Marine Ecology Progress Series
January 2018, Volume 586 Pages 167-179
http://dx.doi.org/10.3354/meps12392
http://archimer.ifremer.fr/doc/00418/52997/

Exploring habitat credits to manage the benthic impact in a mixed fishery

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Abstract :

The performance of a combined catch quota and habitat credit system was explored to manage the sustainable exploitation of a mix of demersal fish species and reduce the benthic impacts of bottom trawl fisheries using a dynamic state variable model approach. The model was parameterised for the Eastern English Channel demersal mixed fishery using otter trawls or dredges. Target species differed in their association with habitat types. Restricting catch quota for plaice and cod had a limited effect on benthic impact, except when reduced to very low values, forcing the vessels to stay in port. Quota management had a minimal influence on fishing behaviour and hence resulted in a minimal reduction of benthic impact. Habitat credits may reduce the benthic impacts of the trawl fisheries at a minimal loss of landings and revenue, as vessels are still able to reallocate their effort to less vulnerable fishing grounds, while allowing the fishery to catch their catch quota and maintain their revenue. Only if they are reduced to extremely low levels can habitat credits potentially constrain fishing activities to levels that prevent the fisheries from using up the catch quota for the target species.

Keywords : Fleet dynamics, Dynamic state variable modelling, TAC, Total allowable catch, Mixed fisheries, Eastern English Channel, Plaice, Cod

Introduction

The impact of bottom trawl fisheries on benthic habitats and ecosystems is a matter of global concern (Kaiser et al. 2006; 2016). Such bottom trawl fisheries use towed gears that make direct physical contact with the seafloor to catch species living or feeding close to the bottom substrate (Valdemarsen et al., 2007). As a consequence, these fisheries potentially reduce structural complexity of habitats, injure or kill target and non-target species, alter species composition, and modify ecosystem processes such as benthic production (Dayton et al., 1995; Collie et al., 1997; Thrush et al., 1998 ; Kaiser et al., 2002).

The extent to which bottom trawl fisheries disturb benthic ecosystems depends on the type of fishing gear used, the frequency and distribution of fishing activities in an area (Kaiser et al., 2006; Rijnsdorp et al. 2015) but also depends on the sensitivity of habitats and benthic ecosystems to fishing disturbance (Collie et al., 2000; Hiddink et al. 2007; Eno et al., 2013). This sensitivity differs across habitats as a result of differences in natural disturbance (bottom shear stress, effects of waves), bottom typology (e.g. slope and depth), sediment composition, and species composition (Hall, 1994; Jennings and Kaiser, 1998; Snickars et al., 2013, van Denderen et al., 2014). Complex biogenic habitats with emergent structures are likely to be more affected as compared to naturally disturbed soft sedimentary habitats (Jennings and Kaiser, 1998; Lindholm et al., 2015).

Fish species caught by bottom trawl fisheries differ in their preference to habitat types, because of their morphological and behavioural characteristics. Habitat preference generally changes along the life cycle of species, because of ontogenetic niche shifts (Thouzeau et al., 1991; Le Pape et al., 2003; Atkinson et al., 2004). Adult roundfish species, for example, have a preference for hard bottom habitats with a high structural complexity providing food and shelter (Tupper and Boutilier, 1995; Wieland et al., 2009), while flatfish species such as plaice

(*Pleuronectes platessa*) and sole (*Solea solea*) prefer soft bottom habitats in which they can burry themselves to avoid predation (Gibson and Robb, 2000). As a result, the impact of a fishery on the sea bed habitat and benthic ecosystem depends on the linkage between the habitat preference of the different species, and the species preference of the fishery.

In many fisheries management systems around the world, fisheries management historically focussed on the sustainable exploitation of commercial fish and shellfish stocks by setting Total Allowable Catches (TACs) but ignoring the potential wider ecosystem effects of fishing (Pikitch et al., 2004; Chu 2009; Holland and Schnier 2006). Policy developments such as the amendments to the Magnuson-Stevens Act in the U.S. and the reform of the Common Fishery Policy (CFP) in Europe have recognised the importance of safeguarding ecosystem composition, structure and functioning and have embraced an ecosystem-based approach. This objective requires managers to assure a sustainable use of natural resources while minimising impacts of fishing activities on the structure and functioning of sea bed habitats and benthic ecosystems. In this context, the EU is establishing marine Natura 2000 sites. While these sites do protect habitat features and species, this is not a fisheries management object, but rather a conservation objective in relation to biodiversity.

The conventional approach of fisheries managers to maintain or restore ecosystem processes focusses on technical measures, including gear restrictions and spatial measures, as well as direct limitations on fleet capacity and fishing effort (Rice et al., 2012). Most spatial management measures aim to either protect habitat, preserve biodiversity, or maintain a reserve of fishes and often do not have a socio-economic management objective (Halpern, 2003; Lester et al., 2009). As a result, socio-economic benefits of spatial management are not necessarily to be expected and one could consider a spatial management measure to be successful as long as it meets its primary objectives without causing any socio-economic harm (Darling, 2014; Caveen et al., 2015). Several studies have proposed the use of a credit system as an alternative

management approach (Holland and Schnier, 2006; Kraak et al., 2012). These credit systems try to balance economic and environmental values associated with fisheries by addressing specific conservation goals with limited effects for the fishery (Van Riel et al., 2013).

Our study explores the performance of individual catch quota combined with a habitat credit system to manage the sustainable exploitation of a mix of demersal species and to minimise the benthic impacts of bottom trawl fisheries. Results are compared to traditional quota management for two commercial species, cod and plaice, which have different habitat associations. We apply an individual based simulation model of the effort allocation and discarding decisions in a mixed fishery (Poos et al., 2010; Batsleer et al. 2013). The model is adapted to include individual habitat credits (IHC) and is parameterised for the French multipurpose bottom trawl fleet in the eastern English Channel. This fleet may switch between dredging for scallops (*Pecten maximus*) and otter trawling for a mix of demersal fish species (Carpentier et al., 2009). We then evaluate the extent to which the incorporation of habitat credits in a quota management system can be a tool for ecosystem based management, in terms of benthic impacts reduction and sustainable exploitation of fish.

Methods

Study area

The Eastern English Channel (International Council for the Exploration of the Seas (ICES) division 7.d) consists of 15 ICES rectangles (~30 × 30 nautical miles), which we have divided into grid cells of 3x3 nautical miles each. Spatial distribution of habitats is derived from a detailed map of Eastern English Channel sea bed habitats in Coggan and Diesing (2011) (Figure 1). Each grid cell was assigned the dominant habitat type present within that cell. We distinguished five habitats based on grain size and depth (soft, infralittoral coarse, circalittoral coarse, deep coarse, and rock), following Coggan and Diesing (2011). Soft sediment habitats, consisting of fine sand or muddy sediments, are found along the coast and in the eastern part where the English Channel borders the North Sea. Coarse sediment habitats were the predominant type in the eastern English Channel. Rocky sea bed habitats were a combination of infralittoral and circalitoral rock and other hard substrates occurring towards the west along the coast with an extensive reef found in the western part of the study area (Diesing et al., 2009). Within each ICES rectangle adjacent cells of the same habitat type were merged and counted as a single fishing area, resulting in 126 fishing areas.

Habitat impact credits were assigned to each fishing area based on the sensitivity of habitats to fishing activities. Rock habitat and deep coarse sediment habitat support emergent epibenthos such as sponges, bryozoans and hydroids, making them more vulnerable to trawling compared to more shallow and dynamic soft sedimentary habitats (Jennings and Kaiser, 1998; Kaiser et al., 2006; Eno et al., 2013; Boulcott et al., 2014). Because of the increasing sensitivity of habitats to fishing activities, impacts credits were divided into three classes with increasing credits: infralittoral coarse and soft sediment habitat were assigned 2 credits, circalittoral course were assigned 5 credits, and deep coarse and rock habitats were assigned 10 credits (Table 1). The classification of infralittoral coarse habitat as being less sensitive to fishing than

circalittoral course and deep coarse habitat reflects the natural, tidal disturbance of the sea bottom in the infralittoral, making its ecological community more resilient to additional disturbance from bottom fishing. If used in policy setting, the amount credits assigned to each habitat should be decided by policy makers, and can be based on sensitivity matrices (Eno et al., 2013).

Study fleet

We selected the French multipurpose bottom trawl fleet as a case study because it uses bottom contact gears that affect bottom habitats. Vessels within this fleet switched between demersal otter trawling (OTB) and dredging for scallops (*Pecten maximus*), making daily trips to their fishing grounds, while operating from several ports around the Eastern English Channel, mainly Boulogne-Sur-Mer and Dieppe. The scallop fishery was fully open between November and April (Guyader et al., 2004). Demersal otter trawling was generally operated with 80mm mesh size nets, targeting a variety of demersal species. The scallop dredge (DRB) lands few other commercial valuable species (Carpentier et al. 2009). The southern part of the eastern English Channel was the most important scallop fishing ground and some fishers temporarily changed harbour to reduce their journey to the scallop fishing grounds.

Catch data were derived from logbooks and sales slip data of the fleet for the period 2006 to 2010. The data included information of individual vessels by fishing trip on vessel length, engine power, gear type, mesh size, fishing ground (ICES rectangle), fishing effort (hours fished), and the weight and value of the landings per species. Aggregated fishing effort estimates per fishing area were derived at the fine scale resolution (3 x 3 nmi) for 2008 from Delavenne (2012) (Table 1).

Spatial and temporal shifts in catch rate

Five species (scallops - *Pecten maximus*, sole - *Solea solea*, plaice - *Pleuronectes platessa*, cod - *Gadus morhua*, sea bass - *Dicentrarchus labrax*) and one taxonomic grouping of cephalopods which included cuttlefish - *Sepia officinalis*, squids - *Loligo vulgaris*, and *L. forbesii*). From now on, these will be referred to as six "species", for the sake of simplicity, keeping in mind that one of these "species" really represented the taxonomic grouping of cephalopods. These species were considered because of their economic importance for the multipurpose trawling fleet, i.e. combined these contribute 67% of the total annual income.

Catches in the present study were estimated on the basis of landings per unit effort of French commercial vessels. For each of the species the mean and variance of catches were estimated from the logbooks at their spatial (ICES rectangle) and temporal (week) scale (Figure 2). These mean and variance in catches (kg) were estimated using generalized additive models (GAMs) (Wood, 2006). In the GAMs, fishing effort (hr) was used as model offset (Zuur, 2012). This use of effort as a model offset allows the prediction of catch rates (kg/hr) from the GAM results. A negative binomial response with a logarithmic link function was applied (Zuur et al., 2009). Scallop catch rates were analysed only including trips with dredges, while catch rates of the other five species were analysed for trips operated by demersal otter trawls. The model estimating the catch *C* per species *s* by area per day is given by:

$$C_s = \propto + \beta(year) + f_1(engine\ power) + f_2(mesh\ size) + f_3(lat, lon, DOY) + \log(effort)$$

Where α is the model intercept and f_1, f_2 and f_3 are smooth functions based on a tensor product smoother (Zuur, 2012). The differences in catch rates among years is estimated in the parameter $\beta(year)$. The tensor product smoother $f_1(engine\ power)$ is included due to its influence on the catch efficiency (Rijnsdorp et al., 2006) and $f_2(mesh\ size)$ is included as the choice of mesh size may indicate the species the fishery is targeting. The interaction term $f_3(lat,lon,DOY)$ fits the effects of space (latitude and longitude based in geographic midpoint of the ICES rectangle) and day of year when the vessel returned to port (DOY). The term is based on a thin-plate spline

(Wood, 2003) for the space variables and a cyclic cubic regression spline for DOY. The cyclic cubic regression spline was chosen to receive equal values and slopes at the beginning and end of the year (Wood, 2006). For scallops the cyclic cubic regression spline for DOY was changed into a cubic regression spline because of the closed season from May to October. The Akaike Information Criterion (AIC) was used to assess the model fit whereby the model with the lowest AIC was selected as best candidate. The best models included a limited degree of freedom for the f_1 and f_2 smoothing terms (k=4), but a higher degree of freedom for the f_3 smoothing term of the space * time interaction (k=9). All analyses were done using the mcgv package within the R statistical program (version 2.12.1; R Core Development Team 2013; Wood, 2006).

Catch rates by fishing area

The GAM provides estimates of catch rates per species per ICES rectangle. The rectangles are composed of mosaics of habitats (Figure 1). To estimate catch rates by fishing area within ICES rectangles, catch rates were assumed to be positively correlated with effort per fishing area (Figure 2). This assumption is supported by observations that fishing effort is not homogeneously distributed within an ICES rectangle, but is distributed on a finer spatial scale, concentrating within areas of high fish densities (Rijnsdorp et al. 2011).

Observed fishing effort per fishing area on the fine scale resolution (3 x 3 nmi) were derived from combining weekly effort from logbooks by ICES rectangle with fine-scale effort distribution (Table 1) as follows: First, the fraction of effort distributed over the habitat types within each ICES rectangle was calculated for each gear type based on Delavenne (2012). Multiplying these fractions with the effort distribution by ICES rectangle in the logbooks resulted in a distribution of effort in habitat type *h* within an ICES rectangle *a* in week *w* (E_{haw}).

Catch rates at the resolution of the habitat type *h* within each ICES rectangle *a* (L_{ha}) were not available, because catch data are not collected at the scale within which different habitats can be detected. Meanwhile, information on the fine scale distribution of fishing effort

was available in Delavenne (2012). Although catch data in logbooks can be distributed over fishing positions recorded in VMS data, such procedures generally assume that catches are uniformly distributed over VMS positions (Dinmore et al., 2003; Gerritsen and Lordan, 2011; Hintzen et al. 2012). However, fishing activities may concentrate within areas and habitat types with a high catch rates of target species (Rijnsdorp et al. 2011). To capture both assumptions of the relationship between effort and catch rates we used the equation:

$$L_{ha} = \frac{\left((L_a * \sum E_{haw}) * \left(\frac{E_{haw} * \left(\frac{E_{haw}}{S_{ha}}\right)^{\propto}}{\sum\left(E_{haw} * \left(\frac{E_{haw}}{S_{ha}}\right)^{\propto}\right)} \right) \right)}{E_{haw}},$$

where E_{haw} is the effort per week w in habitat type h in ICES rectangle a and S_{ha} is the surface area of habitat type h in ICES rectangle a. The coefficient α is a scaling-factor to aggregate the highest fish density within habitat types with the highest effort by area ratio. When α is set to zero, catch rates are equal over each habitat type within an ICES rectangle. Increasing α results in a differentiation in catch rates over habitat types, with larger catch rates in habitat types with the highest aggregation of effort (Figure 3). The value of α is set to 0.5, thus assuming fishing activities concentrate within areas and habitat types with high catch rates of target species (Rijnsdorp et al. 2011).

To scale the catch rates by week, estimates are rescaled to reflect the average fishing effort per week. Fishing effort per week was estimated from the logbooks; resulting in the average time spent at sea (10h day^{-1}) and average number of trips per week (4 trips week^{-1}).

Economic data

Mean weekly market values for the six species are calculated from auction price data in the period 2006-2010 (Figure 4). During the scallop season, scallops contribute to more than 85% of the gross revenue and account for almost 40% of the annual income of the fleet (Carpentier et al., 2009). The five other species included in our study account for another 27% of the total annual income.

The model includes a fine for overshooting individual landings quota or individual habitat credits (IHC). The fines have been set to values of 1950€ kg^{-1} and 5000€ IHC^{-1}, being several orders of magnitude higher than the market prices of the target species, ensuring vessels complied with the management regulations in the model.

Variable costs for this fleet include fuel costs, landing costs, and crew salaries (Table 2). Fuel costs depend on the type of vessel and gear used. Fuel costs were approximately 440€ fishing day^{-1} when operating a dredge and 730€ fishing day^{-1} (F. Daurés, pers. comm.) when operating a demersal otter trawl (in the period 2008-2010). Crew costs are 40% of the total revenue obtained at the end of the fishing trip. Landing costs are defined as the fees paid by the vessel when catches are landed and are 6% of the total revenue. Other variable costs (e.g. ice, bait, food) are 40€ fishing day^{-1}. Landing costs, salary costs and other variable costs are derived from a study of (Daurès et al., 2013) and assumed to be independent of the gear type used during a fishing trip.

Simulation model

The performance of a combined catch quota and habitat credits system is forecasted using a Dynamic State Variable Model (DSVM) (Houston and McNamara, 1999; Clark and Mangel, 2000). Such models have been applied in fisheries research to forecast fishing strategies under different management and market constraints (Gillis et al., 1995; Poos et al., 2010; Dowling et al., 2012).

The model is parameterized for vessels from Boulogne-sur-Mer with the predicted spatial and temporal catch rates of the 6 species under consideration (scallops, sole, plaice, cod, sea bass and cephalopods), ex-vessel prices, and variable costs. Two gear types are modelled that can be used interchangeably: demersal otter trawls can be used throughout the year targeting the 4 finfish and cephalopod species, while scallop dredges can only be used during the scallop season. The model assumes individual skippers will maximize their expected annual

net revenue by making weekly decisions on (i) whether to go fishing or not; (ii) what type of gear to use and, (iii) where to fish. These choices are affected by their annual catch quota and habitat credits.

The optimal fishing strategy in each week of the year, denoted by *t*, depends on the state of the individual skipper. In our case, the cumulative uptake of habitat credits as well as cumulative landings of the quota constrained species affects the possibility to continue fishing without exceeding the annual habitat credits or landing quota. To simplify model results, simulations were done assuming catch quota are restrictive for two species: cod and plaice. These species were chosen because they differ in their preference of habitat types (Tupper and Boutilier, 1995; Gibson and Robb, 2000).

DSVMs find the optimal behavioural strategy by working backwards, starting at the end of the year. The expected net revenue at the end of the year is linked to the choices in the preceding weeks by means of a value function between time *t* and the end of the year *T*. The value function for an individual skipper depends on the cumulative landings of the quota species *L*, the amount of quota *U* for cod or plaice, the cumulative uptake of habitat credits *I*, the amount of habitat credits available *C* and the fine for exceeding the quota or habitat credits *D* and is expressed as $V(L, U, I\ , C, D, t)$. Individuals exceeding their quota or habitat credits pay a fine that depends on the quota (L - U) or credit (I - C) overshoot and the fine per unit weight (d_1) and per credit (d_2). The state-dependent part of the revenue at the end of the year, after all fishing has been completed, $V(L, U, I, C, D, T)$ is defined by the fine of overshooting quota and/or credits

$$\Phi(L, U, I, C, D) = \begin{cases} 0, & L \leq U \text{ and } I \leq C \\ -(L-U)d_1, & L > U \text{ and } I \leq C \\ -(I-C)d_2, & L \leq U \text{ and } I > C \\ -(L-U)d_1 - (I-C)d_2, & L > U \text{ and } I > C \end{cases}$$

For each week before *T*, the expected net revenue is determined by the value function, the weekly gross revenue from the catch and the cost of fishing. Each week individuals choose

to use a type of gear g and to visit a fishing area a (including area 0: "staying in harbour"). For all time t preceding T we use stochastic dynamic programming to find the optimal solution by backward iteration of the net expected revenue H from t to the end of the year considering the choices a and g and the states L and I at t and optimal choices in subsequent weeks

$$H(L,U,I,C,D,t;a,g) = R(a,g,t) * (\frac{100}{\kappa}) - C(a) + \mathbb{E}_{a,g}[V(L',U,I',C,D,t+1)]$$

Where $R(a,g,t)$ is the expected immediate contribution of the gross revenue from the sales of the catch in a week resulting from choices a and g. The term κ represents the percentage that the six species contribute to the total income (i.e. 67%). The term $C(a)$ represents the variable costs in a week resulting from choosing fishing area a and using gear type g including fuel, crew, landing costs and other variable costs. The term L' reflects the change of the state L resulting from the weekly landings for the quota species. This change is stochastic and depends on the means and variances found in the statistical analyses of the catch rates. The term I' reflects the change of state I as a result of the weekly choice of fishing in an area with a given amount of habitat credits. The term $\mathbb{E}_{a,g}[V(L',U,I',C,D,t+1)]$ denotes the expected value taken over all possible states resulting from choices a and g. The future utility given that an individual behaves optimally from time t onwards is

$$V(L,U,I,C,D,t) = \max_{a,g}\{H(L,U,I,C,D,t;a,g)\}.$$

Starting with $V(L,U,I,C,D,T) = \Phi(L,U,I,C,F)$ we can iterate backwards in time and find the optimal choice in terms of location and gear type for all possible states, combining the direct net revenue obtained in a fishing trip and the effect of the fines when exceeding annual quota or habitat credits.

The expected direct gross revenue $R(a,g,t)$ from the sale of the six target species for any choice depends on the catch and the ex-vessel price in a given week. The catch is determined by the choice of gear and the spatial and temporal distribution of the target species.

Management scenarios

This study explores the performance of individual quota management for plaice and cod in combination with a habitat credit system to sustainably exploit resources and minimize the impact of the fishery on the benthic ecosystem. First, the performance of traditional quota management for plaice and cod is evaluated in relation to benthic impact. Individual quota for plaice are gradually increased from 1 to 8 tonnes per year. Given the low observed quotas for cod under the cod recovery plan (Kraak et al., 2013), individual quota for cod are lower and increased from 0.2 to 1.6 tonnes per year. Second, management scenarios were explored that combined individual catch quota and habitat credits. Habitat credits varied from 20 to 300 per year, while quota varied from 1 to 9 tonnes and 0.1 to 1.5 tonnes per year for plaice and cod, respectively. The maximum of 300 habitat credits per year was based on the maximum uptake of habitat credit by fishers in unconstrained model simulations.

Results

Catch quota simulations

First we explored the effect of individual catch quota on habitat impact by estimating the fishing effort in different habitat types. Reduction of plaice quota affects the level of fishing effort and the choice of habitats (Figure 5a). At high quota vessels fish year-round (52 trips yr^{-1}), and the majority of trips occur in low impact circalittoral coarse and soft sediment habitats. If plaice quotas are below 4 tonnes per year, the number of trips is reduced, mainly in the circalittoral coarse sediment habitat. The effort reduction and reallocation result in a decrease in habitat impact over the year, measured as the use of habitat credits (Figure 5a).

A reduction of cod quota also affects the level of effort and the habitat choice (Figure 5b). At the highest cod quota, a vessel will fish year-round, allocating the majority of trips over circalittoral coarse and soft sediment habitats. A decrease in cod quota results in a gradual decrease to 48 trips per year at the lowest cod quota and a slight increase in fishing in the more sensitive deep coarse habitats. This reallocation results in a slight increase in habitat impact over the year in spite of the reduction in the number of trips (Figure 5b).

Catch quota and habitat credit simulations

In this section we explore how a habitat credit system can mitigate benthic impact in a fisheries managed by individual catch quota for the main target species. In this fishery, the amount of habitat credits allocated to the fishery affect the actual credit use up to 220 IHC $year^{-1}$, but this depends on the quota, particularly for plaice (Figure 6a, b).

When habitat credits are combined with plaice or cod quota, a decrease in habitat credits from 300 to 100 IHC has a limited influence on the overall effort of the fishery (Figure 6c, d). At high IHC, effort will be allocated to both gear types, with most effort being allocated to the DRB (Figure 6e, f). A decrease in IHC from 300 to 100 results in a reduction of OTB effort

(Figure 6g, h), but hardly affects DRB effort, irrespective of the quantity of quotas. Only when IHC are < 100 IHC effort decreases and vessels no longer choose to fish using OTB, but only fish with the DRB (as long as IHC > 60).

Decreasing IHC from 300 to 100 only results in a modest (approximately 7%) reduction of net revenue (Figure 6i, j). This is largely the result of a small increase in DRB effort that compensates the reduction OTB effort. When IHC are very low (<100 IHC), and the fishery is fully targeting scallop, net revenue sharply declines below 200 K€. Because plaice and cod have a relatively lower economic value and a lower catch rate, compared to other target species, the loss in revenue from plaice and cod at reduced catch quota is compensated by increasing the DRB effort, targeting scallops. Our results thus suggest that when reducing habitat credits from high to low, the net revenue only decrease slightly at first, and more steeply at low IHCs. This result is largely independent of the individual catch quota available.

Trip allocation over habitat types

When habitat credits are combined with plaice quota, the choice of fishing grounds is determined by the IHC available and the quantity of plaice quota (Figure 7). High IHC (> 160) and high plaice quotas (> 5 tonnes) result in an allocation of trips predominantly to circalittoral coarse and soft sediment habitats, although a few vessels will fish in areas with more sensitive deep coarse sediments. A reduction in IHC (< 160) pushes vessels away from circalittoral coarse sediments to less sensitive infralittoral coarse and soft sediments. The shift from more sensitive to less sensitive habitat types is influenced by the amount of individual plaice quota. Fishing in deep coarse sediments stops when habitat credits are reduced below 140 IHC. At low plaice quota (< 5 tonnes), trips to deep coarse sediments decline but continue until IHC are lower than 100 IHC and trips to these sensitive habitats are no longer operated.

In addition to the IHC available, low cod quota influence the choice of fishing grounds (Figure 7). At high IHC and low cod quota, vessels will allocate more trips to sensitive deep

coarse sediment habitats and less trips to fishing grounds with circalittoral coarse sediment habitat. Nevertheless, circalittoral coarse and soft sediment habitats still remain the dominant fishing grounds. At high cod quota, fishing in more sensitive habitat types rapidly decreases if IHC are reduced (Figure 7). At low cod quota, however, a decrease in IHC initially result in a small increase in the number of trips to circalittoral fishing grounds and a decrease in the number of trips allocated to fishing grounds with deep coarse sediment habitats. A further decrease in IHC will push vessels away from sensitive habitat types and as a result, all effort is concentrated in infralittoral coarse and soft sediment habitats.

Discussion

Overview of findings

The model results indicate that managing fisheries by catch quota does not necessarily reduce benthic impact exerted by French bottom trawlers in the Eastern English Channel. Reduction of individual catch quotas could even result in an increase in the benthic impact as vessels could reallocate effort towards fishing grounds located in more vulnerable habitats to avoid catching quota-restricted species. In the model, we show that benthic impacts can be reduced by introducing individual habitat credits, with limited cost in terms of landings and revenue. Vessels are still able to reallocate their effort to less vulnerable fishing grounds while maintaining their effort and revenue. When IHC are reduced further vessels cannot make any profit out of fishing and they have to stay in port to not exceed their habitat credits.

Simulation Model

The simulation model was parameterized for the Eastern English Channel French bottom trawl fleet. Results of the fleet response are indicative for this particular fleet given the necessary simplifications made. Model simplifications include the assumptions that: (i) fishers are profit maximizers and comply fully with management regulations given severe sanctions for non-compliance, (ii) individuals have perfect knowledge about the temporal and spatial

distribution of catch rates, (iii) the quota for a single species (plaice or cod) is constraining the fishery, and these quota are not transferable, and (iv) there is no competition among fishers. The hypothesized effects of these simplifying assumptions have been discussed in Poos et al. (2010) and Batsleer et al. (2013). We further assume that the scallop season was open from November to April throughout the Eastern English Channel and that vessels did not move from Boulogne-Sur-Mer to other harbours at the opening of the scallop season.. In reality the opening of the season depends on annual scientific advice and the opinion of authorities, and may be different among areas (Carpentier et al., 2009). Also, vessels may temporarily move to harbours close to the best scallop fishing grounds.

Although we had to make a large number of simplifying assumptions, as discussed above, these assumptions will not affect the qualitative results showing that within mixed fisheries the seasonally and spatially variable availability of target species allows a variety of effort allocation patterns that yield similar net revenue with widely different benthic impacts.

In this study, habitat impact credits were set independent of the historic fishing activities in the habitat. However, historic fishing activities can be an important factor determining fishing impact on the benthic ecosystem (Kaiser, 2005). Reducing habitat credits in frequently fished areas may lead to a concentration of fishing activities in those areas, given the reduced cost of fishing (Holland and Schnier, 2006). This reduces the risk of trawling in areas that were previously untrawled (Piet et al., in prep).

The habitat credits in the model do not vary by gear type. Empirical studies, however, indicate that gear type strongly affects the magnitude of fishing impact (Collie et al., 2000; Kaiser et al., 2006; Eigaard et al., 2015). Sensitivity matrices synthesize these results, describing the sensitivity of habitats to different gears based on the physical bottom of each gear and the sensitivity of the benthic community to the additional mortality caused by the

bottom contact. These sensitivity matrices can be used by policy makers to assign gear-specific habitat credits (Eno et al., 2013).

Practical application and broader relevance

There is a growing awareness of effects of fisheries on ecosystems, beyond the obvious reductions in population biomass as a result of the fisheries catches. An ecosystem-based approach to fisheries management aims at mitigating these effects. One aspect of ecosystem-based management is the recovery and conservation of the composition, structure and functioning of ecosystems. Management approaches, such as credit management systems, have been suggested as a mean to protect or improve ecosystem structure and function (Holland and Schnier, 2006; Kraak et al., 2012), in complement to traditional measures such as closed areas (Caveen et al., 2015; Smith et al., 2010; Winter and May, 2001; Raakjær Nielsen, 2003; Abbott and Haynie, 2012). Such systems build on incentivizing responsible fishing practices, constraining fishers with a number of credits or a share of the property while allowing them to adjust their behaviour and chose freely when and where to fish to make optimal use of their credits or share. However, management objectives in such systems will only be achieved if credits or quota are set at the right target or limit reference point (Van Riel et al., 2013). Setting these targets or limit reference points will be a process where policy-makers, scientists, fishing industry and other stakeholders need to be engaged and agree on the goals of the management system. Successful implementation further depends on the availability of data and knowledge on habitats and their functioning, as well as detailed monitoring of vessel locations, and bookkeeping systems of credits in the fishing industry and government institutions.

Our study shows that a complementary use of habitat credits with catch quota could reduce benthic impact, while the fishery can continue to sustainably exploit a mix of resources. The development of credit systems, however, is still in its infancy and requires more knowledge on the relationship between different ecosystem components, the relationship between human

use components, an improved data collection at the right spatial and temporal scale, and extensive monitoring and enforcement (Kraak et al., 2012; Van Riel et al., 2013; Tidd et al., 2015; Sys et al., 2016). The collection of more detailed information and data gathering would require more effort from the fishing industry in terms of privacy and investments on board, but then again fishers will retain their freedom to choose when and where to fish. Hence, for spatial measures to meet ecological objectives and to be cost-effective, an understanding of the adaptive behaviour of fishers to these measures is critical.

Acknowledgements

The contribution of JJP and ADR was funded by the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 312088 (BENTHIS). The contribution of Paul Marchal, Sandrine Vaz and Youen Vermard was funded by European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 266445 for the project Vectors of Change in Oceans and Seas Marine Life, Impact on Economic Sectors (VECTORS). We thank the three anonymous reviewers whose comments helped improve and clarify this manuscript.

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Table and figures

Table 1 Habitat types, associated habitat impact credits and fishing effort distribution (%) for demersal otter trawls (OTB) and scallop dredgers (DRB) estimated from Delavenne (2012).

Habitat	Habitat impact credit	Effort OTB (%)	Effort DRB (%)
Rock	10	1.0	0.2
Deep Coarse	10	14.9	16.4
Circalittoral Coarse	5	68.4	71.3
Infralittoral Coarse	2	9.2	5.7
Soft	2	6.6	6.4
Total (h yr^{-1})		394385	46545

Table 2 Variable cost of the scallop dredgers (DRB) and demersal otter trawl (OTB) used in the simulation.

Variable costs	OTB	DRB
Fuel (€ fishing day^{-1})	730	440
Crew costs (% of revenue)	40	40
Landing costs (% of revenue)	6	6
Other variable costs (€ fishing day^{-1})	40	40

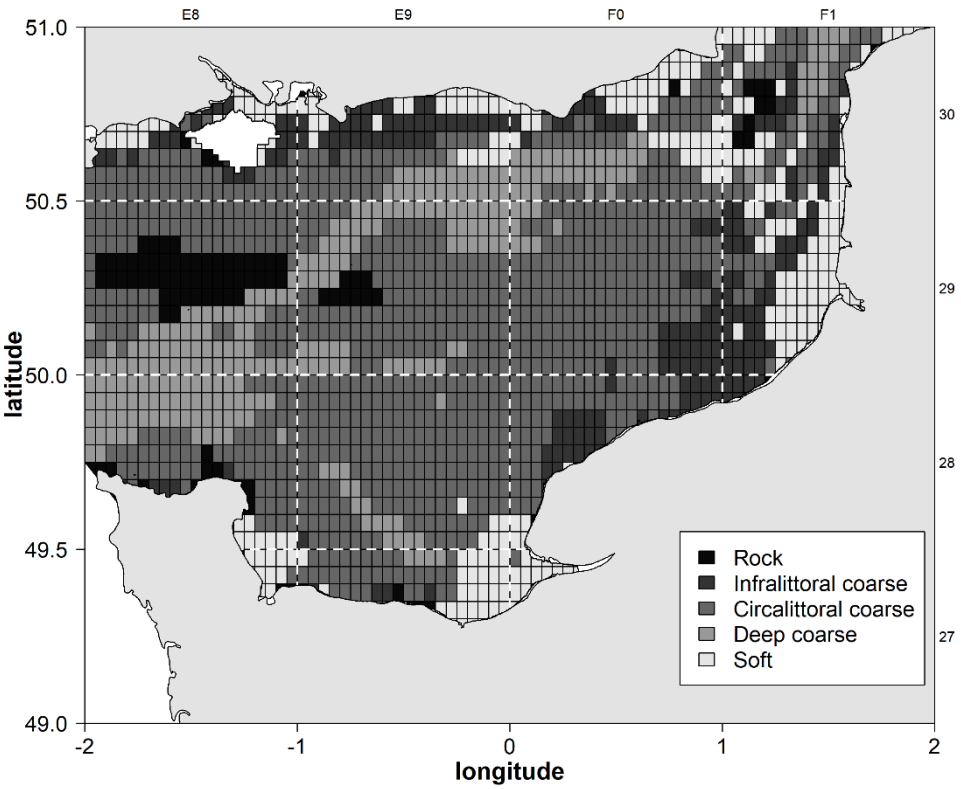

Figure 1. Habitat distribution map based on Coggan and Diesing (2011), with the main French fishing harbours used in this study. ICES rectangles are delineated by the white dashed lines.

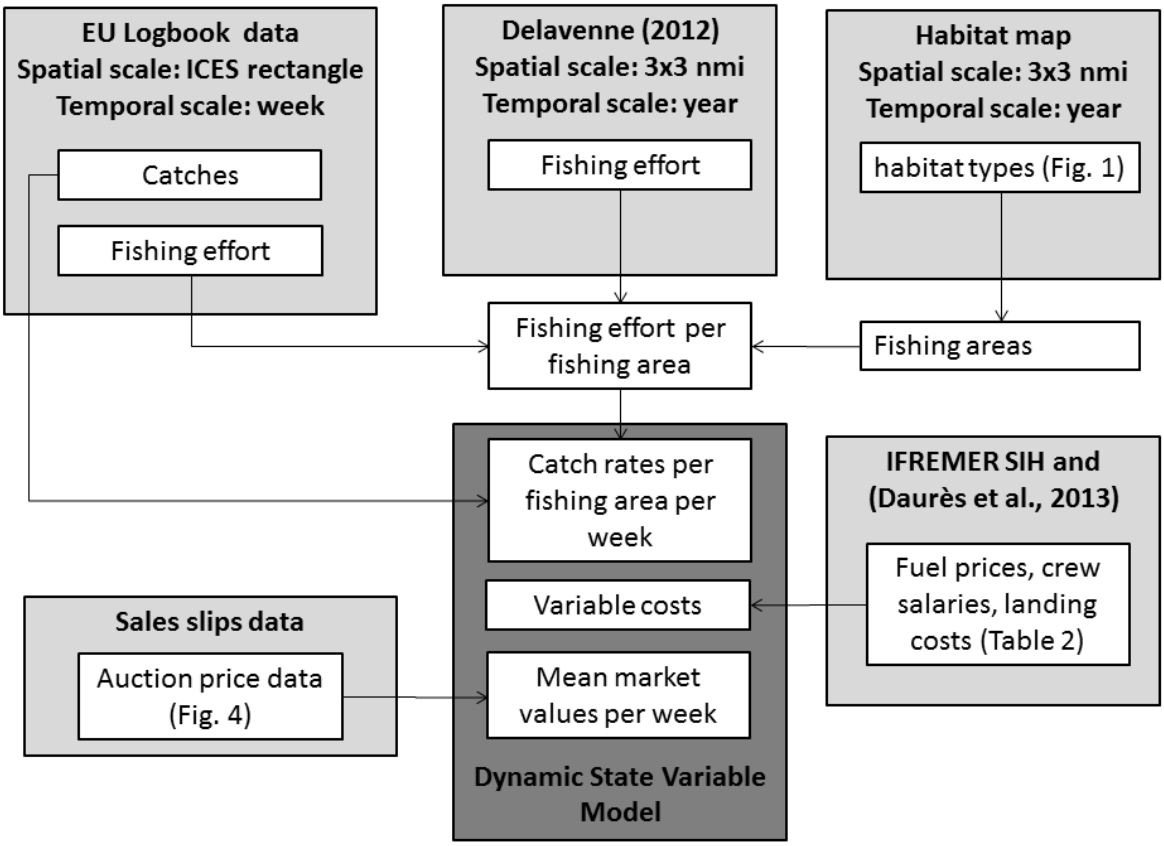

Figure 2. Schematic representation of the methodology and data used in this study.

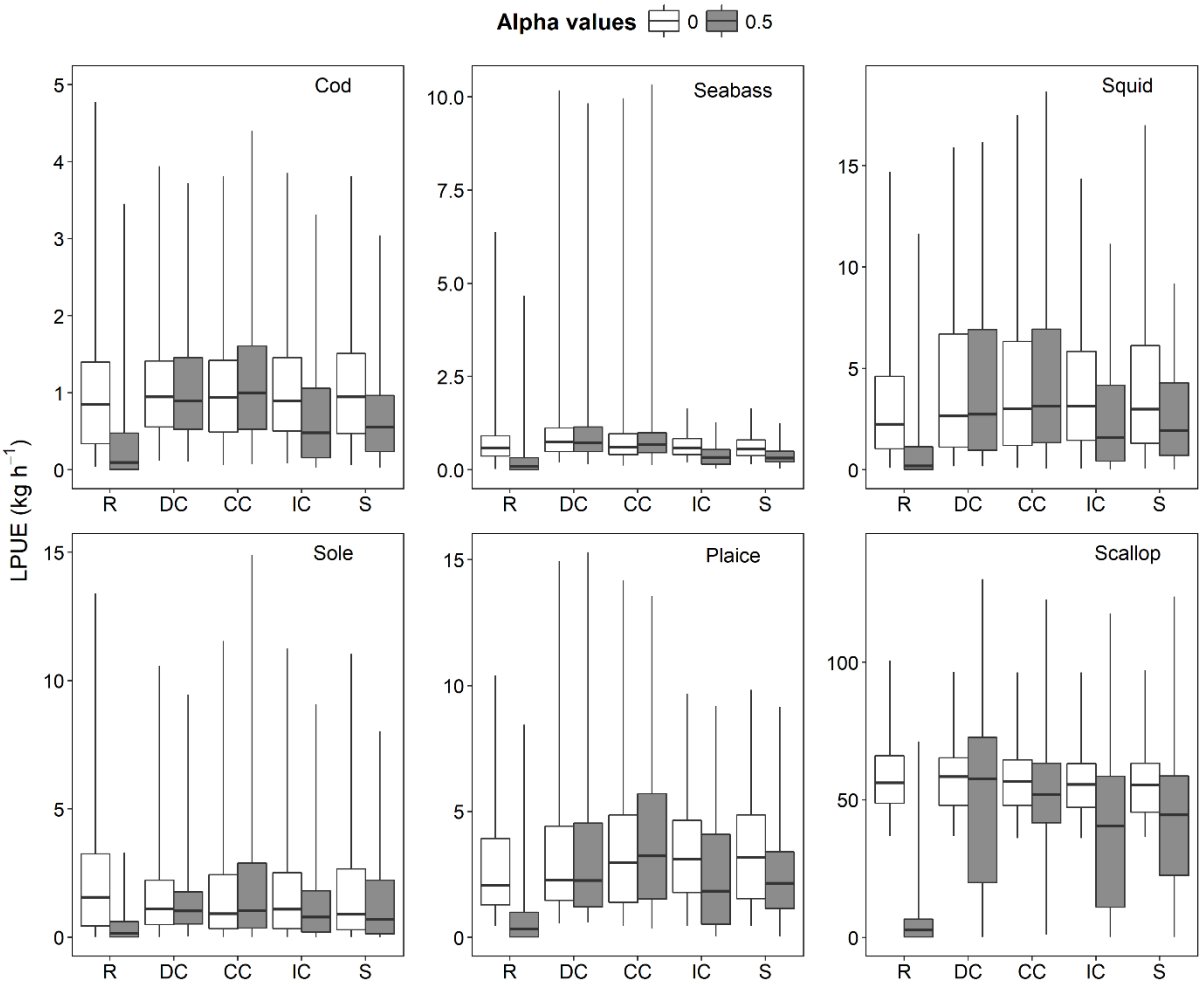

Figure 3. Variation in catch rates (, kg h^{-1}) for 6 target species on different substrates. Rock (R), deep coarse sediment (DC), circalittoral coarse sediment (CC), infralittoral coarse sediment (IC) and soft sediment (S). Black horizontal bars correspond to medians, lower and upper hinges correspond to the first and third quartiles, whiskers extend to data range. The coefficient α is a scaling-factor used to differentiate catch rates over habitat types. Setting α to zero results in equal catch rates over each habitat type, while increasing α results in larger catch rates in habitat types with the highest aggregation of effort.

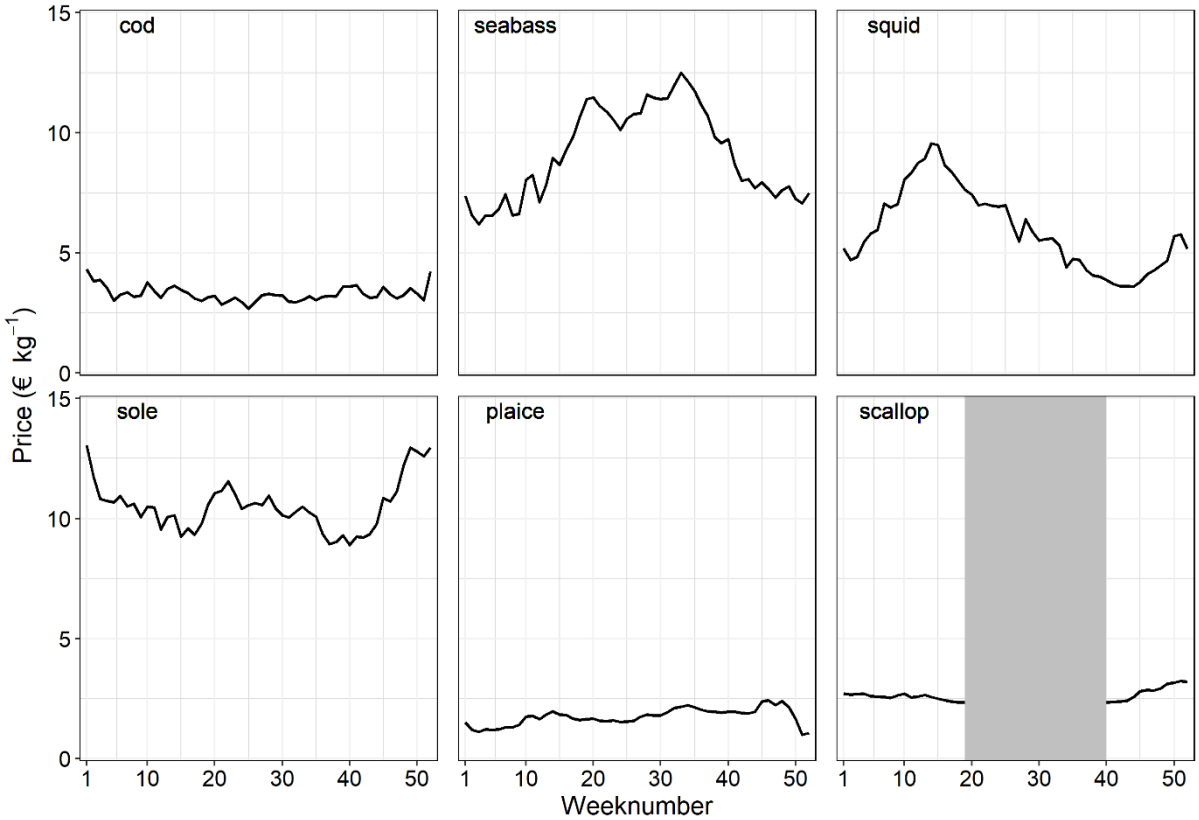

Figure 4. Average ex-vessel price per week for each of the target species in the period 2006-2010. No prices are available for scallops from May to October because of the closed season (shaded area).

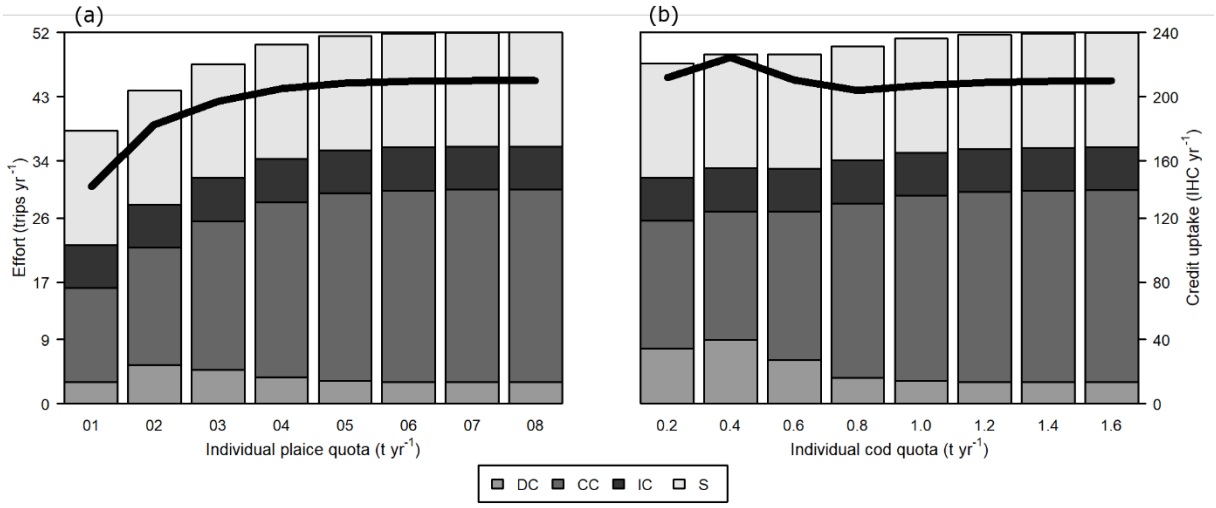

Figure 5. Average number of trips in a year to a substrate-type (DC = Deep coarse, CC= Circalitoral coarse, IC= Infralittoral coarse and S = Soft sediment), depending on the quota of plaice (a) and cod (b). The black line shows the average impact (credit uptake).

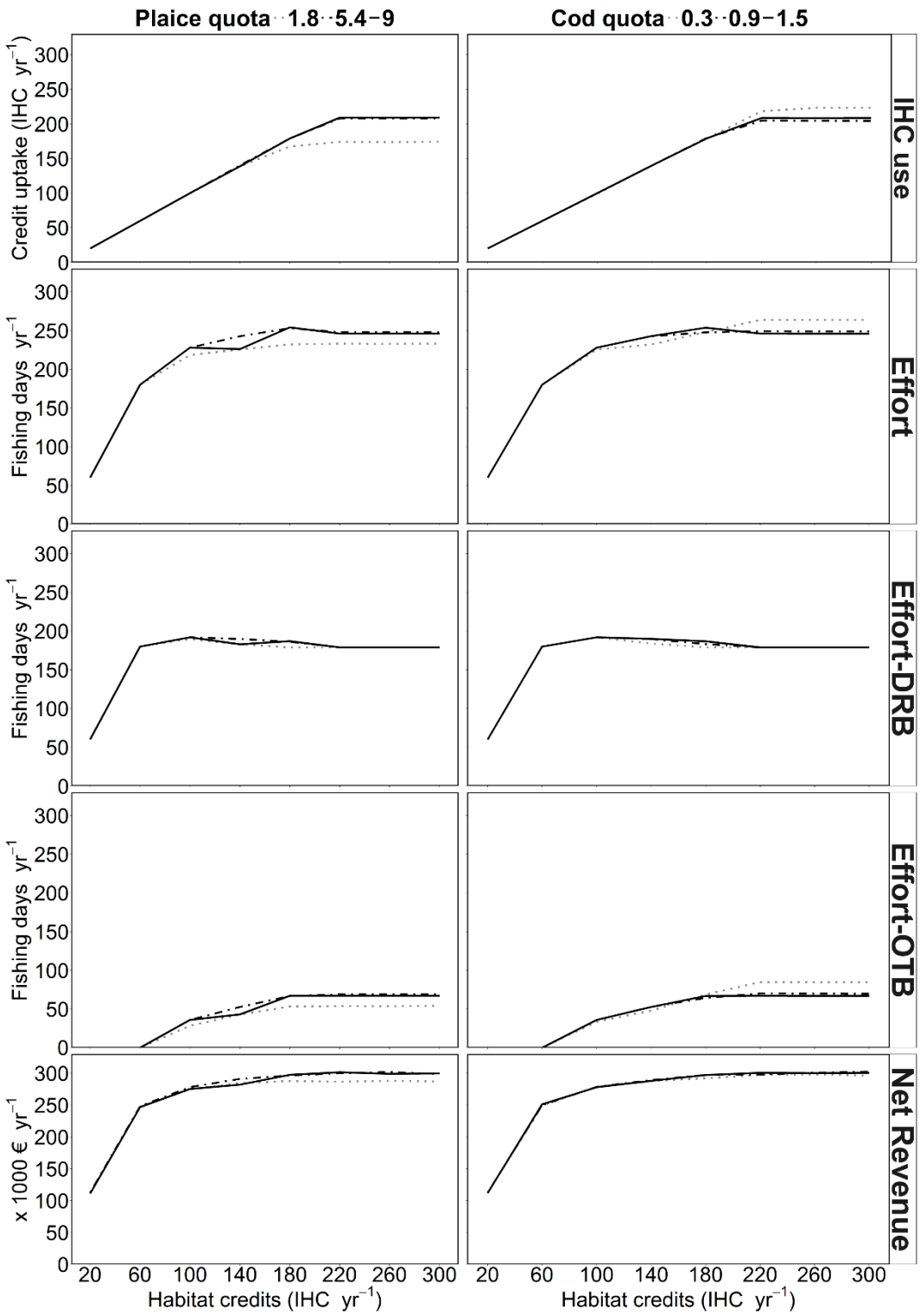

Figure 6. Credit uptake, total effort, dredge effort, otter trawl effort, and net revenue in relation to the individual habitat credits in combination with three levels of individual catch quota for plaice and cod. Plaice quota range from 1.8 to 9 tonnes per year and cod quota range from 0.3 to 1.5 tonnes per year

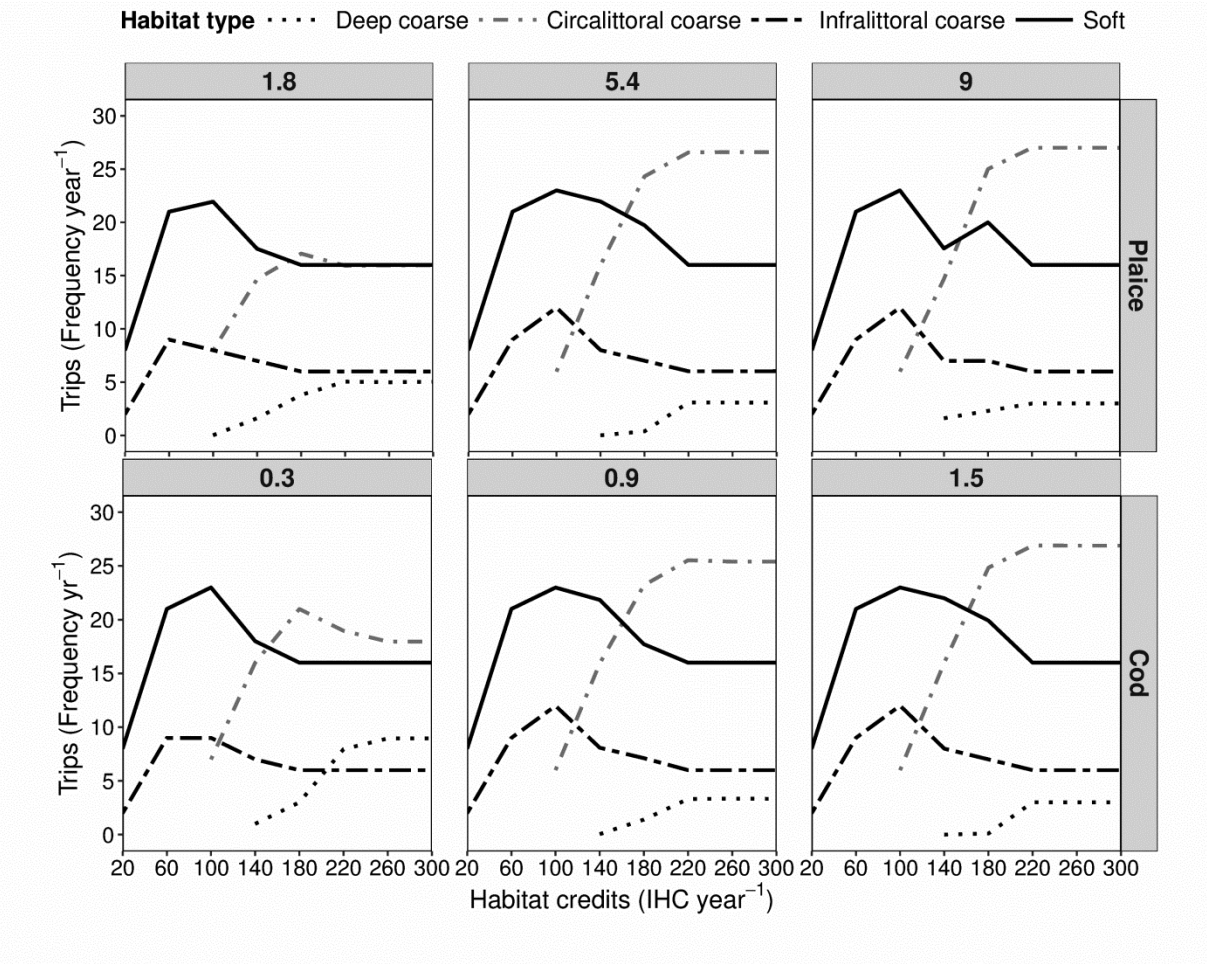

Figure 7. The average number of trips made to a certain habitat type for the different impact scenarios. Top panels are a fishery under plaice quota from 1.8 to 9 tonnes per year. Lower panels are for the fishery constrained by cod quota from 0.3 to 1.5 tonnes per year.