result of the gradual inception of a Landing Obligation (LO) within the 2013 revision of the Common Fisheries Policy (EU, 2013; Marchal *et al.*, 2016).

Discards consist of either undesired marine organisms that are highgraded, or commercial species, which may not be landed due to a mismatch between regulatory measures and stock dynamics. The first category includes damaged, low-value, or unmarketable species, which could otherwise be legally landed. The latter category comprises undersized discards (i.e. of species subject to a minimum landing size), bycatch discards (i.e. of species caught in fishing trips where bycatch limitations apply), and overquota discards (i.e. of species the catch quota of which has been exceeded). Studies have addressed the different facets of discarding, separately, or in combination, with a focus on highgrading (Gillis *et al.*, 1995; Stratoudakis *et al.*, 1998; Batsleer *et al.*, 2015), overquota discarding (Poos *et al.*, 2010; Hatcher, 2014; Macdonald *et al.*, 2014; Batsleer *et al.*, 2015; Calderwood and Reid, 2019), and undersized discarding (Stratoudakis *et al.*, 1998; Rochet and Trenkel, 2005; Feekings *et al.*, 2012; Feekings *et al.*, 2013; Paradinas *et al.*, 2016).

A variety of methods have investigated the market, regulatory, and environmental drivers of discarding. Such approaches included: dynamic programming (Gillis *et al.*, 1995; Poos *et al.*, 2010; Batsleer *et al.*, 2015), Generalized Additive Mixed Models (Feekings *et al.*, 2012; Feekings *et al.*, 2013), Generalized Additive Models (Stratoudakis *et al.*, 1998), Bayesian models (Paradinas *et al.*, 2016), Generalized Linear Mixed Models (Calderwood and Reid, 2019; Wang *et al.*, 2020), linear modelling (Rochet *et al.*, 2002), statistical correlation (Rochet and Trenkel, 2005; Macdonald *et al.*, 2014), and direct interviews with fishers (Eliasen *et al.*, 2014).

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A common driver to fishers' area choices and discarding practices is the spatial distribution of the resources they exploit. Based on earlier findings, it may be hypothesized that, subject to market and regulatory constraints, fishers will visit fishing grounds with high density of targeted species and/or marketable size classes. In doing so, they may be forced to discard species they cannot market and/or species subject to regulatory measures (e.g. catch quotas, minimum landing size, and by-catch limitations) if their distribution area overlaps with that of the targeted species. Fishers have little interest in discarding fish, as such practice either comes at a cost in terms of the time they waste, e.g. to sort fish and clear the deck, or has been banned for several decades, e.g. Norway, Iceland, and New Zealand fisheries. In EU fisheries, the gradual implementation of the LO has been seen as a major advance to limit discards (Catchpole *et al.*, 2017). Still, it has also been recognized that the efficiency of the LO has been challenged by a limited industry support, but also by different exemptions in the regulation (Veiga *et al.*, 2016; Borges, 2021). Overall, although discard plans have been established for pelagic (since 2015) and demersal fisheries (since 2016) operating in north-western EU waters [inclusive of the eastern English Channel (EEC)], these have only partially covered the range of stocks and fisheries subject to high discard levels (EU, 2014, 2015, 2016, 2018a, b, c). One question which may then arise is whether EU fishers are actively avoiding areas where high discards could be expected, and more particularly so since 2015 when the LO started to be legally binding. Although tactical discard avoidance could potentially be an ingredient of within-trip fishing strategies (Rochet and Trenkel, 2005), it has only rarely been investigated from empirical data (Calderwood *et al.*, 2021).

The overarching objective of this study is to investigate the linkages between spatial effort allocation, discarding, and exploited resources in a mixed fishery. Such linkages will be analysed in terms of spatial overlap between the distributions of fishing effort, species biomass/abundance indices, and discard rates. Three questions will be addressed: (i) which species assemblages drive fishing effort dynamics, (ii) how species and/or size compositions determine discarding patterns, and (iii) whether potential discard hotpot areas are avoided by fishers. Our approach is applied to the French bottom trawl mixed fisheries operating in the EEC.

Material and methods

Data

Three data streams have been activated in this study: scientific survey biomass and abundance indices, satellite-based monitoring (VMS—Vessel Monitoring System) fishing effort, and discards information from observers on-board. Fishing effort and discards information were derived from statistics registered by the French directorate for sea fisheries and aquaculture and extracted from Harmonie, the database of the French fisheries information system managed by Ifremer. While the three sources provided complementary information on the EEC fishery system, data were available at different spatial and temporal resolutions, so a common scale currency had to be found to combine them, as detailed below. In addition to these three main data inputs, quota uptake information was also made available to facilitate the interpretation of our results.

Biomass and abundance indices

Biomass and abundance indices of the main species exploited by the French bottom trawl fishery operating in the EEC (ICES Division 7d) were informed by the Channel Ground Fish Survey (CGFS), over the period 1990–2019. The CGFS is conducted by Ifremer, the French Research Institute for the Exploitation of the Sea. It covers the whole EEC every year in October using a GOV (Grande Ouverture Verticale) otter trawl, rigged with a 20-mm codend and towed at a speed of 3.5 knots for about 30 min. The CGFS provides abundance and biomass indices for the main commercial species caught by the bottom trawl fishery. The species under consideration in this study thus included cod (*Gadus morhua*), whiting (*Merlangius merlangus*), red mullet (*Mullus surmuletus*), plaice (*Pleuronectes platessa*), thornback ray (*Raja clavata*), seabass (*Dicentrarchus labrax*), herring (*Clupea harengus*), horse mackerel (*Trachurus trachurus*), mackerel (*Scomber scombrus*), cuttlefish (*Sepia officinalis*), and squids (*Loligo* spp.), which represented 60% of the total October landings (in weight) by the French bottom trawl fishery over the period 2012–2019 (Supplementary Figure S1). Some of these species (whiting, herring, plaice, and horse mackerel) were subject to high discard levels. Other commercial species contributed to 2–6% of total October landings, and could have been considered in this study. However, these were either poorly sampled by the survey (e.g. sole, *Solea solea*, scallops, *Pecten maximus*), or of lesser economic importance (e.g. starry smooth-hound, *Mustelus asterias*, small-spotted catshark, *Scyliorhinus canicula*), so these were not investigated to keep species number tractable. Survey indices (biomass and abundance per km^2 swept area) were averaged within a $15' \times 15'$ spatially resolved grid (Delavenne *et al.*, 2013). The number of hauls sampled per spatial unit varied between one and seven per year. We first derived a yearly and spatially resolved Total Biomass Index (TBI) for each species ($kg\ km^{-2}$). Some of these species are subject to a minimum landing size, more recently referred to as a Minimum Conservation Reference Size (MCRS, terminology used in this study). For MCRS species subject to high discards: herring (MCRS = 20 cm), horse mackerel (MCRS = 15 cm), plaice (MCRS = 27 cm), and whiting (MCRS = 27 cm), we derived an Undersized Abundance Index (UAI), representing the abundance of undersized fish per swept area (numbers km^{-2}), and an Undersized Rate Index (URI), calculated as the ratio between undersized and total abundance (%). The spatial distribution of TBI has fluctuated without clear trends over 1990–2019, except for herring and mackerel, where significant latitudinal displacements (tested with first-order time auto-correlation) could be detected (Supplementary Figures S2 and S3). A significant north-eastwards displacement was found for the URI of herring and plaice (Supplementary Figure S3). No trends could be detected in any horse mackerel or whiting undersized abundance indices (Supplementary Figure S3). The TBIs of seabass, cod, mackerel, herring, plaice, and whiting and the UAIs of herring, plaice, and whiting are concentrated towards coastal areas and/or estuaries, while the TBIs of thornback ray, red mullet, cuttlefish, squids, horse mackerel and both the UAI and the URI of horse mackerel are more evenly distributed with large concentrations in the central EEC (Supplementary Figures S4 and S5). The largest herring, plaice, and whiting URIs are concentrated towards coastal areas, but hotspots are also found in the central EEC (Supplementary Figure S5). Note, however, that many spatial units had zero TBI, and hence no URI value, particularly in the case of herring.

Fishing effort

Fishing effort information (hours fished per 3′ × 3′ rectangles) were derived from satellite-based monitoring (VMS). A consistent fishing effort time series was extracted over the period 2005–2019, for all French bottom trawlers equipped with a VMS and operating in the EEC in October, and aggregated with a 15′ × 15′ spatial resolution, consistent with survey data. Only vessels larger than a certain size threshold were mandatorily equipped with a VMS, and that minimum threshold decreased from 15 m (2005–2011) to 12 m (2012–2019), with visible consequences on fishing effort distribution (Supplementary Figure S6). We therefore used the 2012–2019 fishing effort data only (see spatial distribution in Supplementary Figure S6).

Discards

Total catch information, including the discard fraction, was collected by observers on-board, for a small sample of fishing trips operated by commercial bottom trawlers in the EEC over the period 2009–2019. For instance, 42 fishing trips out of 11745 (0.4%) were sampled in 2019 from bottom trawlers lower than 18 m, operating in the EEC and southern North Sea (Cornou *et al.*, 2021; pp. 49 and 69). The catch data were aggregated by 15′×15′-resolved spatial units, consistent with fishing effort and survey data. There was, however, insufficient monthly information to restrict the discard dataset to month October only, as for the effort and survey datasets. Instead, we aggregated discard data over the fourth quarter. The number of catch-informed fishing hauls operated in the EEC by bottom trawlers in the fourth quarter varied annually between 81 and 184. In addition to the reduced sampling size, the presence of observers on-board was subject to skipper's acceptance, so the trajectory of discard trips effort was not fully representative of VMS-reported fishing effort (Supplementary Figure S6). There was hence insufficient information to investigate spatial and annual variability in discards concomitantly.

In order to reduce sampling error resulting from too few observations, we selected spatial units where at least 5 hauls were operated over 2002–2019. The total amount of hauls (cumulated over 2009–2019) per spatial unit, where discards information was available varied between 5 and 98. Four species contributed to 60% of total discards weight in quarter 4: herring (26%), whiting (15%), horse mackerel (10%), and plaice (8%). For these species, we calculated the discard rate as the ratio between total discards and total catch (in weight), which we averaged across fishing hauls for each spatial unit (Supplementary Figure S7).

Considering the fishing hauls where fish were discarded and measured (between 5 and 29 per spatial unit), three species contributed to 87% of total discards weight of undersized fish: whiting (45%), plaice (25%), and horse mackerel (10%). For these three species, we calculated an undersized discard rate as the ratio between undersized discards and total discards (in weight), which we averaged across fishing hauls for each spatial unit. The spatial coverage of the undersized discard rate was less comprehensive than that of discard rates (Supplementary Figure S8), so it was only used in this study to help interpreting our results.

Most of herring and horse mackerel catches were discarded in almost all spatial units (Supplementary Figure S7) and discards were mainly composed of fish above the MCRS (Supplementary Figure S8). In contrast, the largest proportion of plaice and whiting discards (mostly composed of undersized discards, Supplementary Figure S8) was concentrated in the vicinity of the Baie de Somme and the Baie de Seine estuaries, where important flatfish and roundfish nurseries are located (Supplementary Figure S7).

Quota uptake

Catching fish above quota entitlements may result in over-quota discards. To facilitate the interpretation of our results, we then collated information on French quota uptake for those EEC stocks regulated by a specific EU TAC (Total Allowable Catch) over 2012–2019 (Supplementary Figure S9). While there is a cod TAC for the EEC, ICES Division 7d (COD/07D.), the geographical coverage of all other species' stocks considered here exceeds the EEC; PLE/7DE.: plaice in ICES Divisions 7d-e; WHG/7X7A-C: whiting in ICES Divisions 7b-k; HER/4CXB7D: herring in ICES Divisions 7d and 4c; MAC/2CX14-: mackerel in ICES Divisions/Subareas 6, 7, 8a-b, 8d-e, EU and international waters of ICES Division 5b, international waters of ICES Division/Subareas 2a, 12, 14; JAX/4BC7D: horse mackerel in ICES Divisions 4b, 4c, 7d. The cod quota uptake decreased dramatically from about 75% (2012–2015) to 1% in 2019. Quota uptakes of plaice and whiting also decreased, although less sharply than for cod. Herring and mackerel quota uptakes have fluctuated without trends between 60 and 100%, while horse mackerel quota uptake has slightly increased over 2012–2019.

Methods

We evaluated the spatial overlaps between fishing effort, discard rates, and biomass indices (two by two) using the Horn index H (Horn, 1966):

$$H = \frac{2\sum_{i=1}^{A} p_i q_i}{\sum_{i=1}^{A} p_i^2 + \sum_{i=1}^{A} q_i^2}, \tag{1}$$

where A is the total number of spatial units (15′ × 15′) i for which H was calculated, p and q are the proportions of two metrics in spatial unit i. These metrics may reflect fishing effort, discard rates, or biomass indices (TBI, UAI, URI). H is bounded between 0 and 1, and increases with the degree of spatial overlap. $H = 1$ corresponds to a full match between the distributions of p and q, while $H = 0$ corresponds to a complete mismatch. Although p and q play a symmetrical role in Equation (1), we consider that p refers to the proportion of a metric that may have a causal effect on a metric the proportion of which is q.

To evaluate the extent to which p and q overlap, we compared the actual Horn index value with hypothetical indices obtained by reshuffling the q values from their original spatial unit to other spatial units drawn randomly from a uniform probability distribution (permutation test). A total of 1000 q distributions were drawn and the basic statistics (median, 5 and 95% percentiles) of the resulting simulated Horn index values were derived and contrasted with the actual Horn index. The spatial distributions of p and q were concluded to significantly ($p < 0.05$) overlap (respectively, mismatch) when the actual Horn index was found above the 95th percentile (respectively, below the 5th percentile) of the simulated Horn index values.

Table 1. Summary of the settings underpinning Analyses 1–3.

Analysis	Spatial domain	Overlapping variables	Period/years	No. spatial units	No. species
1	Comprehensive EEC domain	Effort x TBI	2012–2019 (annually)	42–57	11
			2012–2019 (aggregated)	65	11
		Effort x UAI	2012–2019 (annually)	42–57	4
			2012–2019 (aggregated)	65	4
		Effort x URI	2012–2019 (annually)	16–56	3
			2012–2019 (aggregated)	40–63	3
2	Restricted EEC domain	Discard rate x (TBI or UAI)	2009–2019	15–37	4
		Discard rate x URI	2009–2019	22–30	3
3	Restricted EEC domain	Effort x Discard rate	2012–2014, 2015–2019	9–21	3
			2012–2019	15–38	4

Three separate analyses were carried out to evaluate the effects of species distributions on fishing effort allocation (Analysis 1) and discarding spatial patterns (Analysis 2), and the effects of discarding spatial patterns on fishing effort allocation (Analysis 3). The total number of spatial units being considered (A), and the periods over which H was calculated depend on the data available for the different metrics and on which analysis is conducted. Calculations were operated using the SAS package, Version 9.3 (SAS Institute). The different settings underpinning Analyses 1–3 (spatial domain, number of spatial units, time period, number of species) are summarized in Table 1.

Analysis 1: effects of species distribution on fishing effort allocation

In Analysis 1, we quantified the spatial overlap between fishing effort and survey indices, to investigate the extent to which fishing behaviour is driven by the spatial distribution of fisheries resources. In that case p represents the proportion of a biomass or abundance index (TBI, UAI, or URI) in each spatial unit, while q represents the proportion of fishing effort allocated in that spatial unit. The period considered was 2012–2019. This is a similar approach to that carried out by Bourdaud *et al.* (2019), who calculated a targeting index based on the degree of spatial overlapping between fishing effort and commercial species distributions. The main difference here is that we also consider the spatial overlap between the distributions of fishing effort and of undersized fish (as reflected by UAI and URI).

Analysis 1 was applied to the comprehensive ensemble of spatial units structuring the VMS fishing effort dataset, and all commercial species under interest for which a survey index (TBI, UAI, URI) was available (hereby referred to as the *comprehensive EEC domain*). The Horn index was calculated first for each year, to evaluate possible inter-annual changes, and then by aggregating all years of the 2012–2019 period.

Analysis 2: effects of species distribution on discarding spatial patterns

In Analysis 2, we investigated whether the spatial distribution of discard rates overlaps with that of survey indices, with a particular focus on undersized abundance indices UAI and URI. In that case, p represents the proportion of a survey index (TBI, UAI or URI) in each spatial unit, while q represents the proportion of discard rates in that spatial unit. The period considered was 2009–2019. Analysis 2 was applied to all the spatial units drawn from the discard trips, the geographical coverage of which is more limited than that of the fishing effort dataset, and all species for which both survey indices (TBI, UAI, URI) and discard rates were available (hereby referred to as the *restricted EEC domain*). The Horn index was calculated aggregating all years of the 2009–2019 period.

Analysis 3: effects of spatial patterns in discard rates on fishing effort distribution

In Analysis 3, we investigated whether discard rates overlapped in space with fishing effort, with a particular focus on species subject to high discards. In that case, p represents the proportion of discard rates in each spatial unit, while q represents the proportion of fishing effort in that spatial unit. Analysis 3 was applied to all spatial units drawn from the discard trips, for which fishing effort and discard rates were available (restricted EEC domain). The Horn index was first calculated aggregating all years of the 2012–2019 period. In addition, we also applied Analysis 3 considering two periods separately: 2012–2014 and 2015–2019, so to evaluate possible effects of the LO after its legal inception.

Results

Analysis 1: effects of species distribution on fishing effort allocation

Table 2 (column 4) shows a significant spatial overlap between the distributions of fishing effort and of the TBI of cuttlefish, red mullet, seabass and squids, when aggregating all years over 2012–2019. The examination of annual series (Figure 1) indicates that the spatial overlap between fishing effort and TBI was significant in all years for cuttlefish, in half of the years for squids (2015, 2017, 2018, 2019), and more occasionally for red mullet (2015, 2018) and seabass (2017). The spatial distributions of fishing effort and seabass TBI mismatched in 2018 and 2019. There were either no overlap (cod, mackerel, herring, horse mackerel, plaice, and whiting), or a mismatch (thornback ray), between the distributions of fishing effort and of the other species' TBI, over 2012–2019 (Table 2). Considering the annual series (Figure 1), the spatial distribution of fishing effort overlapped that of herring TBI in 2012, and cod TBI in 2017, and it mismatched thornback ray TBI between

Table 2. Horn indices measuring the spatial overlap between the distributions of biomass/abundance indices (TBI, UAI, URI) and of fishing effort, or discard rates.

			VMS effort comprehensive EEC domain 2012–2019	Discard rates restricted EEC domain 2009–2019
Cod	*G. morhua*	TBI	0.08 [0.03–0.23]	–
Cuttlefish	*S. officinalis*	TBI	**0.80*** [0.25–0.50]	–
Mackerel	*S. scombrus*	TBI	0.32 [0.10–0.34]	–
Red mullet	*M. surmuletus*	TBI	**0.62*** [0.30–0.55]	–
Seabass	*D. labrax*	TBI	**0.51*** [0.09–0.34]	–
Squids	*Loligo* sp.	TBI	**0.76*** [0.39–0.58]	–
Thornback ray	*R. clavata*	TBI	*0.21*** [0.23–0.50]	–
Herring	*C. harengus*	TBI	0.08 [0.01–0.16]	0.25 [0.06–0.28]
		UAI	0.09 [0.01–0.15]	0.03 [0.00–0.19]
		URI	0.50 [0.25–0.59]	*0.31***[0.32–0.62]
Horse mackerel	*T. trachurus*	TBI	0.33 [0.26–0.51]	0.65 [0.56–0.69]
		UAI	**0.63*** [0.27–0.53]	0.75 [0.66–0.77]
		URI	**0.73*** [0.45–0.59]	0.96 [0.93–0.97]
Plaice	*P. platessa*	TBI	0.33 [0.16–0.43]	0.44 [0.19–0.48]
		UAI	0.09 [0.06–0.32]	**0.42*** [0.13–0.39]
		URI	0.36 [0.30–0.58]	**0.72*** [0.32–0.63]
Whiting	*M. merlangus*	TBI	0.10 [0.06–0.32]	**0.55*** [0.11–0.54]
		UAI	0.08 [0.04–0.26]	**0.66***[0.08–0.50]
		URI	0.54 [0.28–0.55]	**0.62*** [0.30–0.59]

The actual Horn index is provided and accompanied by the 5th and the 95th percentiles of Horn index values resulting from a permutation test. Actual Horn index values above P95, indicative of a significant overlap ($p < 0.05$), are bolded and marked as "*"; values below P05, indicative of a significant mismatch ($p < 0.05$), are italicized and marked as "**".

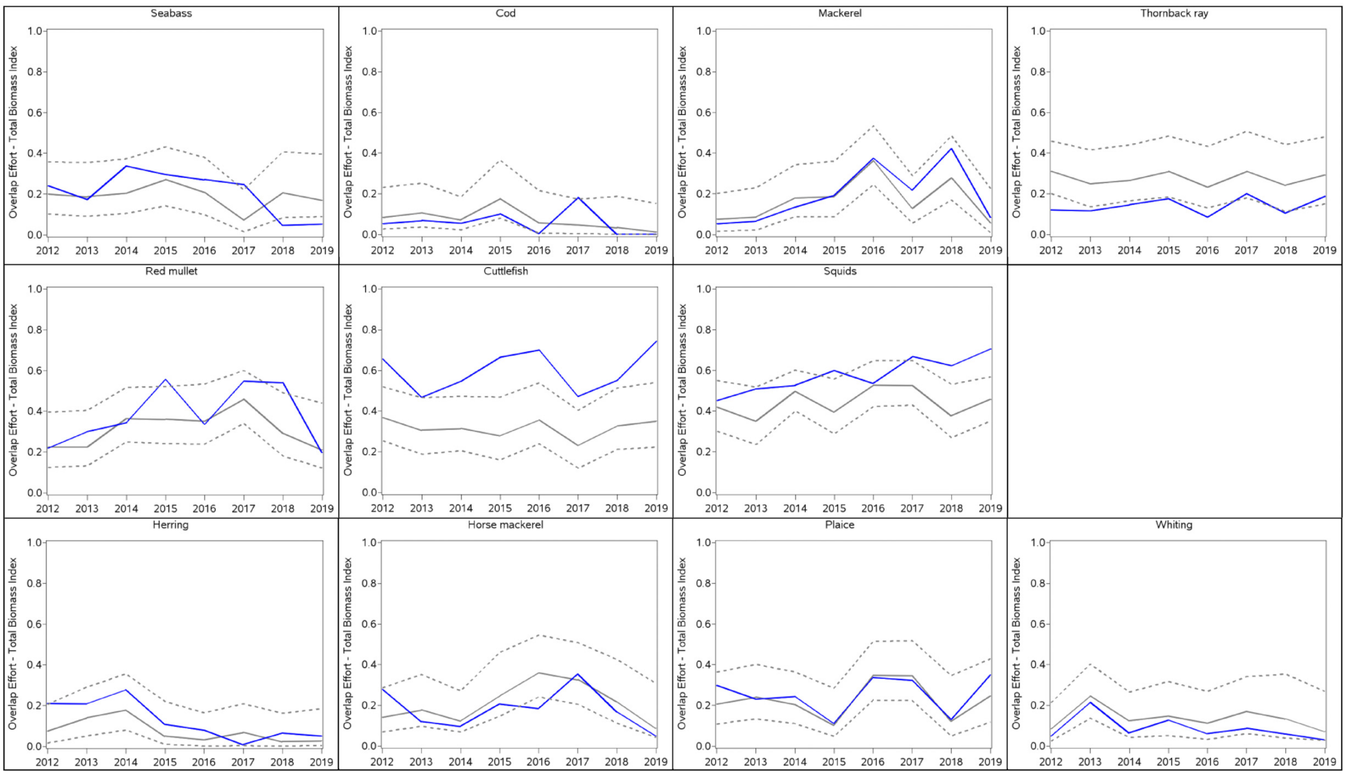

Figure 1. Annual series of Horn indices measuring the spatial overlap between fishing effort and CGFS total biomass indices. The actual Horn index (blue plain line) is compared with the median (grey plain line), the 5th and the 95th percentiles (grey dotted lines) of Horn index values resulting from a permutation test. Fishing effort and total biomass indices significantly ($p < 0.05$) overlap (respectively, mismatch) when the actual Horn index exceeds the 95th percentile (respectively, drops below the 5th percentile) value.

2012 and 2016 and in 2018, cod TBI in 2016 and 2018, and horse mackerel TBI in 2016.

There was a significant spatial overlap between fishing effort and both horse mackerel undersized abundance indices (UAI and URI), over the period 2002–2019 (Table 2) and in specific years (Figure 2). The distributions of fishing effort and UAI did not overlap for herring, plaice, and whiting, globally (Table 2), or annually, except for herring in 2012 and 2014

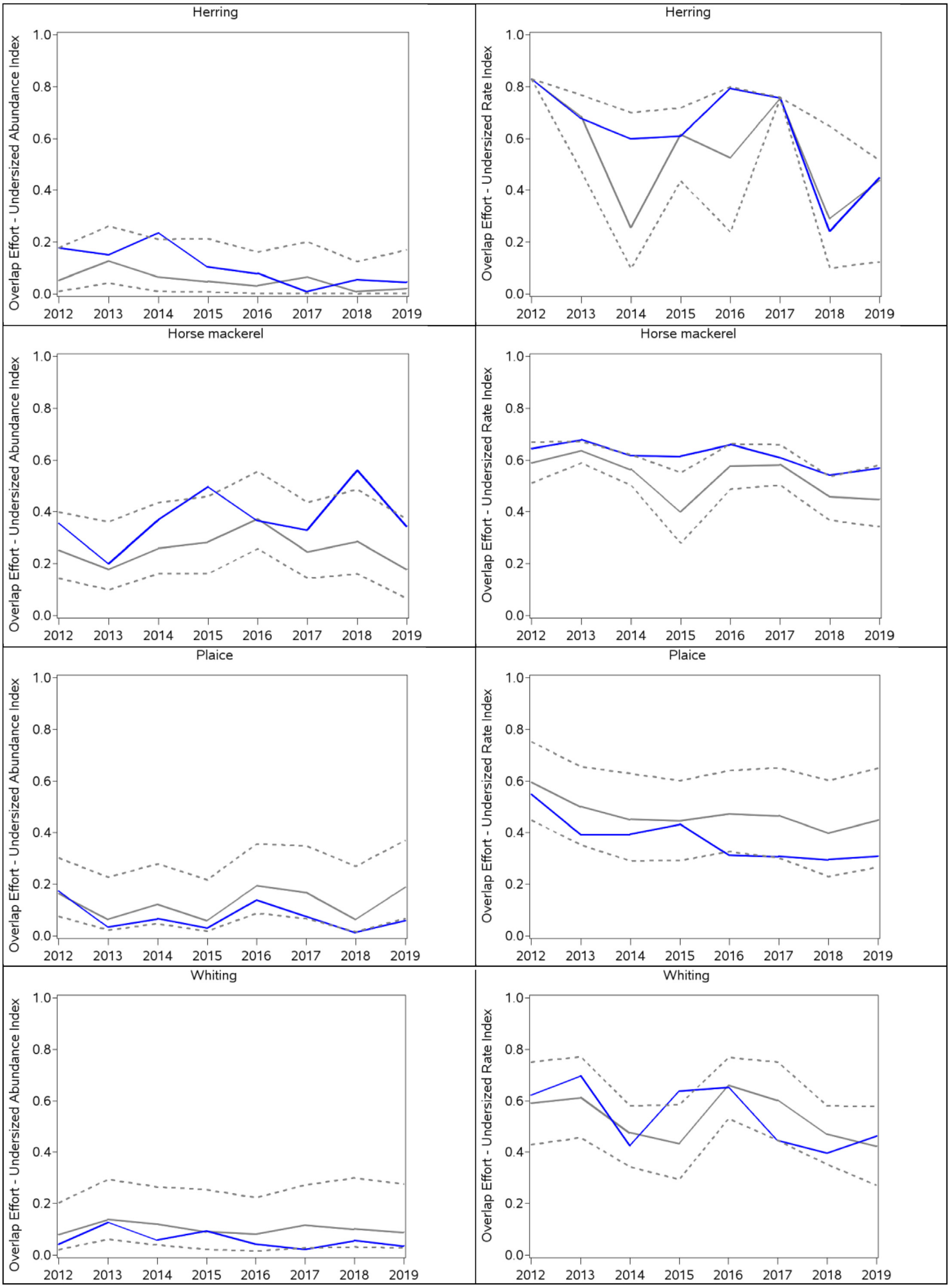

Figure 2. Annual series of Horn indices measuring the spatial overlap between fishing effort and undersized abundance indices (UAI and URI). The actual Horn index (blue plain line) is compared with the median (grey plain line), the 5th and the 95th percentiles (grey dotted lines) of Horn index values resulting from a permutation test. Fishing effort and undersized abundance indices significantly ($p < 0.05$) overlap (respectively, mismatch) when the actual Horn index exceeds the 95th percentile (respectively, drops below the 5th percentile) value.

(Figure 2). Annual mismatches were found for plaice in 2018–2019, and whiting in 2017 (Figure 2).

Fishing effort did not (globally or annually) overlap the spatial distributions of URI for herring, plaice, whiting, except in 2015 in the case of whiting (Table 2, Figure 2). Annual mismatch between both distributions were found in 2016 (plaice) and 2017 (whiting).

Analysis 2: effects of species distribution on discard rates spatial patterns

The spatial distribution of discard rates and of both undersized abundance indices (UAI, URI) overlapped in the case of plaice and whiting. Discard rates overlapped spatially with whiting's TBI, but not with plaice's TBI, or any of the other species' (herring, horse mackerel) survey indices (Table 2, column 5).

Analysis 3: effects of discard rates spatial patterns on fishing effort distribution

Fishing effort significantly mismatched the spatial distribution of horse mackerel discard rates (2015–2019) and of plaice discard rates (2012–2014, 2015–2020, 2012–2019) (Table 3). There were no significant overlaps or mismatches between fishing effort and discard rates distributions for the other periods and/or species.

Discussion

Our results suggest that cuttlefish and squids have been consistently targeted by French bottom trawlers during the period 2012–2019, which was confirmed by their large contribution to total landings. Fishing effort also overlapped the TBI distributions of red mullet and seabass, but less frequently. Fishing effort and mackerel TBI distributions did not overlap significantly during the period 2012–2019, although mackerel dominates French bottom trawlers' landings in several years. This may reflect that the CGFS operates after the peak of the mackerel fishing season in the EEC (Carpentier *et al.*, 2009), but also that the spatial and temporal volatility of mackerel may not be fully captured by the CGFS survey GOV bottom gear.

The lack of significant overlap between the distributions of fishing effort and of the TBI of cod, whiting, plaice, herring, and horse mackerel is reflected by their relatively low contribution in the total landings, and it confirms that these species are merely by-catches of the French bottom trawlers in October. The lack of interest for cod fishing in recent years is likely due to the severe decline of the stock, especially in southern areas (ICES, 2021), where the French fleets have caught less than 5% of their quota since 2017.

Bourdaud *et al.* (2019) found that cuttlefish and red mullet were the main targets of French bottom trawlers during the period 2008–2014, while cod and whiting were less attractive, which is in broad agreement with our own findings. The main difference with our analysis is that the French fleet has increasingly targeted squids in recent years. The increase in squids targeting may result from its economic attractiveness combined with the absence of TAC management. The variable red mullet targeting, as reflected by Figure 1, is not directly driven by management, as this species is not regulated by catch limits, and it may rather reflect stock and/or market fluctuations.

Fishing effort did not overlap with the distributions of undersized herring, plaice, and whiting during the period 2012–2019, either in absolute (UAI), or relative (URI) terms, which could be expected. Still, we also found that fishers distributed their fishing effort on fishing grounds characterized by a high proportion of undersized horse mackerel. Similar to undersized herring, plaice, and whiting, undersized horse mackerel may in any case not be marketed, so this overlap is likely an adverse side-effect of targeting cuttlefish, squids and, to a lesser extent, red mullet and seabass. In addition, the spatial overlap between fishing effort and undersized horse mackerel densities was not reflected in the discards composition, where the proportion of undersized individuals was small, perhaps suggesting that the spatial scale of our analysis was too coarse to fully capture the interaction between fishing effort and undersized horse mackerel distributions. The degree of spatial overlap between fishing effort and undersized herring, horse mackerel, plaice, or whiting was not subject to any meaningful inter-annual variations other than annual effects before and after 2015, which suggests that the legal enforcement of the LO has had limited effects on the spatial distribution of fishing effort in relation to the fishing grounds populated with these undersized groups. This may reflect the absence, or the late implementation, of discard plans relevant to herring, horse mackerel, plaice, and whiting bottom trawl fisheries, and/or the exemptions these have been subject to (Supplementary Table S2).

We evidenced an overlap between the spatial distributions of discard rates and of undersized plaice and whiting. Plaice and whiting discard rates are mainly composed of undersized fish, while horse mackerel discards are mainly above the MCRS (Supplementary Figure S8). This bears out the outcomes of other studies, which showed that the presence of small fish was a major driver to discarding, and particularly so for species subject to an MCRS (Stratoudakis *et al.*, 1998; Rochet *et al.*, 2002; Feekings *et al.*, 2012, 2013). Other factors may affect discarding, e.g. catching fish close to or above quota, highgrading low value or damaged species (Batsleer *et al.*, 2015; Catchpole *et al.*, 2018; Calderwood and Reid, 2019). By operating a discard ban experiment in collaboration with English skippers, Catchpole *et al.* (2018) estimated the respective contribution (%) of different drivers to discard decisions: undersized catch, quota restriction, unmarketable fish, and damaged fish. They found for plaice that undersized catch and quota restriction respectively contributed to 43 and 41% of the discarding decision. The high contribution (43%) given by Catchpole *et al.* (2018) to undersized catch confirms our finding that the spatial distribution of plaice discard rates is to a large extent driven by spatial patterns in undersized biomass. It is, however, unlikely that the risk of catching fish over quota incentivized French bottom trawlers to discard plaice, given the relatively low French quota uptake (<30% since 2016). For whiting, Catchpole *et al.* (2018) estimated the contributions of undersized catch, quota restriction, unmarketable fish, and damaged fish respectively to 13, 11, 72 and 4%. This confirms to some extent our findings that the spatial patterns in whiting discard rates are related to the distribution of undersized biomass. However, the low level of quota uptake suggests that overquota discarding was unlikely in the case of French bottom trawlers. It is still plausible that the low economic value of whiting, relative to other targeted EEC species (e.g. cephalopods) has incentivized discarding, similar to what was found by Catchpole *et al.* (2018), but also

Table 3. Horn indices measuring the spatial overlap between the distributions of fishing effort and of discard rates.

		VMS effort (restricted EEC domain)		
		2012–2014	2015–2019	2012–2019
Herring	*C. harengus*	0.69 [0.65–0.99]	0.52 [0.52–0.67]	0.67 [0.60–0.82]
Horse mackerel	*T. trachurus*	0.74 [0.65–0.86]	*0.70*** [0.70–0.73]	0.82 [0.75–0.85]
Plaice	*P. platessa*	*0.31*** [0.35–0.69]	*0.30*** [0.38–0.72]	*0.37*** [0.40–0.66]
Whiting	*M. merlangus*	0.45 [0.43–0.77]	0.62 [0.45–0.84]	0.36 [0.30–0.60]

The actual Horn index is provided and accompanied by the 5th and the 95th percentiles of Horn index values resulting from a permutation test. Actual Horn index values below P05, indicative of a significant mismatch ($p < 0.05$) are italicized and marked as "**".

Stratoudakis *et al.*, (1998). This could explain why whiting discard rates overlap spatially with total biomass, the bulk of which is composed of commercial-sized individuals.

No overlap was found between the spatial distributions of discard rates and of undersized herring or horse mackerel. This was expected given the low proportion of undersized individuals in discards. In Catchpole *et al.* (2018), herring and horse mackerel were exclusively discarded by the English fleet due to a lack of market. The same rationale may explain why the spatial distributions of herring and horse mackerel discard rates did not overlap with any biomass or abundance index for these species.

Several studies have simulated the effects of discard bans on fishing effort distribution (Simons *et al.*, 2015), or investigated the scientific basis for advising on management measures (e.g. move-on rules) to prevent fishing on discard hot spots (Dunn *et al.*, 2014; Little *et al.*, 2015). However, while a number of research papers have explored discards-avoiding technological solutions, very few studies have investigated empirically the extent to which fishers would avoid fishing grounds were high discard rates are observed (Calderwood *et al.*, 2021), and our study brought a contribution there.

We thus evidenced a significant mismatch between the spatial distributions of fishing effort and of plaice discard rates in all periods (2012–2014, 2015–2019, and 2012–2019). The spatial units with high plaice discard rates are located in the vicinity of the Baie de Seine and the Baie de Somme estuaries, where high proportions of undersized fish are present (Table 2). This could suggest an avoidance of plaice discard hotspots within the EEC restricted domain, which may have been driven by large proportions of undersized fish. However, it could also reflect difficulties for French bottom trawlers to access the 3 nautical miles coastal zone, which is subject to specific management. The lack of a visible effect of the LO might have resulted from the lack of a discard plan until 2019, and by the survivability exemption, i.e. allowing fishers to discard if a substantial proportion of fish survives once released, which has been in effect since 2019 when catching plaice with bottom trawls (EU, 2018c).

There was a significant mismatch between the spatial distributions of fishing effort and of horse mackerel discard rates in 2015–2019, but not in 2012–2014. This result should be interpreted carefully for two reasons. First, Supplementary Figure S7 suggests a lack of contrast among the spatial units where horse mackerel discard rates are informed. Second, horse mackerel bottom trawl fisheries were not subject to any discard plan until 2019. Although a discard plan has since 2019 been incepted, this has been subject to a *de minimis* exemption, i.e. allowing fishers to discard 7% of total annual catches of horse mackerel by bottom trawls (EU, 2018c), so it is uncertain whether and how the LO affected fishing strategies.

The spatial distributions of fishing effort and of discard rates significantly mismatched for plaice but not for whiting, despite some collocation of whiting and plaice discard hotspots. This may result from subtle differences in the distribution of discard rates between those two species off the hotspots, but also from the relatively lower amount of spatial units for which whiting discard rates were informed relatively to plaice discard rates.

Overall, the main conclusions drawn from Analysis 3 are that (1) fishing effort may have avoided spatial units with potentially high plaice discard rates, which may have been driven by large proportions of undersized fish since 2012, economics (fishers having no interest landing unmarketable fish), but also by management measures (MCRS), and (2) the LO had limited effects on fishing effort allocation relative to the distribution of discard rates.

In this study, we investigated the spatial overlap (or mismatch) between the distributions of fishing effort and species biomass/abundance (Analysis 1), discard rates and species biomass/abundance (Analysis 2), and fishing effort and discard rates (Analysis 3). Because the geographical coverage of data available was different across the three analyses, it has not been possible to address the three questions altogether within the same geographical domain. Therefore, it remains to be tested whether the main conclusions obtained with Analyses 2 and 3 and the restricted EEC domain data (e.g. overlap between the spatial distributions of plaice and whiting discard rates and of undersized abundance indices, and mismatch between the spatial distributions of fishing effort and of plaice discard rates) would then be valid when applied to the comprehensive EEC domain. Similarly, we could not infer whether our conclusions would still apply at a finer spatial and temporal scale. For instance, changes in depth and/or fishing time have been reported as a subtle discards-avoidance behavioural mechanism, which could not be evaluated here given the data resolution of our analysis (Calderwood *et al.*, 2021).

We interpreted spatial overlaps (or mismatch) with a causal effect, of fish distributions on fishing effort allocation (Analysis 1) or discarding patterns (Analysis 2), and of discarding patterns on fishing effort allocation (Analysis 3). Although assuming such unidirectional interactions seems reasonable to interpret short-term effects, reciprocal effects could be envisaged in the medium term (e.g. local depletion of fisheries resources induced by fishing; Rijnsdorp *et al.*, 2011) and the longer term (e.g. discarding-induced changes in the overall ecosystem functioning; Groenewold and Fonds, 2000). Exploring such interactions in a bidirectional fashion would require considering not only the spatial overlap but also the temporal interactions between fishing, discarding, and fisheries resource dynamics.

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Supplementary Data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Data availability statement

The survey data underlying this article will be shared on reasonable request to the corresponding author. Fisheries data were kindly provided by the French Direction Générale des Affaires Maritimes, de la Pêche et de l'Aquaculture (DGAMPA). Data may be shared on request to the corresponding author, subject to the permission of the DGAMPA.

Authors' contribution

PM: conceptualization, methodology, analyses, writing, and original draft preparation; PM and YV: data preparation, review, editing. Both authors have read and agreed to the published version of the manuscript.

Conflict of interest statement

The authors declare no conflicts of interest.

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