Discarding in UK Commercial Fisheries

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Abstract

Discarding, or returning unwanted catch to the sea, is a common feature of European fisheries, and is widely acknowledged as morally wrong. It wastes food and economic resources, and has contributed to overfishing in EU stocks. However, under the current Common Fisheries Policy (CFP), catch that is below minimum landings sizes, exceeds quota, or does not match catch composition regulations must be discarded.

The high profile of discarding in recent years has put pressure on the European Commission (EC) to reform the CFP. A key objective is to eliminate discards and reduce unwanted catches. A discard ban and catch quotas for regulated species will be implemented. The EC argues that this will create strong incentives for more selective fishing, but little supporting evidence from EC fisheries is available. This thesis aims to present such evidence.

A desk based analysis of a number of global fisheries found that a discard ban in isolation created little or no incentive to avoid unwanted catches; supporting measures were required to encourage more selective fishing practices. Analysis of the potential impact of introducing a discard ban on English North Sea otter trawlers supported this finding. Models using economic, logbook and observer data showed that the cost of capturing unwanted catch is minimal unless a cap is placed on total catches. Catch quotas cap fishing mortality, creating a strong incentive to reduce catches of limiting species. This incentive is unequally distributed between and within fleets, and is strongest for the least selective vessels. If catch compositions are not adjusted to match available quota, substantial reductions in revenue could occur.

So under the reformed CFP discards of regulated species could be eliminated, the cost of catching unwanted fish will be passed onto the fishers, and strong incentives for more selective fishing practices will be generated.

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Research papers and Author's declaration

Presented in Chapter 2:

Published paper 1 **-** Condie, H. M., Grant, A., and Catchpole, T. L. 2014. Incentivising selective fishing under a policy to ban discards; lessons from European and global fisheries. Marine Policy, 45: 287-292.

Presented in Chapter 3:

Published paper 2 **-** Condie, H. M., Grant, A., and Catchpole, T. L. 2013. Does banning discards in an otter trawler fishery create incentives for more selective fishing? Fisheries Research, 148: 137-146.

Presented in Chapter 4:

Published paper 3 - Condie, H. M., Catchpole, T. L., and Grant, A. 2013. The short term impacts of implementing catch quotas and a discard ban on English North Sea otter trawlers. ICES Journal of Marine Science. 10.1093/icesjms/fst187.

Presented in Chapter 5:

Paper 4 - Condie, H., Dolder, P., Catchpole, T., Grant, A. and Ulrich, C. Incentivising selective fishing under catch quotas: using an Fcube modelling approach to evaluate management options for North Sea mixed fisheries.

Statement: I, Harriet Condie, was the primary author in all three published papers above, and the primary author of paper 4. I designed and undertook the desk based analysis of reports and literature in published paper 1, the findings of which are presented in Chapter 2. I also designed and constructed the models of published papers 2 and 3 under the guidance of my academic supervisors, Professor Alastair Grant and Dr Thomas Catchpole. These are presented in Chapters 3 and 4, respectively. In paper 4 I used a fisheries forecasting model constructed by Ulrich et al. (2011), to conduct investigations I had designed, with the support of my supervisors and Paul Dolder (Cefas). Paul Dolder supplied some of the data used in this analysis. The findings of this research are presented in Chapter 5. I performed the data analysis involved in all 4 papers. I wrote all manuscripts of the published papers, which were then assessed and proof read by all secondary authors.

Chapter 1. Introduction

At least 7.3 million tonnes of catch is estimated to be thrown away in global fisheries each year (Kelleher, 2005). Unwanted or non-mandated catch is thrown back into the sea, often dead, in a process known as “discarding” (Alverson and Hughes, 1996). In some cases the level of discards may even exceed landings (Alverson and Hughes, 1996). Over the past few decades, increasing concern has been raised over biodiversity and the poor state of many global fisheries. 57% of global fish stocks are fully exploited whilst 30% are overexploited (FAO, 2012), and a key factor is the accidental capture and waste of non-target fish (Hall and Mainprize, 2005, Hilborn, 2007a, FAO, 2010). “Fish Fight” (Fish Fight, 2011) and other environmental groups have drawn the public’s attention to the scale of waste and the fishing industry has increasingly acquired a “dirty” reputation (Alverson and Hughes, 1996). With over 1 billion people relying on fish as their primary source of protein (The World Bank Washington, 2008) and in the face of declining stocks, the scale of such potential waste of food, biological and economic resources has angered the public and is viewed as socially unacceptable (Alverson et al., 1994, Stockhausen et al., 2012).

So what are discards? The widely used definition of discards was developed by Kelleher (2005) in his assessment of global discards and bycatch. He defines discards as that portion of catch which is returned to the sea, alive or dead, excluding plant material and offal (Kelleher, 2005). Discards include the unwanted or un-mandated component of “bycatch”, or incidentally caught non-target catch, but also includes individuals of the target species that may be discarded due to a whole host of reasons that are described below (Kelleher, 2005).

Discarding occurs to some degree in all fisheries operations (Bellido et al., 2011), and has been occurring for thousands of years (Alverson et al., 1994). Reference is even made to discarding in the Bible (Matthew 13: 47-48);

“Again the kingdom of heaven is like unto a net that was cast into the sea and gathered of every kind. Which when it was full, they drew onto the shore, and sat down and gathered the good into the vessels, but cast the bad away.”

But, it is only in the last few decades that reducing the capture and discarding of unwanted catch has become a target of fisheries management (Kennelly and Broadhurst, 2002). Below we discuss the scale of discards, particularly in European and UK fisheries, what is causing these discards and what has and is being done about it. The research of this thesis then goes on to focus on the current reforms of the European Union’s (EU) Common Fisheries Policy (CFP), at the heart of which is the objective to eliminate discards and reduce unwanted catches (European Commission, 2013a). In Chapter 2 we explore if such an objective has been met in other fisheries around the world, and what factors have determined any success. In Chapters 3 and 4 we examine the potential for this objective to be met in UK fisheries through incentives for the adoption of more selective fishing practices, using the English otter trawler fleet as a case study. In Chapter 5 we examine if these incentives could be generated on a large scale and how they might be distributed between the many European fleets of the North Sea mixed fisheries.

1.1. What is the most recent scale of discards?

In the latest attempt to calculate the level of global discards, Kelleher (2005) estimated that 8% of the world's fish catch is thrown back into the sea annually, equating to 7.3 million tonnes. This is a decline from previous estimates of 27 million tonnes (Alverson et al., 1994). The two estimates are derived using different methodologies and data which may explain the large reduction, however Kelleher argues that the reduction may also be due at least in part to improved fishing practices such as increases in mesh size, increased utilisation of the total catch, and a reduction in fishing effort (Kelleher, 2005).

Discard rates and estimates vary dependent upon the region. The Northeast Atlantic and the Northwest Pacific show the highest discarding levels, accounting for 40% of the global total (Kelleher, 2005). Area specific discard rates or estimates inside the European Commission's jurisdiction are unavailable for many regions (Kelleher, 2005). However, Davies et al (2009) estimated that 19.8% of catch in the North-East Atlantic is discarded, whilst the aggregated discard rate of the Baltic Sea was 1.4% (Kelleher, 2005). In total, an estimated 1 million tonnes of biomass is discarded annually in the North Sea (Tasker et al., 2000).

1.1.1. Scale of discards in UK fisheries

Catchpole et al (2013) estimated that between 2002 and 2010 23,000 to 45,500 tonnes were discarded annually by all English and Welsh vessels sampled in the Cefas (Centre for Environment, Fisheries and Aquaculture Science's) Observer Programme (COP). The COP places fisheries observers on a sample of randomly selected English and Welsh vessels allowing the documentation of total catches (Catchpole et al., 2011). Enever et al (2009b) used this COP data to estimate the discard rates of all English and Welsh vessels in the North Sea; data suggest that between 2003 and 2006 discarding of fish, cephalopods and Norway lobster (*Nephrops norvegicus*, hereafter referred to as *Nephrops*) occurred at an annual rate of 36% by number and 25% by weight (Enever et al., 2009b). Dab (*Limanda limanda*), whiting (*Merlangius merlangus*), plaice (*Pleuronectes platessa*), *Nephrops*, gurnards (*Trigla* spp.), cod (*Gadus morhua*), haddock (*Melonogrammus aeglefinus*) and sole (*Solea solea*) were amongst the top 10 most discarded species by number (Enever et al., 2009b). Cotter et al (2002) showed similar estimates for discards by English vessels over 12m in length operating from ports on the North East English coast; 20-48% of cod, 30-41% of haddock and 51-61% of whiting by number were discarded during 1997 to 1998. Similar levels have been observed in the Scottish demersal fleets; 15, 50 and 35% of cod, whiting and haddock by weight were discarded annually between 1988 and 1993 (Stratoudakis et al., 1999). The COP data also showed that 63% by number of fish caught annually in the English Channel, Western approaches, Celtic and Irish Seas by English and Welsh vessels were discarded between 2002 and 2005 (Enever et al., 2007). 53% of discards were accounted for by 10 species, including gurnards, dab, plaice and dogfish (*Scyliorhinus canicula*) and whiting (Enever et al., 2007), many of which also dominate discards in the North Sea (Enever et al., 2009b). Total discarding by English and Welsh vessels has reduced since 2002, from 48% of the total catch by weight to 33% in 2008, but discarding of commercial species has remained fairly constant since 2005 (Catchpole et al., 2011). The reduction is at least partly explained by a reduction in allowable fishing effort (Catchpole et al., 2011).

1.2. What is the cause?

1.2.1. The selectivity of fishing gear

The root causes of discarding lie in the design of modern fishing gear (Alverson et al., 1994). Developments in fishing technology were traditionally focused on improving fishing power rather than the selectivity of gear (Crean and Symes, 1994). Consequently many gear types are inefficient at catching only the species, sex and sizes that are targeted, resulting in the accidental capture of unwanted individuals (Alverson et al., 1994). The problem is exacerbated due to the majority of target species occurring in mixed assemblages, fishers targeting one species are likely to also catch those species associated with it (Cook, 2003, Gezelius, 2008).

Some types of fishing gear are more selective than others. If the target species is small the capture of unwanted fish is particularly likely; capturing small species such as *Nephrops* requires relatively non-selective gear that will also capture larger non-target species (Drewery et al., 2010, Johnsen and Eliasen, 2011). Consequently, over 27% of global discards are contributed by shrimp trawl fisheries. Beam and pair demersal trawl fisheries also have high discard rates varying from

14 to 69% in the EU (Kelleher, 2005). Much lower rates are seen amongst fisheries using purse seines, handlines, jigs, pots or traps (Kelleher, 2005, Uhlmann et al., 2013, AFMA, 2009). Gears targeting pelagic species tend to be more size and species selective as these species tend to form dense, single species schools reducing interactions with non-target species (Cook, 2003, Borges et al., 2008). For example, matje herring (pre-spawning Atlantic herring, *Clupea harengus*) shoals targeted off Scotland have a distinct sonar profile reducing the likelihood of catching non-target species (Pierce et al., 2002).

In the North Sea, Europe's Science, Technical and Economic Committee for Fisheries (STECF) estimate that discard rates vary from around 20% to 60% by weight. Three mixed-species fisheries are responsible for the majority of discards in the North sea; the flatfish beam trawl fishery, the *Nephrops* otter trawler fishery and the roundfish otter trawler fishery (Johnsen and Eliasen, 2011). Since 1929, the Belgian flatfish and roundfish fisheries have accounted for 39% and 34% by weight of Belgium's discards in the North Sea respectively (Lescrauwaet et al., 2013). In the Irish Sea, Borges et al (2005) estimated that Irish beam trawlers discarded 67% of their catch by weight, mostly dab and plaice, whilst otter trawlers discarded mainly whiting, haddock, bluemouth (*Heliocolenus dactylopteus*) and dogfish, accounting for 20-60% of their catch. Scottish seine vessels discarded relatively less, 25% of their catch, mainly whiting, haddock and grey gurnard (*Eutrigla gurnardus*) (Borges et al., 2005). Similarly, Uhlmann et al (2013) found that Danish seines are more selective showing lower discard rates of plaice in the North Sea than other fisheries.

In UK fisheries, Enever et al (2009b) found that 42% of North Sea discards by number between 2003 and 2006 were contributed by beam trawlers, whilst *Nephrops* and otter trawlers were responsible for 33% and 24% respectively. Netters accounted for less than 1% of discards (Enever et al., 2009b). Catchpole et al (2005a) estimated that in 2001-2002 the English north east coast *Nephrops* trawlers discarded 43% of catch by weight, 72% of which was whiting. These vessels were responsible for 16% of whiting discarded by all commercial fleets in the North Sea during this period (Catchpole et al., 2006a). Stratoudakis et al (2001) found comparable levels for *Nephrops* trawlers in the Firth of Clyde, where up to 60% by weight of non-target fish were discarded. Whiting was the dominant species and accounted for almost 40% of discards (Stratoudakis et al., 1999). As in the North Sea, English and Welsh beam trawlers in the English Channel, Western Approaches and Celtic and Irish Seas accounted for the majority of UK discards, 58% by number, whilst otter trawlers contributed 35%. Beam trawlers discarded at a rate of 71% of their total catch by number, whilst otter trawlers discarded 65% of their catch (Enever et al., 2007).

1.2.1.1. Factors influencing capture rates of unwanted catch

The likelihood that fishing gear captures unwanted catch will vary dependent upon a number of factors including the condition of the exploited stocks (Cook, 2003), and where (Morizur et al., 2004) and when fishing takes place (Bellman and Heery, 2013). If the stocks of target species being exploited are in a poor condition the capture of unwanted individuals by fishing gear is more likely (Alverson et al., 1994). Cook (2003) describes the change in the levels of bycatch as exploitation progresses; initially more selective gear can be used to target the largest most valuable individuals but as the numbers of these individuals decline a fisher must use a finer mesh to retain more of the smaller but still marketable catch. This reduction in the mesh size will continue as fishers target smaller and smaller marketable individuals. However, the less selective gear will also catch more and more non-target and small unmarketable individuals which will be discarded (Cook, 2003). Alverson et al (1994) argue that it was this absence of larger individuals that triggered fishers of the Northwest Atlantic groundfish fishery to exploit strong year classes of haddock or yellowtail flounder (*Pleuronectes ferruginea*) when they first entered a fishery, despite the likelihood of high discard rates of small unmarketable fish. In such a situation, a stronger year class will result in more discards of small unmarketable individuals (Alverson et al., 1994, Borges et al., 2005). Icelandic fisheries biologists state that the variation in the recruitment of exploited stocks was responsible for the annual changes in discarding levels and compositions in national fleets (Sanchirico et al., 2006).

The geographic location of fishing activities has been shown to influence the level, species and size composition of discards (Borges et al., 2005, Stratoudakis et al., 1998), even if the same gear is used (Morizur et al., 2004). The level and species diversity of discards was significantly higher in *Nephrops* trawlers operating in the north of the Clyde Sea compared to the south (Bergmann et al., 2002). Lewison et al (2009) found that spatial patterns of bycatch per unit of fishing effort did not vary randomly within the US Pacific and Atlantic longline fisheries, indicating that some locations were hotspots for both high levels of bycatch and high bycatch diversity (Lewison et al., 2009). Similarly, Enever et al (2007) identified “hotspots” in the Irish Sea and English Channel, where discard rates were higher than average.

The timing of fishing can also influence the levels of unwanted fish captured by fishing gear (Bellman and Heery, 2013). The level of discards exceeded landings during spring but not at other times of the year in a study of two trawlers targeting deep sea decapods off the Balearic Islands (Moranta et al., 2000). Moreover, the species discarded in two Portuguese trammel net fisheries were shown to vary throughout the year with particular species associated with particular seasons (Batista et al., 2009). Discarding by English and Welsh beam trawlers was highest during winter months, whilst otter trawlers discarded more in summer months (Enever et al., 2007).

Other factors such as weather conditions, tidal state and depth of fishing can influence discarding. Catchpole et al (2005a) found discarding of *Nephrops* was higher on sunny days in the Farns Deep *Nephrops* fishery, with more than a 50% increase compared to cloudy days. During periods of thicker cloud cover the lower light intensity was associated with an increase in the number of large *Nephrops* individuals being retained (Catchpole et al., 2005a).Tidal range also influenced discarding in the same fishery, with more fish discarded close to spring tides and more *Nephrops* discarded during neap tides (Catchpole et al., 2005a). Depth of fishing may also alter discarding activities (Damalas and Vassilopoulou, 2013); in the Mediterranean 20-70% of the total catch is discarded by trawlers fishing at depths less than 150m compared to 20-40% at depths below 350m (European-Commission, 2002). Discarding levels in the deep sea decapod trawl fishery off the Balearic Islands decreased and the relative contribution of different species varied with depth; fish species dominated all of the discards however the contribution of crustaceans and cephalopods increased at 489m and 616m respectively (Moranta et al., 2000).

1.2.2. A fisher's decision to discard

Whether the unwanted fish are then discarded ultimately results from a fishers decision to keep all or only part of their catch (Bellido et al., 2011). This decision is largely based on two main factors; i) regulations: catch is discarded to comply with fisheries regulations and ii) economics: catch is discarded to maximise income (Alverson et al., 1994, Crean and Symes, 1994).

1.2.2.1. Regulatory Discards

Prohibited species - A fisher may be obliged to return individuals to the sea if they are listed as prohibited species, and are illegal to land (Hall et al., 2000, Grafton et al., 2005). In the Northeast Pacific prohibited species include herring (*Clupea pallasii*), halibut (*Hippoglossus stenolepis*), and salmon (*Oncorhynchus* spp.) and commercial crab species (*Paralithodes scamtschaticus*, *Chionoecetes opilio, Chionoecetes bairdi*) (Alverson et al., 1994). The capture of certain species may also be prohibited during particular seasons or by certain gear types, requiring discarding of the incidental catch (Clucas, 1997).

Illegally sized discards - Current EU regulations require individuals to be discarded if they fall outside the size or age classes that may be legally landed, or if they are not of the appropriate sex (European-Commission, 2002). Minimum Landing Size (MLS) limits are in force for a number of species, individuals that fall below this limit are illegal to land and must be discarded at sea (Casey, 1996). In overexploited stocks the majority of individual fish within a population will be approaching the minimum size due to progressive size selection, forcing fishers to target the smallest legal sizes in order to maintain a profit and increasing the likelihood of capturing and having to discard undersized individuals due to the use of less selective gear (Alverson et al., 1994). Higher levels of discarding occur when the MLS is set too high compared to the size of fish caught by fishing gear; undersized fish are still retained by the gear but are illegal to land and must be discarded, a major management issue in EU fisheries (European-Commission, 2002, Bullough et al., 2007). The required mesh size of 100mm for the Dutch beam trawl fishery primarily targeting sole does not correlate with the MLS of plaice and has resulted in the substantial discarding of undersized fish (Cappell, 2001). The situation is exacerbated where there are multiple target species, each with a different MLS (Cappell, 2001). The whitefish fishery of the North Sea targets multiple species, including cod, haddock and whiting (Cappell, 2001). When targeting whiting, which has the smallest MLS, fishers will also capture undersized cod and haddock, which are illegal to land and must be discarded (Cappell, 2001). At the end of the 1990s, 66% of discards in this fishery were estimated to be commercial species, the majority of which were thought to be undersized (Cappell, 2001). Fishers may also discard catch that is close to but above the MLS to ensure they are in compliance with the regulation (Arkley and Dunlin, 2002).

Quota associated discards - Quotas that restrict the number or weight of fish that may be extracted from stocks have been linked to high discarding rates (Graham et al., 2007, Bergmann et al., 2002). If a fisher does not hold sufficient quota to cover their catch, or the fleet quota has been fulfilled, there may be a requirement to discard any excess catch (Hall et al., 2000). This is particularly common if quotas are set for landings rather than the total catch (Pope, 2002). Over-quota discards are a common problem in mixed fisheries where quotas for different target species are fulfilled at different times; as a fisher continues to fish for species with available quota, the catch of over-quota species must be discarded (Cappell, 2001, Turner, 1997). This situation occurs when quotas are not set in accordance with the relative ability of a fisher to catch that species (Borges et al., 2008).

Catch composition regulations - Fishers may also be forced to discard catch to ensure that their landings match specific catch compositions stipulated for the target species and gear in use (European-Commission, 2002). For example, only 20% of the catch of *Nephrops* trawlers using a minimum codend mesh size of 80mm can be cod (Catchpole et al., 2006a).

The different regulations that are present in different fisheries and regions explains some of the variation that is seen in discarding rates, for example the MLS for hake is 27cm in the Celtic Sea and only 20cm in the Mediterranean, which may contribute to the higher discard rates (proportion of the total catch that is discarded) of this species seen in the Celtic Sea (Uhlmann et al., 2013). Similarly, Bergmann et al (2002) found that more *Nephrops* were discarded by vessels operating in the south of the Clyde Sea than in the north, as more *Nephrops* fell below MLS restrictions in this area (Bergmann et al., 2002).

1.2.2.2. Economic discards

Many authors highlight that it makes economic sense for fishers to discard some of their catch, even when it is not required by regulations (Arnason, 1994, Vestergaard, 1996), at least in the short-term. If the value of a fish is too low to cover landing and processing costs, discarding is the optimal economic course of action (Clucas, 1997, Turner, 1997). Consequently, discarding is likely to increase for lower grade fish, especially if the cost of landing catch is high (Arnason, 1994). This agrees with Morizur's et al (1999) statement that a substantial proportion of discarded catch may be of species or market grades which have little or no economic value. Batista et al (2009) found that 35% of catch in two Portuguese trammel net fisheries was discarded due to a lack of commercial value. The size composition of catches may also influence a fisher's opinion on what is marketable; Rochet and Trenkel (2005) found that the capture of larger fish increased the length at which other individuals would be retained. As market values for a catch fluctuate so will discarding levels; discards of roundfish and flatfish, or rockfish, in Alaskan and British Columbian fisheries respectively increased by more than 10% when prices were low (Melnychuk et al., 2013). High prices or high catch rates were associated with increased retention of catch in Portuguese trammel net fisheries (Batista et al., 2009). Similarly, Catchpole et al (2005a) found that whiting were more likely to be discarded in the Farns Deep *Nephrops* fishery if catches or market prices were considered to be too low. Whether a species has a market value will also be determined by where it is landed; Dutch and Danish fishers discarded much higher levels of North Sea whiting compared to French fishers due to a lower local popularity of the species (Crean and Symes, 1994).

High grading - Individual fish of more commercial species may still be discarded in a process known as high grading. A fisher can try to maximise the economic value of his landings through discarding lower value fish and replacing them with higher value individuals of the same or different species (Hall et al., 2000, Piet et al., 2009). Crean and Symes (1994) observed that even valuable bycatch was not retained in the peanid shrimp fishery as the cost of handling and storing it was outweighed by relative ease and low cost of catching more shrimp. Karagiannakos (1996) argues that in fisheries managed under quota systems high-grading is encouraged as fishers try to maximise the value of a quota. Fishers may retain only the higher grade individuals that will achieve the best prices at auction in order to maximise the economic value of the quota, particularly if the quota is small (Cappell, 2001, Borges et al., 2008). In addition, if a market has been flooded with a glut of a particular species the value of catch may be depressed, particularly for lower grades, encouraging fishers to high grade when more valuable individuals are readily available (Cappell, 2001). A limit on hold capacity or refrigeration may also encourage high grading; a fisher may choose to discard lower value species to free space or resources for more valuable individuals, maximising the economic yield of his catch (Anderson, 1994, Gillis et al., 1995). Where it is prohibitively expensive to increase hold capacity, high grading is more likely to occur (Anderson, 1994). Similarly, fishers may choose to discard small catches at the beginning of a trip. Once catch is on board fishers only have a limited time left to continue fishing before catch starts to deteriorate; by discarding small catches early on in a trip fishers can spend longer searching for more valuable larger catches (Gezelius, 2006). Those species that may damage other catch due to their morphology (spines, mucus etc.) may also be discarded in favour of more valuable catch, or in protecting the value of the other catch (Hall et al., 2000, Alverson et al., 1994). Whether high-grading occurs will depend on the cost and effort required to replace discarded catch; Anderson (1994) and Turner (1997) argue that high grading is more likely to occur when catch per unit of effort (CPUE) is high relative to the cost of fishing. Where CPUE has fallen, each individual fish caught becomes more valuable in relation to the cost of catching it, with a higher cost of fishing and a lower chance of replacing discarded fish the incentive to high grade is reduced (Anderson, 1994). So, whether high grading is economically favourable will vary with each trip and throughout the year (Anderson, 1994, Turner, 1997).

Catch Quality - Individuals, including those with high commercial value, may be discarded due to their quality (Hall et al., 2000, Catchpole et al., 2005b). Pierce et al (2002) found that damaged individuals of valuable matje herring were discarded due to a strong consumer demand for high quality products. Fish damaged by scavengers or during the capture process are also commonly discarded (Bjordal, 2002, European Commission, 2002). Rochet and Trenkel (2005) argue that discarding increases nonlinearly with the duration of fishing. Over the period of a trawl fish are more likely to be damaged by the weight of fish in the codend, simultaneously the mesh is more likely to become clogged as trawling continues preventing the escape of undersized fish and increasing crowding in the codend. 90% of the marketable fish discarded in two Portuguese trammel net fisheries (Batista et al., 2009) and more than 50% of discarded elasmobranchs in the Portuguese trammel net fishery were discarded due to damage (Baeta et al., 2010). Diseased catch may also be discarded, as occurs in the fisheries targeting southern blue whiting (*Micromesistius australis*) where individuals may be infected with parasites (Clucas, 1997). Catch that has deteriorated to a point where it will be of little or no value will also be discarded; for example if stormy conditions prevent the retrieval of gear, catch can deteriorate, as described in the Portuguese trammel net fisheries (Batista et al., 2009, Baeta et al., 2010). This may be a particular problem in the tropics due to elevated water temperatures (Clucas, 1997). Trip length is a related influence, with fishers choosing to discard some species early on in the trip to ensure that all catch is fresh when landed (Bellman and Heery, 2013).

Other factors - The choice to discard part of the catch may also be social in nature. A study into the UK whitefish trawl fishery found that skippers may encourage discarding to reduce the workload of the crew on a successful trip, or if the trip is near its end (Cappell, 2001). Bad weather may also encourage discarding (Cappell, 2001).

1.2.3. Major causes in EU fisheries and in the UK

Under the CFP the exploitation of many commercial stocks by European fisheries is managed by quotas in the form of Total Allowable Catches (TACs); these define the amount of catch that can be *landed* rather than how much can be *caught* (Daw and Gray, 2005). Numerous technical measures support these TACs and help conserve other non-quota species (Daw and Gray, 2005). These measures include MLSs, catch composition regulations, temporal and spatial closures, and gear regulations. Capacity and effort regulations have also been implemented to try to restrict fishing to more sustainable levels (Daw and Gray, 2005).

Under the CFP it is illegal to retain any catch that does not comply with catch compositions or MLS regulations. Instead this catch can be legally discarded (European-Commission, 2002). Over-quota catch can also be discarded, the alternative is to stop fishing and incur the associated economic losses (Bellido et al., 2011). Consequently regulatory discards are a common feature of EU fisheries (European Commission, 2002). MLS restrictions are responsible for all discards of hake (*Merluccius merluccius*) from EU vessels in the North East Atlantic (STECF, 2006). MLS regulations are also a major cause of cod discards. In 1997, 73% by weight of cod discarded by UK whitefish trawlers in the North Sea were under the MLS (Cappell, 2001). However, economic reasons may be a more important driver of discards in other species. Megrim (*Lepidorhombus whiffiagonis*) caught in in the North East Atlantic are discarded at sizes well above the designated MLS; the STECF suggests this may be due to a miscorrelation between legal size regulations and the size at which fish acquire a market value (STECF, 2006). Similarly, MLS restrictions appear to have no influence on the discarding of whiting and saithe (*Pollachius virens*) in the North Atlantic, and horse mackerel (*Trachurus trachurus*), haddock and whiting in the North East Atlantic, with the majority of discards being larger than the MLS (STECF, 2006). Catchpole et al (2013) estimated that between 2002-2010 17% of discards in English fleets sampled in the COP were <MLS, 37% were non-marketable (non-commercial species or not of a marketable size), 24% were due to inconsistencies in markets or catch sorting and 22% due to quota restrictions. The main drivers of discarding were also found to vary with location. Discards in the North Sea were driven mainly by regulations; MLS and quota restrictions. Discarding in the Irish Sea was mostly driven by a mismatch between gear selectivity and MLS or minimum marketable sizes. In the Western Channel and Celtic Sea, a fulltime or occasional lack of market and inconsistencies in catch sorting were the main drivers of discarding (Catchpole et al., 2013).

1.3. Why does discarding matter?

Despite the general opinion of the public, fishers and scientists, that discarding is “bad” (Bellido et al., 2011), for relatively resilient species such as crustaceans it may be best practice and contribute to the sustainability of fisheries (Kelleher, 2005). Discarding becomes a social, ecological and economic problem when the survival of individuals is low (Johnsen and Eliasen, 2011, Mesnil, 1996, Morizur et al., 2004, Clucas, 1997). The survival rates of discarded fish may be very low due to the cumulative stress of being caught, exposed, handled and thrown back into the sea (Broadhurst et al., 2006). Discarding of dead or dying catch results in fishing mortality with no economic benefit, the catch cannot be sold or eaten, and cannot contribute to the fishery in future years (Bellido et al., 2011).

1.3.1. Economic impact

The economic cost of discarding is hard to assess on a global level due to a lack of accurate discard data, however Alverson et al (1994) suggest that the foregone value of discards may match that of landings, equating to potentially billions of dollars lost. An instant economic loss occurs if discarded individuals are of commercial species, as the value of that catch is foregone (Alverson et al., 1994, Alverson and Hughes, 1996, Campos and Fonseca, 2004). The economic value of discarded cod, haddock and whiting in 1999 was estimated conservatively through a skipper survey of the North Sea whitefish trawl fishery at around £6.3 million, £14.9 million, and £2.7 million respectively, assuming 100% mortality of discarded individuals (Cappell, 2001). Scotland’s marine authority, Marine Scotland, estimated much higher values of the discards for 1999, £10.5 million of cod, £29.6 million of haddock, and £5.2 million of whiting (Cappell, 2001). Whiting discards from the English *Nephrops* fishery in 2001-2002 had an estimated value of £1.6

million (Catchpole et al., 2006a). The value of cod discards equated to 11% of the value of cod landings whilst haddock discards would have had a value equal to 37% of the landed catch for this species (Catchpole et al., 2006a). If the target of one fleet is an incidental catch of another and is subsequently discarded, catches of the targeted fishery may be reduced, potentially endangering its economic status (Alverson and Hughes, 1996, Fonseca et al., 2005).

A future economic loss results from the capture and discarding of small and juvenile fish of commercial species. These individuals could have grown to a more valuable size and contributed to future catches (Catchpole et al., 2005b). Their reproductive potential has also been lost, dead fish cannot contribute to future stock replenishment (Catchpole et al., 2005b). Najmudeen and Sathuadhas (2008) analysed the economic impact of catching juvenile finfish in the fisheries of the Kerala coast of India, where they are landed for sale opposed to being discarded. They argued that the removal of individuals before they have reached mature sizes could result in a reduction in the future yield of a fishery through a decline in biomass and future recruitment, thereby resulting in an economic loss through foregone catch. Moreover, juvenile fish have a much lower market value than the adults of the same species, if capture or natural mortality had not occurred, the individuals could reach a much larger size and attain higher prices. The annual potential economic loss of market sales through the capture of juveniles was estimated to be roughly US$ 19,445 million, compared to the US$ 836 million actually generated through the capture and sale of these individuals (Najmudeen and Sathiadhas, 2008).

Capture and discarding of non-commercial species may also result in a loss in future income, as new markets may develop for these species (Stockhausen et al., 2012). These economic losses will not only be felt by fishers, but also by the processing and marketing industries further down the supply chain (Gillis et al., 1995). Other economic costs associated with discarding include the cost of enforcement and observer programmes; the reduction of fishing operations and or catch of target species through bycatch quotas; the cost of new gear or gear modifications to reduce bycatch levels; the banning of particular gear types reducing fishing opportunities; the loss of target catch after the subtraction of discarded individuals from target species fishing quotas; and the costs of catching, sorting and discarding individuals (Alverson et al., 1994).

1.3.2. Ecological impact

The ecological impact will vary dependent upon the discarded species, and the levels at which discarding occurs. High discarding levels of a particular species may not necessarily be damaging to a species or ecosystem, for instance large amounts of discarded walleye pollock (*Theragra* *chalcogramma*) in the Bering Sea represent less than 1% of the fished stock (Alverson et al., 1994). In other situations a very low incidental catch can represent a significant fraction of the local population potentially endangering those stocks (Morizur et al., 2004), for example capture of the endangered vaquita (*Phocoena sinus*) in the gillnets of the Gulf of California (D'Agrosa et al., 2000).

Commercial species - For commercial species discarding not only represents a waste of resources but may also threaten the future of stocks, endangering fisheries and the livelihoods of many fishers (Crean and Symes, 1994). One of the major issues associated with discarding commercial species, particularly in EU fisheries, is that it means that catches are in excess of the TACs, which can result in fishing mortality exceeding targets (Rijnsdorp et al., 2006, Morizur et al., 2004, Eliasen et al., 2009). Landings accounted for only 32-56% of the total catch of North Sea cod in 2005-2009, with the remainder contributed by discarding <MLS cod and high grading, as well as a large percentage due to unreported over-quota catches (Kindt-Larsen et al., 2011). On top of this, the capture and discarding of dead fish results in the loss of potential productivity (Crean and Symes, 1994); dead fish cannot grow and reproduce, and make no contribution to stock biomass (Catchpole et al., 2005b, Bellido et al., 2011). Discarding has been linked to the decline of cod off the North East coast of Canada (Kulka, 1997) and the overfishing of European fish stocks (European Commission, 2011b).

Discarding is particularly detrimental for commercial stocks when it is undocumented, affecting the accuracy of fisheries data (Eliasen et al., 2013) and stock forecasts (Alverson and Hughes, 1996). Inaccurate data could result in under or over-optimistic targets being set and under or over exploitation of stocks (Cotter, 2010, Chen et al., 2007, Cook, 2003). This reduces the confidence fishers have in fisheries regulation and can result in higher levels of non-compliance (Bellido et al., 2011, Catchpole et al., 2005b).

Non-commercial stocks - Non-target species may also be overexploited as a result of incidental capture and discarding (Hall et al., 2000). Piet et al's (2009) model suggests that fishing mortality of non-target species may match or even exceed that of target species in the North Sea (Piet et al., 2009). Cook (2003) suggests that this capture and mortality of non-target species, is likely to result in a decline in species diversity and abundance. Such changes in community structure will have an impact on the economic and ecological status of commercial species (Catchpole et al., 2006a). For example, the viability of commercial stocks may be reduced if declining non-target species are consumed as prey (Alverson et al., 1994).

Impacts on the wider ecosystem - The impacts of discarding extend beyond the commercial and non-target fish species (Witherell et al., 2000, Jennings and Kaiser, 1998). Discarding may affect the balance, diversity and functioning of ecosystems (Bellido et al., 2011). For example, discarding can result in a disruption of ecosystem nutrient cycles (Eliasen et al., 2013, Groenewold and Fonds, 2000). It may take many years for the nutrients of discarded biomass that is not consumed to be recycled back to the original ecosystem from which it was removed by fishing (Hall et al., 2000), whilst consumption of discards may alter benthic communities (Alverson et al., 1994). Discards that reach the seabed create an additional food source of a magnitude that is not usually available for facultative scavengers (Furness et al., 2007). Castro et al (2005) found that 60% of discards from the Portuguese deep water crustacean fishery reached the sea floor, with 20% removed within the first hour. Small scavenging species were thought to be the most important in consuming discards and recycling the discarded organic material, and benefitted through an increase in biomass. These species then provided an increased food source themselves for the target species of the fishery and were found in the stomachs of deep-water rose shrimp (*Parapenaeus longirostris*) and *Nephrops* (Castro et al., 2005).

Some seabird species are also able to utilize discards and have experienced population increases through access to previously inaccessible food resources (Garthe and Scherp, 2003, Furness et al., 2007, Gislason, 2003). Garthe and Scherp (2003) estimated that 6500t of discarded fish, mainly cod, were consumed by seabirds each year in the Baltic Sea. However, changes in relative species abundance may also trigger changes in predator-prey relationships and alter intra-specific competition (Gislason, 2003). Feeding on discards has also altered how some species behave; Bartumeus et al (2010) found that seabird movement patterns may be altered by the distribution of discarding fishing vessels (Bartumeus et al., 2010). Some species have also become reliant upon discards as a food source; the instigation of an annual moratorium on trawling in the Ebro delta of the western Mediterranean resulted in the complete prevention of discards, and was linked to a significant reduction in clutch and egg size of a local population of Audouin's gull (*Larus audounii*) (Tasker et al., 2000). In addition it is also possible that consuming discards may increase parasite transmission to seabirds (Groenewold et al., 1996).

The practice of discarding may also indirectly affect megafana. Reports from fishing vessels suggest that cetaceans may come in close proximity with fishing gear, risking entanglement, in order to take advantage of discarded fish (Couperus, 1994). Populations of these and other megafauna may be more at risk from the additional mortality, due to their life history characteristics (Morizur et al., 2004).

1.4. Why is discarding so difficult to manage?

Catchpole et al (2005b) argue that the current high levels of global discards are due, at least in part, to the inability of past regulations to restrict fishing effort to available fishing opportunities, such as TACs. Managing the resulting discards is complicated by considerable variation in discarding levels, the causes of discarding, and the corresponding impacts, within and between fisheries (Kelleher, 2005). This variability is dependent upon the fishing ground, season, regulations, market forces and gear choice, and the behaviour, characteristics and demographics of target and non-target species, (Catchpole et al., 2005b, Kumar and Deepthi, 2006, Tasker et al., 2000, Alverson et al., 1994, Bozzano and Sarda, 2002, Guénette et al., 2001). Discarding activities may even vary during a single trip, dependent on available hold space and day to day variability in markets (Bellido et al., 2011). Moreover, the relative economic and ecological impact of discarding will vary between fleets and fisheries, and may not be reflected by estimated discard rates. Low discard rates do not necessarily mean that only a few fish are discarded. Discards may represent only a small proportion of the total catch, however discards could still represent a large number of fish (Graham et al., 2007, Alverson and Hughes, 1996, Morizur et al., 2004). Conversely fisheries with low landings may have high discard rates despite discarding only a few individuals (Alverson et al., 1994, STECF, 2006). 100% of herring caught in EU demersal trawlers is discarded, however the species is rarely encountered (STECF, 2006). Differences in the mortality rates of discarded individuals in each fishery will also influence the impact of the activity and the appropriateness of management measures (Clucas, 1997, van Beek et al., 1990). Moreover, there has been no comprehensive evaluation of the mortality generated by discards versus the mortality generated by other factors (Alverson and Hughes, 1996). So, each fishing fleet will have a unique scale and composition of discarding, the impact of which will vary dependent upon the species involved (Clucas, 1997, van Beek et al., 1990), potentially requiring fleet specific management measures (Borges et al., 2005). Management of discards is made even more complex as the social, economic and biological aspects of reducing discarding must be accounted for within the wider management regime of commercial fisheries (Kelleher, 2005). In some nations management priorities may be to maximise the profits of fisheries or to provide much needed employment opportunities, aims that may conflict with efforts to control discarding activities (Pope, 2002). In such cases the final discard management measures put in place may be structured to satisfy political rather than conservation objectives (Pope, 2002). On top of this, the management challenge is often exacerbated by a lack of effective enforcement or willingness of fishers to accept and comply with new gear technology or regulations aimed at reducing discards (Catchpole and Gray, 2010).

Beyond the variability of discards, effective management is also hampered by a lack of data on discarding (Cochrane, 2002b). Until recently most data collection was focused on commercial landings (Lescrauwaet et al., 2013, Bellman and Heery, 2013), and data on which species were discarded was often absent (Guénette et al., 2001). Some countries and fisheries have no systematic system for documenting discards; eastern USA data held by the National Marine Fisheries Service database does not include information on discards (Ryan et al., 2001). Similarly, before 2001 observers in the Canadian Atlantic pelagic longline fishery did not collect data on the length composition or the relative condition of discards, preventing accurate assessments of discard levels and discard survival rates (Carruthers et al., 2009). In other cases discard data may only be available for a few species or sectors of a fleet (European-Commission, 2002), resulting in estimates that lack precision (STECF, 2006). However, accurate data on fishing mortality, including estimates of discarding, are required for the assessment of commercial fish stocks; exclusion of these data may affect the accuracy of stock forecasts and the appropriateness of management decisions, as mentioned above (Alverson et al., 1994).

The paucity of discard data may be due to the nature of discards; data collection must occur at sea (Alverson et al., 1994). On board observers are considered to be the most accurate source of discards data (Kelleher, 2005). Campana et al (2006) argue that it is only through observer presence that an estimate of the scale of blue shark bycatch in the Atlantic EEZ of Canada can be made; nominal landings of longline fisheries represent only 5% of the estimated catch for this species in this area. However, the costs of observer programmes may be prohibitive (Kelleher, 2005), the data may not show a high level of precision (Cook, 2003), and observers may be refused access to vessels (Catchpole et al., 2011). In addition, the presence of observers may alter the behaviour of the skipper and crew, biasing discard data (Murawski, 1992). Moreover, where observer coverage is not 100% sampled discard data must be raised to fleet level, requiring the use of raising factors which may introduce an additional source of bias (Rochet and Trenkel, 2005). CPUE or reported landings are often chosen as raising factors, however the relationship between these variables and discarding may not always be linear, particularly where discards events are sporadic, resulting in inaccurate estimates of discarding (Borges et al., 2008, STECF, 2006). Rochet and Trenkel (2005) found no evidence that discards were proportional to fishing effort or catch levels.

An alternative to observer data is the use of fisher's logbooks, however the quality of this data is often poor and incomplete, resulting in inaccurate profiles of discarding (Clucas, 1997). The quality will be dependent upon a number of factors, including the skipper's estimation of how important compiling logbooks are; the degree of literacy within a fishery, and the structure of the management and regulation regime that is in place (Bergh and Davies, 2002). Clucas (1997) notes that the bycatch recorded in mandatory logbooks of Falkland fisheries represented only 24% of that reported by observers during the same time period.

Even if discard information is available, differences in collection methodologies and processing of data from different sources may render it incompatible (Clucas, 1997, STECF, 2006). For example, discard estimates may be based on the number of individuals or weight of discarded catch, influencing the interpretation of data (Catchpole et al., 2011). It is hard to compare the effectiveness of different measures if results are expressed in different ways, i.e., change in numbers of fish opposed to changes in weight (Davies et al., 2009). In the EU different classifications of metiers and fleets leads to difficulty in estimating and comparing discarding estimates (Uhlmann et al., 2013). Even what is defined as discards may vary between different scientists and managing authorities (Alverson et al., 1994, Kelleher, 2005), potentially altering estimates of discarding (FAO, 2010) and resulting in misinterpretation of reports and policy aims (Clucas, 1997). The European Commission defines discards as catch that is returned to the sea after being retained and landed on board vessels (European-Commission, 2002); this definition excludes catch that is purposefully released or "slipped" before gear is hauled onto vessels. However, the FAO definition includes that fraction (FAO, 2010); a definition that was also used by the Workshop on Discarding in Nordic Fisheries (Valdemarsen, 2003). Different management authorities may also have different definitions dependent upon the priorities of that group; the Inter-American Tropical Tuna Commission only includes commercially important tuna fisheries in its definition of discards (Kelleher, 2005). In some instances the term bycatch may also be used interchangeable with the term discards (Clucas, 1997). Such differences may make comparing estimates and reports from multiple sources inappropriate, preventing quantification of the wider scale of discarding (Clucas, 1997).

1.5. What can be done?

As discards have become a major focus for fisheries managers, the development of more effective measures to control the capture of unwanted individuals has become an important target for fisheries research (Hall and Mainprize, 2005). An EC Communication of the Community Action Plan to reduce discards of fish argues that the first response of member states in trying to reduce discards is to improve the condition of commercial stocks; overexploitation has altered the size composition of target populations to one that is dominated by the undersized, immature individuals that are most likely to be discarded, whether for economic or regulatory reasons (European-Commission, 2002). Similarly, the 2010 International Guidelines on Bycatch Management and Reduction of Discards encourages management authorities to include objectives for the regulation and utilisation of discards in wider fishery management plans in line with the FAO Code of Conduct for Responsible Fisheries (FAO, 2010). The nature of the discard management measures is dependent upon the aim of the policy setters; to reduce waste of a resource, to address ethical concerns raised by the capture of charismatic species, or to reduce the impact of fishing activities on non-target catch (FAO, 2010). The waste of resources can be addressed through increased utilisation of catch that would normally be discarded whilst ecological impacts may be addressed through preventing capture in the first place or by increasing the survival of the discarded component of the catch (Alverson et al., 1994, FAO, 2010). In reducing the impact of discarding on non-target species survival rates are important, more robust species could benefit from measures designed to improve survival rates, where as those more vulnerable to discarding mortality are more likely to benefit from measures that reduce the initial chance of capture (Carruthers et al., 2009, FAO, 2010).

1.5.1. Reduce unwanted catch

Management measures to reduce discarding include technical measures, input or output controls, and fishery use regulations. Technical measures aim to control the selectivity of gear and the timing and location of fishing activities (Pope, 2002). Conversely, input and output controls aim to limit total fishing mortality. Input controls regulate the intensity of fishing operations, usually through restrictions on fishing effort. Output controls are aimed at controlling how much is actually caught, primarily through quotas (Pope, 2002). Use regulations control the number of vessels or individuals who have a right to access a fishery or use specified gear, for instance a set number of pots (Charles, 2002).

1.5.1.1. Input Control

Input controls include measures aimed at controlling the total amount of fishing that occurs through placing limits on the amount of time that can be spent fishing, the amount of gear that can be used, and the size and number of vessels allowed to fish (Pope, 2002). Fishing time can be controlled through regulating the number of days that vessels can fish, or be out of port, often in the form of days-at-sea quotas (Shepherd, 2003, Pope, 2002). The advantages of days-at-sea quotas are that they can be easily enforced (Cotter, 2010, Branch et al., 2006a, Shepherd, 2003) and should result in a reduction in total catches and so the amount of fish that are discarded (Catchpole et al., 2005b, Alverson et al., 1994, Cappell, 2001). Discards of commercial species may also be reduced as with less time allowed at sea, fishers are less likely to high-grade as there will be fewer opportunities to catch more valuable fish (Catchpole et al., 2008a). In addition, days-at-sea restrictions can be used as an economic incentive for fishers to reduce bycatch; those fishers that employ more selective gear can be rewarded by being granted additional days at sea (Catchpole et al., 2005b). Replacing TACs with a system of days-at-sea quotas would also prevent over-quota discards (Cotter, 2010, Branch et al., 2006a). However, such effort controls are not without disadvantages; discarding due to market forces or size regulations can persist (Eliasen et al., 2009, Shepherd, 2003) and extreme reductions in fishing effort may encourage fishers to operate less selectively in an attempt to fulfil their quota (Cappell, 2001) and or maximise landings (Catchpole et al., 2005b, Johnsen and Eliasen, 2011). Fishers may also spend less time steaming offshore to historic fishing grounds, remaining further inshore in order to maximise the amount of time spent fishing, potentially in areas where bycatch rates may be higher (Catchpole et al., 2008a, Paramor et al., 2005). In addition, the positive impacts of such effort controls can be counteracted by the continual development of more efficient fishing gear and refinement of a fisher’s skills, requiring continual modifications of effort regulations (Pope, 2002, Shepherd, 2003). The potential impact of days-at-sea quotas in incentivising more selective fishing practices is investigated further in Chapter 3.

The number of vessels engaged in a fishery can be reduced through introduction of a limited number of fishing licenses, or through government decommissioning schemes (Pope, 2002). In 2003 US$46 million was spent in decommissioning part of the US West Coast groundfish fishery, reducing the number of vessels from 263 to 171 in an effort to reduce the fishing mortality of overexploited rockfish (Branch et al., 2006b). Such reductions in the number of vessels in a fishery may reduce the “race for fish,” allowing fishing to occur at a lower rate and freeing time for fishers to operate more selectively (Alverson et al., 1994). However, the success of these schemes is limited as fishers who remain in the fleet are likely to be the most successful and more able to invest in increasing the catching efficiency of vessels, resulting in a smaller decrease in fishing mortality than would be expected (Pope, 2002). The level of fishing can also be regulated through controlling the type and amount of gear that is carried by individual vessels (Pope, 2002). Gear controls may be particularly important in preventing fishers deploying additional gear or more efficient gear when restricted by days-at-sea regulations (Pope, 2002, Shepherd, 2003), but can reduce the economic efficiency of the fishery (Ulrich et al., 2002).

1.5.1.2. Output controls

Output controls can include restrictions on the weight or the number of individuals that can be caught, usually in the form of TACs (Pope, 2002). However, the regulation of fisheries through output measures alone is likely to result in high discard rates (Graham et al., 2007). Over-quota fish is often illegal to land, requiring that portion of the catch to be discarded at sea (Hall et al., 2000). However, how quotas are released or allocated to fishers may reduce the level of discards. For example, only a small amount of quota could be made available during spawning seasons, reducing the level of effort applied during this period and consequently discards of undersized or poor quality fish (Cappell, 2001). Quotas could also be set for particular grades of fish to reduce the incentive to high grade (Cappell, 2001). Alternatively, a share of a TAC could be allocated to each vessel in a fishery in the form of Individual Quotas (IQs) (Casey et al., 1995). Such quota programs are widespread and can be found in, amongst other places, Iceland, Canada, the USA and New Zealand who set up the first system in 1986 (Casey et al., 1995, Buck, 1995). With an IQ the incentive to "race for fish" reduces as catches are assured (Casey et al., 1995, Branch et al., 2006b). Fishers have more time to choose areas with low bycatch rates, to deploy more selective gears (Alverson et al., 1994, Branch et al., 2006b, Buck, 1995, Sigler and Lunsford, 2001), or to operate in seasons when the quality or market value of fish is higher (Gauvin et al., 1994, Casey et al., 1995), potentially influencing the proportion of catch that is landed (Batista et al., 2009). The use of IQs since 1993 in the British Columbian halibut fishery resulted in a shift from intense short seasons to a slower pace fishery and a survey of skippers suggested that IQs had resulted in a reduction in discarding of catch (Casey et al., 1995). In some systems any over or under use of quotas within defined limits may be "rolled over" to the following fishing season, reducing the likelihood of over-quota discards; the amount that is allowed to be rolled over can be controlled in line with conservation needs of the regulated species (Sanchirico et al., 2006). Alternatively fishers may be allowed to surrender over-quota catch to management authorities rather than be forced to discard, reducing the unaccountable mortality of discarded catch (Sanchirico et al., 2006). In the Nova Scotia mobile gear groundfish fishery fulfilment of the fleet quota, which is divided into IQs, results in area closures reducing the likelihood of discarding of over-quota fish (Sanchirico et al., 2006). Since the implementation of an IQ system in the Alaskan sablefish (*Anoplopoma fimbria*) fishery, discard rates have fallen from 24% to under 10% (Buck, 1995). Even if discarding persists, Buck (1995) argues that the slower pace of fishing, allowing improved handling practices, is likely to result in higher discard survival rates reducing the ecological impact of the process.

The effectiveness of IQs in reducing discards is increased when transfer of quotas between vessels is allowed, becoming Individual Transferable Quotas (ITQs) (Branch et al., 2006b, Eliasen et al., 2009). Fishers can buy, sell or lease extra quota allowing skippers to match the composition of their catch (Branch et al., 2006b, Sanchirico et al., 2006). The leasing or transfer or quotas may be controlled to ensure that the distribution of effort remains appropriate for the fishing grounds (Sanchirico et al., 2006). Under this system the cost of additional quota or the alternative of discarding over-quota marketable fish represent an economic loss for fishers, and may encourage the use or development of more selective fishing practices (Branch et al., 2006b). Fisheries models also suggest that ITQs will incentivise rational fishers to shift targeting to species with less constraining quotas (Poos et al., 2010, Toft et al., 2011).

However, Charles (2002) and Buck (1995) argue that IQs and ITQs based on landings rather than total catch may increase the incentive to discard. Fishers may try to maximise the value or their quota and recoup the price of any additional quota through high grading (Cappell, 2001). Moreover, fishers may choose to discard over-quota fish if the price of additional quotas is too high in comparison to the value of the catch (Eythórsson, 1996, Branch et al., 2006b). Sanchirico et al (2006) also suggest that high levels of quota transfer, rollover or leasing complicate estimating total fishing mortality, resulting in less precise stock assessments. However, Buck (1995) argues that the development of an observer programme and the inclusion of total catch rather than just landings in the quota would help eliminate high-grading in ITQ systems, alternatively quotas could be set to account for the additional mortality that results from discarding. When unwanted catch is accounted for there is an economic cost to discarding; a proportion of the quota will be fulfilled by individuals that have no market value (Catchpole et al., 2008a). Fishers will have to operate in a more selective manner in order to maximise the profit from quotas (Catchpole et al., 2008a). Accounting for discard mortality against quotas has reduced the incentive to discard cod in Canada's Northern cod and shrimp fisheries (Kulka, 1997). Similarly, counting the estimated discard mortality of marketable fish against ITQs has removed the incentive to discard catch and encouraged the adoption of more selective fishing practices in the British Columbian groundfish fishery (Grafton et al., 2005, Branch et al., 2006b, Sanchirico et al., 2006). Grafton et al (2005) argue that near complete observer coverage has been essential in generating these changes.

1.5.1.3. Use Rights

Fishery use rights place restrictions on which fishers have the right to operate in or "use" the fishery (Charles, 2002). The allocation of use rights imparts a sense of ownership of the resource onto fishers, which may in theory encourage more sustainable use of the fishery to protect future income (Eythórsson, 1996). Use rights can be divided into two categories, access rights or harvest rights (Charles, 2002). Access rights control which individual or vessels are allowed to operate in a fishery, and the locations where these vessels may operate, effectively regulating fishing effort (Charles, 2002). Access rights can be effective in controlling discarding activities through economic incentives or disincentives; those fishers who employ more selective fishing gear or practices may be granted access to restricted fishing grounds, promoting conservative practices (Catchpole et al., 2008a). Use of Square Mesh Panels (SMP), a gear modification designed to increase escape of incidental catch from trawls, is used as a prerequisite for granting access to a restricted area in the French *Nephrops* trawl fishery operating in the Bay of Biscay (Catchpole and Gray, 2010). Hall et al (2000) promote this form of discard management suggesting that those fishers operating in a more selective manner could be rewarded through access to more profitable fishing areas or species, or be granted the rights to fish for longer periods. Harvest rights regulate which fishers have the right to harvest a resource and how much of that resource they have a right to extract and include IQs and ITQs (Charles, 2002). Harvest rights could be granted based on the discarding activities of vessels (Buck, 1995). For example, the FAO Guidelines for Reducing the Incidental Catch of Seabirds in Longline Fisheries (1999) encourages the use of mandatory seabird bycatch mitigation devices as a condition for licensing (FAO, 1999). Moreover, Hall et al (2000) argue that when bycatch is controllable through the skill of fishers, discarding could be reduced through a requirement that a set of performance standards are met by all skippers and crews wanting access to a fishery. Compliance with this code of conduct could be encouraged through ensuring that products originating from low discarding fisheries receive a premium market price (Hall, 2000).

1.5.1.4. Technical measures

Technical measures may include input and output controls, but are usually subdivided into restrictions on gear type, gear modifications, or temporal and spatial controls on fishing activities (Cochrane, 2002a). A number of technical measures are aimed at improving the selectivity of fishing gear and consequently levels of incidental catch and discarding. The selectivity of fishing gear is not only related to its characteristics (i.e. mesh size), but also the way in which a fisher may use that gear (Bjordal, 2002). Selectivity may be improved through altering the properties of the gear, such as the addition of selectivity devices (Bjordal, 2002), or through avoiding periods or areas where incidental capture of non-target species is more likely (Hall, 2002). Particularly efficient unselective gear could be banned to reduce bycatch levels, alternatively the gear could be modified to improve its ecological performance (Alverson et al., 1994).

Gear-based technical modifications - Gear-based technical measures can involve modifications to the gear itself or alterations to the configuration of the gear. These measures are often favoured more by the fishing industry as they do not reduce fishing opportunities (Catchpole et al., 2005b). More selective fishing results in catches that require less effort to sort and may be of higher quality due to a reduction in damage caused by the interaction of target and non-target catch (Catchpole et al., 2005b). Gear modifications also tend to be more visible, and therefore more easily enforced (Catchpole et al., 2005b), but efforts must be made to ensure that fishers do not disable selectivity modifications at sea to increase the likelihood of catching the maximum amount of marketable fish (Alverson et al., 1994). Gear modifications may be the most appropriate management measure where levels of discarding are unpredictable and not related to season or fishing areas (Graham et al., 2007). Modifications can be made to a wide range of fishing gears. For example, in pot fisheries adding size restrictive escape gaps allows the release of undersized target species, or small non-target species before the gear is hauled (Bjordal, 2002). In longline fisheries the type and size of hooks may be restricted to improve selectivity (Kelleher, 2005). However, the vast majority of the literature on improving the selectivity of fishing gear to reduce discards has focused on modifications to trawls.

Larger mesh sizes - The most traditional technical measure for reducing the capture of undersized fish in trawl fisheries is the regulation of the mesh size of codends (Catchpole et al., 2005b, Alverson et al., 1994). Increases in the mesh size of English *Nephrops* beam trawlers to above 90mm has resulted in a significant reduction in discarding rates since 1999 from 83% to 60% by number (Enever et al., 2009b). Similarly, increasing the size of mesh from the commercial standard of 80mm to 100mm in the Bristol Channel skate (Rajidae) fishery resulted in a decline in discards of 72% with only a 3% fall in the value of landings (Enever et al., 2010). Kronbak et al (2009) analysed the long term theoretical biological and economic implications for *Nephrops*, cod, plaice and sole of increasing mesh sizes in the Danish *Nephrops* trawl fishery; the use of 100mm and 120mm mesh sizes over the standard 90mm resulted in an increase in the stock biomass of all four species, and resulted in a rise in the overall cash flow of the fleet (Kronbak et al., 2009). Increase in mesh size in other parts of a trawl can also improve selectivity; increasing the mesh size in the upper panel of a *Nephrops* trawls can reduce retention of undersized haddock and whiting, and potentially increase the retention of marketable individuals (Ingólfsson, 2011). Use of the “Orkney trawl” which is characterised by very large mesh in the upper sections of the trawl has shown promise in reducing catches of smaller cod whilst maintaining and even increasing catches of haddock in roundfish fisheries (Campbell et al., 2010, Kynoch et al., 2010). Similarly, the large mesh "Eliminator trawl" has had positive results in trials, cod catches were reduced by 89% compared to a standard trawl whilst maintaining catches of haddock and whiting (Holst and Revill, 2009, Revill and Doran, 2008).

Escape panels - The capture of unwanted individuals can be reduced through the inclusion of panels made from larger mesh sizes (Bjordal, 2002, van Marlen et al., 2005, Madsen et al., 1999, Madsen and Stæhr, 2005). van Marlen et al (2005) found that such escape panels behind the ground rope of beam trawls resulted in a 13% reduction in the bycatch of benthic species. A number of trawl fisheries have introduced a square mesh panel (SMP), into the diamond mesh of codends (Catchpole and Gray, 2010, Catchpole et al., 2006a). Under load diamond mesh becomes distorted, reducing the intended mesh size and therefore the size selectivity of the gear (Bjordal, 2002). Square mesh does not become distorted allowing undersized catch to pass through (Cook, 2003, Graham et al., 2003). The use of a 100mm SMP was found to be the most effective gear modification at reducing hake discards in the French Bay of Biscay *Nephrops* fishery (Catchpole and Gray, 2010). Likewise, the addition of a SMP to mesh sizes of below 120mm in English *Nephrops* otter trawlers resulted in a significant reduction in discarding rates from 63% to 45% by number, comparable to the effect of using a mesh size above 120mm (Enever et al., 2009b). Bullough et al (2007) showed that SMPs could reduce catches of <MLS whiting by 34% in a commercial demersal trawl. Reducing catches of cod has also been achieved in flatfish otter trawl fisheries through the combined effect of large square mesh in the top section of the trawl and SMPs in the codend (Madsen et al., 2006). Using knotless netting can further improve the performance of escape panels by increasing the escape area (Arkley and Dunlin, 2002). Twine diameter and colour can also influence efficacy (Revill et al., 2007). However, escape panels can become masked by weed, mud and debris (Broadhurst et al., 1996), and performance is reliant upon correct positioning within a trawl (Krag et al., 2008, Briggs, 2010, Graham et al., 2003).

Square mesh codends - The use of codends constructed solely of square mesh has also been investigated. 100mm square mesh codends in the Bristol Channel skate fishery resulted in a 68% decline in discards and a 1% increase in the value of landings compared to the standard 80mm diamond mesh codend (Enever et al., 2010). The use of a square mesh codend on an Italian vessel in the Mediterranean allowed the escape of undersized illegal hake, whilst maintaining a similar catch level of target individuals (Catchpole and Gray, 2010). Wade et al (2009) showed that the performance of a square mesh codend in a modified beam trawl could be increased by inclusion of two 200mm SMPs, reducing unwanted catches of finfish by 54-63% by number and benthic invertebrates by 39-45%. The weight of landings was reduced, however this was mitigated by an increase in the value per kilogram of the catch when compared to the standard trawl (Wade et al., 2009).

Selection grids - Selection grids can be added to fishing gear to guide unwanted fish out of the codend of trawls, through excluding particular size ranges or exploiting the behavioural characteristics of different species (Cook, 2003, Campos and Fonseca, 2004, Fonseca et al., 2005, Valentinsson and Ulmestrand, 2008). Alternatively, different species can be diverted by selection grids into separate trawl codends (Ferro et al., 2007) with different mesh sizes, allowing undersized catch of different target species to escape from the trawl (Cook, 2003, Graham and Fryer, 2006). Reductions in unwanted catch have been seen in Canadian, Norwegian and Australian shrimp fisheries as a result of selection grids (Clucas, 1997). Swedish grids, a type of selection grid, are designed to prevent large finfish from entering the codend of trawls targeting *Nephrops*, instead individuals are guided to an escape hole in the upper section of the trawl (Catchpole et al., 2006b). Retention of small fish and undersized *Nephrops* is then reduced through the application of a square mesh codend (Catchpole et al., 2006b). Similarly, the Nordmøre grate, designed to reduce the capture of roundfish, has been compulsory in shrimp fisheries and demersal trawls operating in the Barents Sea since 1997 (Graham et al., 2007). It has also been compulsory in all Swedish vessels targeting *Nephrops* in Swedish waters since 2004 (Catchpole and Gray, 2010). Selection grids are also mandatory in many Canadian, Icelandic and North American shrimp fisheries (Clucas, 1997). New shrimp fisheries have been developed in Canadian waters with the use of the Nordmøre grate allowing fishers to exploit areas that were formerly avoided due to the high proportion of non-target species in the catch (Clucas, 1997). However, selection grids do have disadvantages; Kronbak et al (2009) analysed the long term theoretical biological and economic implications of implementing various technical measures in the Danish trawl fishery targeting *Nephrops* in the Kattegat and Skagerrak; these fishers also retain adult sole, cod and plaice but discard juveniles. The implementation of a selection grid in a trawl with a 90mm codend was predicted to result in an increase in cod, plaice and sole stock biomass over a ten year period (Kronbak et al., 2009). However, this technical measure resulted in a decline in the potential net cash flow of the fleet over the following ten years due to a loss of marketable catch (Kronbak et al., 2009). Catchpole et al (2006b) also found that the use of a Swedish grid and a standard diamond mesh codend in a *Nephrops* trawl, resulted in a dramatic reduction in retention of finfish above MLS, but also resulted in an increase in the retention of small cod; a result that has also been seen in other *Nephrops* fisheries (Frandsen et al., 2009, Drewery et al., 2010).

Reducing the capture of unwanted fish is not the whole picture; the success of more selective fishing gears relies on the survival of individuals passing through and escaping from a codend being greater than if the fish were just discarded (Ryer, 2002, van Beek et al., 1990). Individuals that are escaping fishing gear may become stressed or sustain injury through contact with the gear or other fish, influencing long-term survival rates (Ryer, 2002, van Beek et al., 1990). Undersized sole escaping from large mesh sizes in beam and otter trawls showed lower survival rates than expected; only 60% of individuals who escaped immediately survived the interaction with the fishing gear (van Beek et al., 1990). The behaviour of juvenile walleye pollock and sablefish was impaired after simulated escape from a trawl codend, particularly when the individuals had experienced crowding before escape; individuals suffered predation linked to a reduction in schooling ability and apparent awareness of predators (Ryer et al., 2004, Ryer, 2002). Such behavioural impairments or injuries may reduce the success of gear modifications, particularly where predators are readily available to take advantage of vulnerable individuals (Ryer, 2002). As a result the success of technical measures in reducing the impact of fishing operations on non-target catch may not be as high as expected (van Beek et al., 1990).

Non-gear-based modifications - The selectivity of fishing gear can also be improved through alterations to fishing practices. In pot fisheries the use of different bait, or bait in varying states of deterioration can be used to attract particular species, improving selectivity (Bjordal, 2002). Changes in the deployment or retrieval of gears may also be sufficient to increase its selectivity without further modifications (Hall et al., 2000). The Kerala Marine Fishing Regulation Act which controls fisheries within the Kerala state of India, prohibits trawling at night in order to reduce the higher levels of bycatch associated with this operation period (Kumar and Deepthi 2006). Likewise, the duration of soak times of static gear are regulated in both the Mediterranean and Baltic European fisheries in an effort to reduce discarding as a result of deteriorated or predator-damaged catch (European-Commission, 2002). Alternatively the capture of unwanted catch can be reduced through technical measures that control or alter fishing activities.

Spatial and Temporal Closures - Temporal and spatial closures can be used to control fishing operations, and can vary in severity from the prohibition of all fishing activities within an area or time period, to the restricted access of particular vessels or gear types (Hall, 2002). Closures can be used to exclude fishing operations from areas or during periods where bycatch levels may be high (Pope, 2002, Grech et al., 2008, Murawski, 1996, Melvin et al., 1999). For example, real-time area closures have been used in Australian fisheries to limit bycatch of southern bluefin tuna (*Thunnus maccoyii*) by vessels lacking quota (Hobday and Hartmann, 2006). In Alaska levels of bycatch above a defined limit will trigger fishery or area closures (Graham et al., 2007, Kelleher, 2005, Clucas, 1997). Areas or periods when there are a higher proportion of juvenile, or undersized individuals that would be discarded may also be protected through a closed area or season (Hall, 2002). Seasonal closures have seen success in the shrimp fisheries of the Gulf of Mexico; closure of the fishery during May to July allows juvenile shrimp to mature in inshore waters before they migrate offshore into areas where they may be caught, preventing the capture and subsequent discarding of undersized individuals (Hall, 2002). Similarly, real-time area closures are enforced in Norway if levels of small fish exceed a threshold, and are maintained until levels decline (Graham et al., 2007). Closures can also be employed to protect breeding (Grech et al., 2008) or spawning grounds when adult fish may be particularly vulnerable to the mortality caused by discarding or are of poor quality (Catchpole et al., 2005b, Hilborn, 2007b). Spawning requires energy, as a result plaice are often of reduced weight and therefore less valuable which could encourage high-grading (Catchpole et al., 2008a). Similarly, temporal closures of a fishery may be used to reduce discarding or high grading by ensuring that fishing only takes place when the target of the fishery is more likely to be of good quality and marketable size, and is in demand and commanding a good market price (Hall, 2002, Kelleher, 2005). For example, the opening of the Bering Sea pollock fishery is timed to coincide with the highest market prices (Hall, 2002). Moreover, openings could be planned to coincided with peaks in the abundance of target species reducing the fishing period required to fulfil a quota and consequently the period in which non-target species may be taken as bycatch (Melvin et al., 1999). Spatial and temporal closures may be particularly important in regulating gears that are already fairly selective such as purse seines and pelagic trawls in which discarding is sporadic (European-Commission, 2002). However, the use of area or temporal closures must be viewed with caution, these restrictions may result in the shift of fishing effort to other areas or seasons (Bastardie et al., 2010, Branch et al., 2006a, Goodyear, 1999), and result in an increase of bycatch of other species (Baum et al., 2003). Moreover, if area closures aimed at reducing bycatch of non-target species do not cover the vast majority of the species’ distribution, fishing effort may just be shifted to other regions where the species will be equally affected by discarding (Catchpole et al., 2006a). However, large area closures may be difficult and costly to enforce (Hall, 2002).

Bycatch quotas - Bycatch quotas or limits are another technical measure that can be employed to reduce discarding (FAO, 2010); they may act to restrict the total catch of non-target species, or the proportion of total catch that is of non-target species (Pope, 2002). Once a bycatch quota has been reached a fishery may be closed to ensure that no further individuals are taken, and fishing mortality remains sustainable for the species in question (Pope, 2002). Such quotas give non-target species an economic value as catching them creates a cost for the fisher, incentivising their avoidance (Grafton et al., 2005). For example, if the number of crabs in a haul exceeds a defined threshold of 3 individuals per metric ton of fish, vessels of the US North Pacific and Alaska trawl fishery targeting winter rock sole (*Lepidopsetta bilineata*) will voluntarily move to below the 56 degrees North latitude (Gilman et al., 2006). Moreover, if bycatch catch quotas are set for individual vessels an incentive is created for fishers to improve their selectivity, not only reducing the likelihood that fishing will be constrained, but also creating surplus bycatch quota that could be sold or leased, increasing income (Hutton et al., 2010). However, bycatch quotas require observer programs to ensure compliance, due to the need for continuous monitoring (Pope, 2002).

Communication programmes - Communication between vessels in a fleet allows skippers to avoid areas where catches result in high discarding rates, reducing the impact of fishing on non-target individuals over time; and where regulations are in place, the forced closure of fisheries (Gilman et al., 2006). A voluntary communication programme is in place for members of the Blue Water Fishermen's Association in the US North Atlantic longline swordfish (*Xiphias gladius*) fishery, aimed at reducing the capture of sea turtles by indicating areas where bycatch is low (Gilman et al., 2006). A 50% reduction in the incidental capture of turtles has been linked to the success of this communication programme (Gilman et al., 2006). The North Pacific longline fishery has a fleet wide communication programme coordinated by a private contractor, designed to reduce the incidental capture of halibut and seabirds (Gilman et al., 2006). The contractor uses observer data and information from vessel owners to evaluate bycatch levels, those vessels with high bycatch rates are contacted by managers and warned. Vessel owners can contact managers or contractors for advice on how to improve their performance. Reports on bycatch data are produced after the close of the fishing season and maps showing bycatch hotspots are posted to skippers each month of the following season (Gilman et al., 2006). Gilman et al (2006) argue that the influence of this measure amongst others is hard to quantify, however non-participating vessels had bycatch rates which were as much as 30% higher than vessels in the programme. Moreover, fishing effort redistributed away from areas of increased bycatch (Gilman et al., 2006). Overall bycatch rates of halibut have declined by one third since the programme was initiated, and declines in seabird bycatch have also occurred (Gilman et al., 2006). In 1994 the US North Pacific and Alaskan trawl fisheries instigated a contractor coordinated communication programme to reduce the bycatch of several species within each of the fisheries. The contractor uses observer and skipper data to produce daily information on bycatch rates and hotspots, vessel-to-vessel communication also occurs, industry approved responses to this information can then take place to avoid high bycatch levels and fishery closure. Gilman et al (2006) argue that fleet communication programmes in the North Pacific may prove to be very important to the economic turnover of a fishery; communication allows vessels to avoid high bycatch potentially avoiding area closures that may increase steaming costs or trigger the premature closure of the fishery. The above examples highlight the reductions in bycatch and therefore discarding that can be achieved through effective fishery wide communication programmes; however such programmes are less likely to be successful where bycatch is unpredictable and non-target species occur across the range of the fishery (Gilman et al., 2006).

Sustainability certification - Those fisheries that perform well, with low levels of incidental catch, may be rewarded through certification as a sustainable fishery (Hall et al., 2000). The use of ecolabels to identify products originating from fisheries with low bycatch levels may provide an economic advantage for better performing fisheries (Hall et al., 2000) and provide the public an opportunity to influence fishing activities (Lewison et al., 2004, Catchpole et al., 2008a).

Discard education programmes - The FAO encourages member states to develop education programmes for fishers and managers, not only highlighting the importance of reducing bycatch but also in the effective implementation of mitigation measures (FAO, 1999, FAO, 2010). Catchpole et al *(*2006a) found that *Nephrops* fishers out of the English port of North Shields were unaware or did not accept that a reduction in discards would result in conservation benefits, contrary to the opinion of scientists. The authors argue that educating fishers on the positive ramifications of discard reduction could help reconcile the industry and scientists and encourage acceptance of management measures (Catchpole et al., 2006a). Moreover, educating fishers on the scale of discarding within a fishery may itself help to reduce discarding; Gilman et al (2006) state that many fishers in the US Alaskan demersal longline fishery were oblivious to the high rates of seabird bycatch of some individual vessels; once apprised of the situation fishers were able to take measures to reduce incidental rates.

1.5.2. Prohibiting the act of discarding

Another option for reducing discards is to impose a ban on the activity for the total catch or defined species (Alverson et al., 1994). A discard ban on its own will not reduce the fishing mortality imposed on bycatch, but will allow this additional source of mortality to be accounted for, improving the information on which management decisions are based (Diamond and Beukers-

Stewart, 2011, European Commission, 2002). For example, a ban on the discarding of commercial species in Norwegian waters has been in place since 1990 including an ever increasing number of species (Graham et al., 2007, Crean and Symes, 1994). The aim of this ban was to improve the accuracy of total fishing mortality estimates, with managers believing that accountability was favourable to the discarding of species with low discard survival rates (Clucas, 1997). In addition, Kelleher (2005) states that discard bans are widely favoured by the industry as long as the measure is implemented in an equitable manner. However, a discard ban will simply shift waste from at sea to on-shore unless it is incorporated with other measures to encourage a reduction or increased utilisation of the unwanted catch, resulting in only limited ecological and moral benefits (Bellido et al., 2011). However, a supporting discard ban can improve the performance of ITQ programmes in mixed fisheries, preventing high grading (Branch et al., 2006b) and encouraging fishers to fish more selectively or cover their bycatch with sufficient quota (Sanchirico et al., 2006). Similarly discard bans can facilitate the documentation of total catches, including discards, against quotas, encouraging fishers to operate more selectively in order to ensure that the quota is fulfilled by more valuable larger fish (Catchpole et al., 2008a). All marketable bycatch in Canadian groundfish fisheries is counted against quotas (Clucas, 1997). In Icelandic fisheries, where discards are banned, the capture of undersized fish is discouraged as 50% of the weight of commercial species will be counted against quotas (Clucas, 1997). However, high levels of enforcement are required to ensure that discarding does not continue away from the eyes of observers (European-Commission, 2002). In addition, economic incentives may be required to compensate fishers for the cost of landing unwanted catch and encourage compliance (Sanchirico et al., 2006), however the incentive must not be at such a level to encourage fishers to target those species in order to achieve additional income (Clark and Kahn, 2009, Clucas, 1997, Gezelius, 2008, Hutton et al., 2010, Diamond and Beukers-Stewart, 2011). In New Zealand fisheries a tax, called a “deemed value”, is applied for landing over-quota fish or non-vulnerable bycatch species. The tax is set at a level that tries to strike a balance between encouraging the landing of all catch, thereby reducing regulatory and economic discards, and discouraging fishers from pursuing species with insufficient quota (Sanchirico et al., 2006, Batstone and Sharp, 1999, Peacey, 2002). The 2010 International Guidelines on Bycatch Management and Reduction of Discards promotes the use of discard bans, or full retention legislation, but only when bycatch species cannot be released alive with high rates of survival (FAO, 2010). Likewise, only those species with high survival rates or those that cannot be utilized are permitted to be discarded in New Zealand and Canadian groundfish fisheries (Clucas, 1997, Sanchirico et al., 2006).

1.5.3. Increase discard survival rates

If the capture of non-target individuals is unavoidable it is vital that the survival rates of discarded catch are maximised, reducing the impact of discarding on these species and the wider ecosystem (Campana et al., 2009, Carruthers et al., 2009, Mesnil, 1996). Bellido et al (2011) suggest that increasing the survival rates of catch may be as effective as improving the selectivity of fishing.

1.5.3.1. Discard survival rates

The ability to tolerate the capture and release events of discarding varies among species (Cook, 2003). For example, short-term mortality rates of crustaceans discarded in the Clyde Sea *Nephrops* fishery varied between species and individuals from 7-25% for swimming crabs (*Liocarcinus depurator*) to 2-23% in squat lobsters (*Mundis rugosa*) (Bergmann and Moore, 2001b). Moreover, juvenile walleye pollock were found to be much more sensitive to the stress of trawling in comparison to juvenile sablefish, displaying higher levels of mortality and a more impaired ability to feed (Olla et al., 1997).

Short-term and long-term survival rates are also influenced by the degree of damage sustained during the capture and discarding process (Bjordal, 2002). Enever et al *(*2009a) showed the initial condition of skate (Rajidae) after capture was indicative of discard survival rates. Similarly, delayed mortality of hermit crabs (*Pagurus bernhardus*) in the Clyde Sea *Nephrops* fishery was greater in damaged individuals (Bergmann and Moore, 2001b). The level of damage sustained may vary between and within the same species; Bergmann et al (2001) found that the number of damaged individuals of different invertebrate species in the Clyde Sea *Nephrops* fishery ranged widely from 2% for queen scallops (*Aequipecten opercularis*) to 100% of the more vulnerable brittlestars (*Ophiura ophuria*). Damage rates were influenced by sex, with berried female swimming crabs sustaining less damage (Bergmann et al., 2001). Similarly, the condition of discarded skate in the Bristol Channel skate fishery was related to sex, size and species, as well as codend weight (Enever et al., 2010). Larger fish appeared more resilient to trawling, and female skates captured in a square mesh codend were in better condition than males of the same species (Enever et al., 2010). The negative impact of damage may be compounded if wounds become infected resulting in delayed mortality (Bjordal, 2002). Davis (2005) found injured sablefish were more likely to develop skin infections, leading to delayed mortality for up to 35 days after simulated capture in a trawl. Moreover, the damage sustained during discarding may reduce an individual's ability to avoid predators (Bergmann et al., 2001). Moreover, behavioural and reflex impairments as a result of discarding may also make fish more vulnerable to predators, or less able to feed resulting in delayed mortality (Olla et al., 1997, Davis, 2002).

Survival rates are also related to the nature of fishing operations. The level of damage incurred by an individual may vary with gear type; Bergmann et al (2001) found that damage rates in benthic invertebrates caught in the Clyde Sea *Nephrops* fishery were influenced by the type of fishing gear and the size of the catch. Likewise, van Beek et al (1990) found that the condition and survival of discarded plaice was higher in otter trawls compared to beam trawls. In trawl fisheries, survival is also related to duration, speed and depth of a tow (Davis, 2002, Bergmann et al., 2001). *Asterias Rubens* showed short-term mortality rates of up to 18% with more deaths occurring at greater tow depths and durations (Bergmann and Moore, 2001a). van Beek et al (1990) found the condition of plaice deteriorated with longer haul durations reducing the rate of discard survival. Olla et al (1997) showed that juvenile walleye pollock became entangled in the mesh of a simulated trawl when speeds became too high, damaging individuals and impairing their ability to feed and avoid predators, elevating delayed mortality rates to 100% after 2 weeks. The size of the catch was influential on mortality rates of brittlestars captured by *Nephrops* trawl in the Clyde Sea which varied from 8-31% (Bergmann and Moore, 2001a). Likewise, higher codend weights reduced skate condition in the Bristol Channel skate fishery (Enever et al., 2009a). Extended exposure to air whilst fishers sort the catch or redeploy fishing gear also affects survival rates; Davis (2005) found that immediate mortality of sablefish increased with the duration of exposure, an effect that was more extreme in young fish.

Environmental factors will also influence survival rates; the survival of discarded plaice decreased as water temperatures increased (van Beek et al., 1990). Air temperature was also shown to affect the survival of discarded catch (Giomi et al., 2008). Exposure to winter air temperatures of 9-12˚C for 20 minutes resulted in the mortality of less than 2% of harbour crabs (*Liocarcinus depurator*) captured in trawls in the Northern Adriatic Sea, opposed to mortalities rates of 96% after exposure to summer temperatures of 26-28˚C (Giomi et al., 2008). The light level may also influence the survival of individuals; Olla et al (1997) found that sablefish and juvenile walleye pollock failed to swim during a simulated trawl event in the absence of light, independent of the speed applied. Fish became entangled in the net resulting in impaired behaviour, scale loss and lesions; mortality was 100% within 6 days of the experiment. Under daylight conditions and comparable towing speeds, no change in behaviour or mortality was observed (Olla et al., 1997).

1.5.3.2. Improving survival rates

Increased discard survival rates can be achieved through changes in fishing operations. More efficient handling of catches by fishers, including a rapid return of unwanted catch to the sea will improve discard survival rates. Returning unwanted sablefish to the sea in 15 minutes opposed to 30 reduced the rise in core body temperature by 3˚C, which may prove critical to the immediate or delayed discard mortality of an individual (Olla et al., 1998). Sole and plaice discards that are kept wet and sorted rapidly display lower mortality rates (van Beek et al., 1990). Keeping catches shaded as well as wet may also help to reduce the higher discard mortality associated with fishing in warmer months (Davis, 2002). However, improving handling techniques and times will only benefit those species that are resilient to the stress incurred through capture in fishing gear (Olla et al., 1997). This stress associated with capture could be reduced if fishers were restricted to operating in cooler months (Davis, 2002, Giomi et al., 2008). Reducing towing speeds of trawls may also improve discard survival rates through limiting gear inflicted damage; at lower speeds fish are more able to swim in the centre of the trawl away from the mesh where injury is incurred (Broadhurst et al., 2006). Use of more selective gear can also improve survival rates; increasing the size of mesh from the commercial standard of 80mm to 100mm in the Bristol Channel skate fishery resulted in slight improvements in the discard survival rates of skate, 59% compared to 57% survive (Enever et al., 2010). Skate survival was also higher in a square mesh codend, 67% compared to 55% in the standard codend (Enever et al., 2010). Broadhurst et al (2006) argue that the application of acoustic pingers or tori lines deployed to reduce the bycatch of megafauna may also act to increase the survival of discarded fish as they are sheltered from predation immediately around the vessel or fishing gear.

1.5.4. Increase utilisation of unwanted catch

When the aim of management authorities is to prevent waste, discarding can be reduced through increasing the utilization of incidental catch (Clucas, 1997). However, increased utilisation should only be encouraged if the discarded species are being exploited at sustainable levels, and the current level of removals can be supported by the stocks (Bellido et al., 2011, Davies et al., 2009). Nevertheless, increased utilisation could be used as a supporting measure; Clucas (1997) states that it is unlikely that successful discard management measures will result in completely “clean” fisheries, capture of non-target species will still occur albeit at a sustainable level. Faced with this situation, Clucas advocates discard utilisation if individuals cannot be returned to the sea alive. Utilisation of discards relies upon fishers choosing, or being required to land normally discarded catch, a process that may require incentives (Clark and Kahn, 2009, Clucas, 1997). One option is to reduce the landing charges of discarded catch, as is the case for European tuna purse seiners (European-Commission, 2002). Another is to generate or increase access to markets for unwanted catches (Clucas, 1997). For example, development of a market for small tailed *Nephrops* has reduced discarding levels in the English Farns Deeps *Nephrops* fishery (Catchpole et al., 2005a). Declining catches and accompanying price increases of traditional species are encouraging consumers to try formerly discard species (Kelleher, 2005). New markets for dab, flounder (*Platichthys flesus*), Norway pout (*Trisopterus esmarkii*) and grey gurnard have resulted in a fall in discarding rates of these species in the Dutch beam trawl fishery (Catchpole et al., 2008a). In Iceland marketing of underutilsed species is facilitated through a "bycatch bank" which encourages fishers and consumers alike to embrace non-traditional fish species (Clucas, 1997). Similarly, those species which lack a local market could be exported to countries where they are more valued (European-Commission, 2002). Poor quality or damaged fish could be sold as a raw product for fish meal production (Coelho and Stobberup, 2001) or for use in agriculture and aquaculture (Kelleher, 2005). For example, discard utilisation has increased across Southeast Asia as the demand for animal feed rises (Kelleher, 2005) and some unwanted catch from local Spanish fisheries is sold as feed for farmed octopus (European-Commission, 2002). Using unappealing and undesirable catch to create value-added products could create new markets for these species (Kumar and Deepthi 2006); traditional products could be made for local markets and more widely accepted products such as surimi for export (Clucas, 1997, Kelleher, 2005). However, Clucas (1997) highlights the lack of success that has been achieved in piloting such products in the past, citing the lack of markets and sufficient profit to cover production as the main factors for these failures. In addition, discard utilisation programmes must be implemented with caution; it is important that a market for undersized fish or vulnerable bycatch species is not developed such that there is an incentive for fishers to actively target these species (Hall and Mainprize, 2005). In Icelandic fisheries where discards are banned, there is a limit placed on the amount of undersized fish that can be landed discouraging the direct targeting of smaller fish (Clucas, 1997).

1.5.5. What influences success of discard management measures?

Appropriate management measures - It is important that the correct management measures are chosen for individual fisheries. Not all management measures will be appropriate for the protection of all species; closed areas would be ineffective for a highly migratory species unless they were of considerable size (Hall, 2002). In mixed fisheries the implementation of effective technical measures may be complex; measures may be appropriate for one species but not for another (Pope, 2002). Kronbak et al (2009) modelled the impact of a 90mm codend and 120mm mesh panel in the Danish *Nephrops* trawl fishery compared to a standard commercial 90mm codend. The model suggested that this selective gear would result in an increase in the cod stock but a decline in the *Nephrops* stock over the following 10 years due to increased retention and subsequent discards of this species (Kronbak et al., 2009). Deciding on the most suitable combination of management measures is important. Implementation of single management measures in fisheries, particularly those targeting multiple species, is unlikely to be sufficient (European-Commission, 2002). In order to preserve the fisheries whilst reducing discards, limited technical measures in combination with controls on fishing effort may be most appropriate (European-Commission, 2002). Hall (2002) argues that it was the failure to combine technical measures to improve selectivity with any effort controls that resulted in the inability of managers to control the decline of Georges Bank demersal stocks. Similarly, the implementation of new discard regulations must take into account other legislations that are already in force within a fishery, including those of other countries (Raakjær Nielsen and Mathiesen, 2003). Non-compliance in Danish vessels has resulted from the interaction of the Norwegian discard ban, requiring commercial fish to be processed and stored whilst in Norwegian waters, and the Danish requirement that over-quota fish be discarded (Raakjær Nielsen and Mathiesen, 2003). Moreover, appropriate measures must be chosen with the ecosystem in mind, not just one species, or the discard problem may just be shifted between species (Lewison et al., 2009). Banning of some gear types may result in a shift to a different gear type that may have its own bycatch problems, as has been seen with the expansion of longline fisheries after the prohibition of high sea drift nets in 1992 (Hall and Mainprize, 2005). Closures may also result in a shift in the discarding problem; Dietrich et al (2009) found that temporal closures in the Alaskan longline cod fishery led to a 54% reduction in the bycatch of all seabird species overall but led to a 23% increase in the bycatch of albatross species. Baum et al (2003) found that an area closure in Northwest Atlantic aimed at reducing sea turtle bycatch, resulted in an increase in the capture of 11 shark species and 6 species of finfish of conservation concern, due to the displacement of fishing effort to an area of higher biodiversity.

The economic impact on a fishery will also be important in determining if the management measure is the most appropriate. New gears must be affordable and cost effective (Arkley and Dunlin, 2002), those that result in a decline in profits are unlikely to be accepted or may trigger non-compliance or a compensatory increase in fishing effort (Suuronen and Sardà, 2007, Catchpole and Revill, 2008, Hall and Mainprize, 2005, van Marlen et al., 2005). Catchpole et al (2006b) evaluated the theoretical use of Swedish grids and square mesh codends in the English Farns Deep *Nephrops* trawl fishery. The use of the Swedish grid alone resulted in a loss of marketable fish resulting in half the landings by weight of a standard trawl, representing an economic loss of 40% (Catchpole et al., 2006b). The combined use of a square mesh codend and grid resulted in a significant reduction in discards, due to the escape of finfish across all size classes, but also resulted in a 75% reduction in the total value of the landings compared to a standard trawl (Catchpole et al., 2006b). Similarly, van Marlen et al (2005) found that the addition of drop out panels in beam trawlers resulted in a significant reduction in bycatch but at a cost, a loss of 6-26% of valuable flatfish catch. Raakjær Nielsen and Mathiesen (2003) argue that an economic loss is the most likely cause of non-compliance with regulations in Danish fisheries.

Stakeholder collaboration - Many authors (Revill et al., 2007, Melvin et al., 1999, Eliasen et al., 2009, Pinkerton, 2002) emphasise the need for collaboration between the fishing industry and managers in the development of any successful management program, including those tackling discarding. Many fishers believe that controlling politicians who set management measures are ignorant of the nature of fishing, particularly due to their central location removed from the regional nature of fisheries (Raakjær Nielsen and Mathiesen, 2003). Estrangement from policy setters is a common feeling in the English *Nephrops* fishery, with over 75% of skippers expressing this view (Catchpole et al., 2006a), a view reflected by the wider UK fishing industry (Hatcher and Gordon, 2005). By consulting at all stages, including throughout the period of restriction (Catchpole and Gray, 2010), fishers will gain a greater understanding of the detrimental effects of discarding, and the aims and mechanics of the management measures being imposed on a fishery (Catchpole et al., 2008a). This will encourage mutual respect between the fishing industry and managers (Raakjær Nielsen and Mathiesen, 2003). Fishers can gain a sense of ownership over management measures, encouraging compliance, monitoring and enforcement from within the fishery (Raakjær Nielsen and Mathiesen, 2003, Gilman et al., 2006, Pinkerton, 2002). In return managers can gain from the experience and advice of the industry helping to develop practical measures with the greatest chance of success (Pinkerton, 2002, Melvin et al., 1999, FAO, 2010). A number of successful technical measures have originated from the fishing industry, including the “backdown” procedure and the Medina panel designed to aid the escape and reduce the entanglement of dolphins in the Eastern Pacific tuna purse seine fishery (Hall, 1998). Moreover, many authors (Broadhurst et al., 1996, Eliasen et al., 2013, Kennelly and Broadhurst, 2002, Melvin et al., 1999) argue that measures, including gear modifications, introduced with industry collaboration are more likely to be accepted by fishing fleets, particularly if the industry has been involved in the initial collection of discard data (Catchpole and Gray, 2010). The FAO encourages states to implement frameworks to cement the collaborative working of all interested parties over the life of the fishery, and highlights the need for dissemination of successful management measures between fisheries as well as the wider global fisheries community (FAO, 2010).

Compliance with management measures - The level of compliance will impact heavily on the success or failure of any management programme, so how compliance can be encouraged and what the impact of non-compliance is likely to be must be evaluated (Bergh and Davies, 2002). Higher levels of compliance can be encouraged through flexible regulations, allowing generic management measures to be adapted into more practical forms for individual fisheries (Raakjær Nielsen and Mathiesen, 2003). Equity amongst fishers will also influence compliance; compliance is likely to be higher when fishers feel that all sectors targeting a stock are equally affected by regulations (Catchpole et al., 2006a, Raakjær Nielsen and Mathiesen, 2003, Hatcher and Gordon, 2005). Catchpole et al (2005b) suggest that fleet-wide deployment of gear changes ensures equity amongst fishers improving voluntary uptake of modifications and compliance with those that are legislated. The economic impacts of management measures will also affect compliance levels (FAO, 2010, Raakjær Nielsen and Mathiesen, 2003, van Marlen et al., 2005). Low compliance in the face of economic loss as a result of discard reduction measures can be combated through economic incentives or disincentives, either as direct compensation or use rights (Catchpole et al., 2006a, Catchpole and Gray, 2010). Fishers using more selective gear can be rewarded by being granted additional days-at-sea (Catchpole et al., 2005b) or be granted access to more profitable fishing areas (Hall, 2002). In addition the granting of fishing licenses can be used to ensure compliance; the uptake of a minimum of one gear modification is compulsory if a fishing license is to be granted in the French *Nephrops* fishery (Catchpole and Gray, 2010). However, any incentives or disincentives that are implemented must be strong enough to outweigh any potential benefit of non-compliance (Branch et al., 2006a). Raakjær Nielsen and Mathiesen (2003) found that fishers were likely to continue to fish despite having exceeded a quota if there was a low chance that they would be caught. However, non-compliant behaviour is reduced if the cost of detection and prosecution exceeds expected benefits (Beddington et al., 2007). Any infringement of management restrictions must be penalised immediately and in such a way as to make non-compliance costly to the guilty fisher (Bergh and Davies, 2002). This will deter others from similar behaviour, preventing the development of a general positive attitude towards non-compliance in a fishery (Raakjær Nielsen and Mathiesen, 2003). A set number of infringements during a ten year period will result in expulsion from the profitable Western Australia rock lobster fishery, providing a strong incentive for compliance (Bergh and Davies, 2002). Consequently, enforcement is vital in ensuring compliance to new regulations, particularly seasonal or area closures (Bergh and Davies, 2002).

1.6. What has been done in EU and UK fisheries?

A number of technical measures have been implemented under the CFP in an effort to reduce the capture of unwanted fish and control total fishing mortality (Gezelius, 2008). Effort restrictions have been implemented in many EU fisheries with the aim of reducing fishing to levels that are more in line with constraining single-species TACs, and in so doing reduce over-quota discards (van Oostenbrugge et al., 2008). A high grading ban is in place; it is illegal to discard catch of quota species that is of a legal size if sufficient quota is available to allow its landings (Eliasen et al., 2013). Mandatory use of selective gears and incentives to adopt more selective fishing practices have also been introduced (Johnsen and Eliasen, 2011, Madsen and Valentinsson, 2010). For example, the use of sievenets and selection grids has been mandated in the North Sea brown shrimp fishery (*Crangon crangon*) to reduce catches and discards of <MLS plaice that occur in high abundance on the same fishing grounds (Catchpole et al., 2008b). SMPs were introduced in the UK North Sea *Nephrops* fishery in 1991, in response to a call from both managers and the whitefish fishery (Graham et al., 2007). These fishers were concerned about the decline in the status of their target species, haddock, whiting and cod, which were commonly discarded as juveniles in the *Nephrops* fishery (Graham et al., 2007). SMPs were made compulsory in UK *Nephrops* fisheries in 1992 and in all EU fisheries targeting North Sea demersal fish in 2000 (Catchpole et al., 2006a). In 2002 the mesh size of panels was increased and codend circumferences were restricted (Graham et al., 2007). Enever at al. (2009b) suggest that these technical measures are responsible for the reduction in the proportion of the total catch of English North Sea *Nephrops* trawlers contributed by juvenile whiting, from 22% to 3%. The authors also suggest that addition of a SMP to mesh sizes of below 120mm in English otter trawlers resulted in a significant reduction in discarding rates from 63% by number to 45%, similar to the effect of using a mesh size above 120mm (Enever et al., 2009b). Moreover, increases in the mesh size of English beam trawlers to above 90mm since 1999 resulted in a significant reduction in discarding rates from 83% by number to 60% (Enever et al., 2009b). Closed areas, including the “plaice box” in the North Sea have also been introduced (Pastoors et al., 2000). Nevertheless, discarding still remains an issue in EU fisheries (Suuronen and Sardà, 2007) and has been linked to the overfishing of European stocks (European Commission, 2011b). TACs, catch composition and MLS regulations defined in the CFP continue to generate legal discards (Österblom et al., 2011, European Commission, 2002). In addition, some regulations, such as the Cod Recovery Regulation, have created perverse incentives for fishers to adopt less selective gear (Graham et al., 2007). Under this regulation *Nephrops* fishers operating with small mesh escaped reductions in allowable fishing effort, in addition 20% of their catch could be incidentally caught cod. Larger vessels, some

of which were voluntarily using mesh of >100mm, were granted less than half the days at sea of these other vessels and only 5% of their catch could be cod. The intention was to restrict the fishing activities of the larger vessels who contributed the majority of cod fishing mortality. However, fishers were instead incentivised to adopt smaller mesh sizes and avoid the tougher restrictions (Graham et al., 2007).

1.6.1. The reform of the CFP

The majority of fishers see discarding as morally wrong (Paramor et al., 2005); 100% of Danish fishers in the North Sea believe discarding dead fish is unconscionable (Raakjær Nielsen and Mathiesen, 2003). Similarly, for fishers in the English *Nephrops* trawlers having to discard commercial species due to regulations is senseless, as they represent a waste of current or future valuable catch (Eliasen et al., 2013). Fishers are not alone; the public and managers also believe that discarding of dead catch is unacceptable (Bellido et al., 2011). In 2009 the European Commission released a Green Paper proposing a complete reform of the CFP to address the poor management of EU fisheries, including not only discards but also overexploitation of stocks, declining catches, over-capacity fleets, high subsidies, and economically fragile fisheries (European Commission, 2009). The Commission set out its vision for future European fisheries, where exploitation levels are in line with the maximum sustainable yield of stocks, and economically viable fleets are of a size that is proportionate to the resource, using environmentally friendly fishing practices. In addition, the Green Paper stated that the reformed CFP should prevent discards (European Commission, 2009). A view reiterated in the UK's response (United Kingdom Permanent Representation to the European Union, 2009). In March 2011, Maria Damanaki, the European Commissioner for Maritime Affairs and Fisheries, gave a speech in Brussels announcing that in her opinion discards were unethical and a waste of both resources and effort (European Commission, 2011a). She proposed a discard ban supported by a system of effort controls, controlling days-at-sea, or catch quotas accounting for the total catch of vessels (European Commission, 2011a). The objective of eliminating discards and reducing unwanted catches is now at the heart of the 2012 reform of the CFP (European Commission, 2013a). A discard ban covering regulated species has been agreed by Member States and will be phased in from 2015. Total removals of important commercial species will be controlled through catch limits requiring the full documentation of catches, with the aim of achieving stocks exploited at or below their maximum sustainable yield by 2015 where possible, and 2020 at the latest (European Commission, 2013a). The reforms of the CFP are in the final stages; negotiations between Member States are complete, the Commission has accepted the reformed policy. The final approval of this policy by the European Parliament is expected to occur in December 2013 (European Commission, 2013b).

1.7. Introduction to research

The European Commission aims to meet the objective of eliminating discards and reducing unwanted catches through the introduction of a discard ban for regulated species (European Commission, 2013a). A discard ban may reduce discards and improve data collection if compliance is high. However, unless incentives are created for the adoption of more selective fishing practices, a discard ban is unlikely to reduce unwanted catches (Bellido et al., 2011). A discard ban may just result in unwanted catch being landed rather than discarded.

In Chapter 2 we examine experience from a number of fisheries around the world where a discard ban has been introduced. Using primary literature, government reports and the findings of stock assessments we evaluate whether a discard ban can incentivise change. We also analyse the role of supporting measures such as bycatch quotas and real-time closures.

Under the reforms of the CFP the discard ban will be supported by effort controls and or catch quotas for important commercial species. In Chapter 3 we analyse whether the combination of a discard ban with such measures will generate incentives for fishers to adopt more selective fishing practices. We use observer and logbook data, combined with economic data from the fishing industry, to assess how the income of a case study fleet, the English North Sea otter trawler fleet, might change on an average trip under a discard ban combined with effort controls or catch quotas. The analysis is based on two alternate behavioural scenarios; the continuation of existing fishing behaviour and catch compositions, or the avoidance of all <MLS catch. Comparing these two scenarios allows us to discern if fishers would benefit from avoiding <MLS catch, and therefore if an incentive for the adoption of more selective fishing could be generated.

The model presented in Chapter 4 builds upon the finding of Chapter 3. Using the logbook, observer and economic data we construct a model which includes data from all trips undertaken by the English North Sea otter trawler fleet in 2010. We assess how the operating profit of the fleet would have changed in 2010 if a discard ban and a single or multiple catch quotas had been implemented for four demersal finfish species. We examine how operating profits might have changed under a range of behavioural scenarios including the adoption of more selective gear. This allows us to identify not only what behaviour changes might take place when the CFP reforms are introduced, but also which vessels will have the strongest incentives to change fishing practices.

In Chapter 5 we use the Fcube (Fleet and Fisheries Forecast) model (Ulrich et al., 2011) to explore how introducing catch quotas and a discard ban may impact on the multiple stocks and fleets of the North Sea demersal finfish fishery. We go further in evaluating how different methods of setting catch quotas may affect fleets and the generation of an incentive for more selective fishing practices. We identify how this incentive may be distributed amongst fleets, and what factors determine its strength. This allows us to explore who is likely to be a winner or a loser over a much larger scale than our previous models, giving us an idea of how the level and nature of fishing may change in the North Sea once the CFP reforms come into force.

The text of the research chapters reflects the version of the CFP reforms that was current at the time that they were written, and that published papers haven’t been revised to account for subsequent changes.

Chapter 2.

Incentivising selective fishing under a policy to ban discards; lessons from European and global fisheries.

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Abstract

The reduction of discards in European fisheries has been identified as a specific objective of the reform of the EU Common Fisheries Policy. To reduce the uncertainty in catch data and the socially unacceptable waste of resources that results from the disposal of catch at sea, a policy to ban discards has been proposed. Discard bans are currently implemented in Alaska, British Columbia, New Zealand, the Faroe Islands, Norway and Iceland. Experience from these countries highlights that a policy of mandatory landings can result in a reduction in discards, but relies upon a high level of surveillance or economic incentives to encourage fishers to land more of their catch. Discard bans will also not result in long term benefits to stocks unless total removals are reduced, through the avoidance of undersized, non-commercial or over quota catch. Experience shows that additional management measures are required to incentivise such a move towards more selective fishing. Success has resulted from the use of area closures and bycatch limits, with potential applications in EU fisheries. However, selective fishing will not be a panacea for the current state of European fisheries; discard bans and accompanying measures must be embedded in a wider management system that constrains fishing mortality to reasonable levels before sustainable exploitation can occur.

Keywords: Discard ban; Selective fishing; Catch quotas; Bycatch

1. Introduction

Discarding, where a portion of a vessel's catch is returned to the sea dead or alive (FAO, 2010), is a widespread problem in EU fisheries. 40-60% of catch is discarded by North Sea beam trawlers, whilst discard rates of 30% are estimated for bottom trawlers in the Northeast Atlantic (STECF, 2006). The incentives for discarding are numerous, but result from multiple species and size of fish occurring in the same area and being captured by fishing gear of limited selectivity (MRAG, 2007). In EU fisheries, regulations define the catch that can be legally landed. Fish that exceed quota, are below minimum landing size (MLS) or do not meet catch composition regulations cannot be retained and must be discarded (European Commission, 2002). Catch will also be discarded if it is of poor quality, small size, or of a non-commercial species resulting in a low market value (Catchpole et al., 2005). Disposal at sea results in much of this catch being undocumented, introducing additional uncertainty into the stock assessments of commercial species and making it more difficult to determine appropriate fishing mortality levels (MRAG, 2007). Consequently, the reduction of discards in European fisheries has been identified as a specific objective of the proposed reform of the Common Fisheries Policy (CFP) (European Commission, 2011b). To facilitate this aim, the implementation of a discard ban in combination with catch quotas has been proposed (European Commission, 2011a). Dependent upon the level of compliance a discard ban should result in a reduction in discards. However this will only benefit stocks in the long term if a reduction in total removals and therefore fishing mortality is achieved (MRAG, 2007). In the case of commercial species, reducing the fishing mortality of juvenile fish would allow a greater number of individuals to survive and reproduce (Sigler and Lunsford, 2001), with a subsequent growth in the size of stocks and exploitable catch (Valdemarsen, 2003). However, experience shows that in the absence of incentives to fish more selectively and avoid the capture of formerly discarded catch, a discard ban will not result in more sustainable fisheries (Bellido et al., 2011). Discard bans have been implemented in a number of fisheries around the world, including the US Alaskan and British Columbian groundfish trawl fisheries, and in New Zealand, Icelandic, Norwegian and the Faroese fisheries. This paper briefly assesses the effect of these discard bans and the surrounding management system, identifying whether any benefits of the policy have been observed, primarily through the reduction of discards and incentivising of more selective fishing through the avoidance of undersized, over quota and non-target species. The experience from UK fisheries projects and pilot schemes in incentivising a behaviour change in fishers is also evaluated. Finally, conclusions are drawn from both sets of observations to provide a number of lessons that can be used by UK fisheries managers when implementing the new discards policy under a reformed CFP.

2. Incentives for selective fishing under a discard ban – lessons from abroad

2.1 US Alaskan groundfish fisheries

The US Alaskan groundfish fisheries have operated a discard ban for Pacific cod (*Gadus macrocephalus*) and pollock (*Theragra chalcogramma*) since 1998 (Graham et al., 2007), supported by one of the most comprehensive observer programs in the world (Hall et al., 2000). Commercial species are managed through Individual Vessel Quotas (IVQs) or fishing cooperatives, placing constraints on the capacity of the fishery (Sigler and Lunsford, 2001). Non-target species are protected through fishery specific bycatch levels (Graham et al., 2007). Those that are vulnerable or commercially important, including herring (*Clupea pallasii*), halibut (*Hippoglossus stenolepis*), salmonids (*Oncorhynchus spp*) and commercial species of crab (*Paralithodes camtschaticus, Chionoecetes opilio, Chionoecetes bairdi*) (NPFMC, 2012) are defined as Prohibited Species. Exceeding the proscribed bycatch levels will trigger area or fishery closures (Graham et al., 2007, Alverson et al., 1994, Gilman et al., 2006).

Since the discard ban was implemented, the discard rates of the Alaskan walleye pollock pelagic trawl fishery have fallen. Pacific cod discard rates fell from 6.8% to 0.4% by 2003, and pollock discard rates are less than 1% (Graham et al., 2007). It is not clear from the literature whether the existing low level of discarding is due to non-compliance or is deemed as acceptable by the managing authorities. Changes in the selectivity of fishing have also been observed in response to bycatch limits. A voluntary change to more selective pelagic trawls from semi-demersal trawls occurred in the walleye pollock fishery in response to high catch rates of prohibited crab and halibut. Pelagic trawls are now mandatory and levels of bycatch are less than 2% (Graham et al., 2007). The selectivity of fishing has also been improved in the demersal longline fishery after a voluntary fleet wide communication programme designed to reduce the incidental capture of halibut was implemented (Gilman et al., 2006). Observer catch and bycatch data are collated by the Fisheries Information Services and the locations of bycatch hotspots, along with advice on bycatch reduction techniques, are reported to vessels within the program. As a result fishing effort has redistributed away from areas associated with increased bycatch and the bycatch rates of participating vessels are 30% lower than the rest of the fleet. Gilman et al. (Gilman et al., 2006) argued that the programme has contributed to a 33% reduction in the levels of halibut bycatch.

The introduction of IVQs has reduced the capacity of the sablefish (*Anoplopoma fimbria*) and halibut longline fishery. With fewer vessels operating, fishing grounds are less crowded allowing the remaining effort to concentrate in more productive areas where the abundance of juvenile fish is lower. Improved choice of fishing grounds resulted in a 9% increase in proportion of mature female sablefish in the catch, leading to a 9% increase in the spawning biomass per recruit by 2001 (Sigler and Lunsford, 2001).

The use of a discard ban in the Alaskan groundfish fishery has reduced discard levels of the designated species (Graham et al., 2007). Placing limits on bycatch that will constrain fishing have incentivised more selective fishing, with a shift in fishing grounds and gear choice, and increased fleet communication (Gilman et al., 2006, Sigler and Lunsford, 2001, Graham et al., 2007). This has been aided through a high level of observer coverage and allocation of individual quotas. Under this management system, in which the discard ban is embedded, no groundfish stocks are considered to be overfished with only 3 stocks falling below target biomass levels (Aydin et al., 2010).

2.2 British Columbia groundfish trawl fishery

The discarding of rockfish (*Sebastes*) species is prohibited in the British Columbia groundfish trawl fishery. Only those species designated as Prohibited Species, which cannot be legally retained, are excluded from the ban and mitigation measures are required to maximise their survival rates (Rice, 2003). The fishery is managed under an Individual Transferable Quota (ITQ) system supported by 100% observer coverage. When a species quota is exhausted, fishers must stop operating in that area, or purchase additional quota within defined limits (Grafton et al., 2005, Branch and Hilborn, 2008). Overages of up to 37.5% for halibut and 15% for hake (*Merluccius productus*) can be legally landed without the purchase of additional quota, reducing the incentive to discard. This overrun is subtracted from the following year’s quota and the value of the catch is forfeited. This removes any incentive to target over quota catch that can be legally landed, whilst encouraging fishers to match catches to available quota (Rice, 2003, Sanchirico et al., 2006). Marketable discarded catch is counted against quotas, after allowing for estimated discard survival rates, discouraging highgrading where fishers try to maximise profits by landing only the larger more valuable individuals (Grafton et al., 2005, Branch and Hilborn, 2008). Non-target and non-quota species are managed through bycatch limits (Sanchirico et al., 2006, Grafton et al., 2005).

The direct effect of the discard ban in promoting more selective fishing has not been evaluated in the literature. Reductions in the discards of Pacific ocean perch (*Sebastes alutus*), yellowmouth (*Sebastes reedi*), redstripe rockfish (*Sebastes proriger*), and shortspine thornyheads (*Sebastolobus alascanus*) have been observed, but are linked to constraining quotas and the accounting of discard mortality by onboard observers (Grafton et al., 2005). Targeting of species with less constraining quotas has been observed, with fishers avoiding areas where fish with limited quota are more abundant; in the case of rougheye (*Sebastes aleutianus*), yelloweye (*Sebastes ruberrimus*) and shortraker rockfish (*Sebastes borealis*) this has resulted in a 50% reduction in catches (Branch and Hilborn, 2008). Bycatch limits have also triggered more selective fishing. Discard rates of spiny dogfish dropped by 5% between 1997 and 2004, and the annual bycatch mortality of halibut has been reduced by 15% (Grafton et al., 2005).

More selective fishing has been incentivised, but the role of the discard ban in this change is unclear. Constraining bycatch limits and a reduction in the benefits of discarding, facilitated through a full observer programme, have encouraged fishers to match catches to available quota and avoid excessive bycatch (Grafton et al., 2005, Branch and Hilborn, 2008). Under this system of management the majority of groundfish stocks are considered to be in a healthy condition, however not all stocks are being adequately protected (Fargo et al., 2007).

2.3 Faroe Island fisheries

The Faroese Islands have operated under a full discard ban since 1994 (Gezelius, 2008). 90% of the Faroese fishing fleets are managed under effort controls (Løkkegard et al., 2007), whilst larger vessels operating in deeper waters are managed under quotas and bycatch limits for cod and haddock (Reinert, 2001b, Reinert, 2001a). Trawling is prohibited inside the 12 nautical mile limit (Johnsen and Eliasen, 2011, í Jákupsstovu et al., 2007), except for a limited number of small trawlers targeting plaice (*Pleuronectes platessa*) and lemon sole (*Microstomus kitt*) during summer months (Reinert, 2001b, Løkkegard et al., 2007). Fishers operating in this area are obliged to report high catches of undersized fish (Eliasen et al., 2009, Løkkegard et al., 2007); if juveniles of cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) or saithe (*Pollachius virens*) contribute more than 30% of the catch, an area closure will be implemented (í Jákupsstovu et al., 2007, Reinert, 2001b, Løkkegard et al., 2007). Fishers must also vacate fishing grounds if 4% or more of the total trip catch of cod is below 40cm (Gezelius, 2008). Outside the 12 nautical mile limit, the mandatory use of large minimum mesh sizes and sorting grids in trawls is thought to reduce the capture of undersized fish (Løkkegard et al., 2007).

Discarding in the demersal fisheries targeting Faroe Plateau cod, saithe and haddock is thought to be low (ICES, 2011). These fisheries are managed through effort controls which do not generate incentives for discarding as fish are not counted against quotas (Eliasen et al., 2009, Løkkegard et al., 2007). Highgrading may be incentivised in the fisheries managed under TACs, but has not been quantified (Sanchirico et al., 2006). No discard data are currently available to evaluate the efficacy of the discard ban (Løkkegard et al., 2007). However it is known that the ban is not always enforced and some discarding does occur (Reinert, 2001a). Information on changes in fishing behaviour to avoid bycatch and juvenile fish is also sparse. However, Løkkegard et al. (Løkkegard et al., 2007) argue that juvenile haddock have not been effectively protected through technical measures in the longline fisheries.

Without discard data it is difficult to assess whether selective fishing has been incentivised. It is clear that the current management system and any changes in selectivity have not prevented the status of cod, haddock and saithe stocks falling below optimum as a result of unsustainable effort levels (ICES, 2011). Haddock stocks are currently depleted and cannot sustain directed fisheries, whilst dramatic reductions in effort of over 30% have been advised by ICES for the Faroe Plateau cod and saithe stocks (ICES, 2011). Clearly avoiding the capture of juveniles, bycatch and over quota fish will not result in sustainable fisheries unless fishing effort is first set at an appropriate level.

2.4 Iceland fisheries

The landing of catch has been mandatory in Icelandic fisheries since 1989, as part of an ITQ management system (Johnsen and Eliasen, 2011, Sanchirico et al., 2006, Clucas, 1997). Legal landing of over quota and non-target catch is allowed. ITQ overages of 5% can be covered by quota from the following year (Sanchirico et al., 2006, Hutton et al., 2010), alternatively fishers can forfeit the catch value which will then be used for fisheries research (MFA, 2011). Fishers will receive 20% of this value to cover landings costs (Hutton et al., 2010, Sanchirico et al., 2006). Larger overruns and non-target catch can be covered through the purchase of additional quota (Johnsen and Eliasen, 2011). Failure to cover non-mandated catch with allowed overages or purchased quota can result in the revoking of fishing licences (Sanchirico et al., 2006). The capture of juvenile fish is discouraged through the closure of fishing areas for two weeks if catch levels exceed proscribed limits (MFA, 2011). Non-compliance can lead to revoking of fishing licenses, fines or even gaol sentences (Johnsen and Eliasen, 2011). Catches are monitored onshore by the Directorate of Fisheries, supporting at sea observers and coast guard inspections (MFA, 2011).

Despite a policy of mandatory landings, discarding still occurs but has declined since the early 1990s (Valdemarsen, 2003). Haddock discard rates have fallen from an already low level of 2.8% to under 1%, whilst cod discard rates have not exceeded 2% since 2001 (Pálsson et al., 2010). Total discards of saithe are currently between 1-2% (ICES, 2011). Anecdotal evidence also suggests that fishers have attempted to avoid catching cod as a result of a constraining TAC, shifting targeting to haddock. However the Icelandic haddock stock is currently harvested unsustainably (ICES, 2011). The effect of the area closures has not been evaluated. ICES suggests that juvenile fish are unlikely to be protected by small temporary closures but highlight that multiple successive closures in a single fishing ground may have an effect which has not been quantified (ICES, 2011). However, approximately 2000 closures have been initiated since 1986 with over 60% triggered by high abundance of juvenile cod (MFA, 2011). Moreover, direct targeting of small saithe has increased over recent years and the issue of bycatch also remains. The sustainability of high levels of juvenile anglerfish (*Lophius piscatorius*) captured in trawl fisheries and bycatch of lumpsuckers (*Cyclopterus lumpus*) has raised concerns and should be closely monitored (Hafrannsónastofnunin, 2010).

Although the discard levels are low it is unclear if the discard ban itself has incentivised more selective fishing. Information on the landing weights of undersized individuals and bycatch species is sparse. In its absence it is difficult to assess whether fishers avoid the capture of this unwanted catch or simply land more of it. However, around 10 000t of over quota or undersized catch is still landed annually under the allowed 5% quota overages (MRAG, 2007), suggesting that selectivity remains a problem. Discarding is low under a policy of mandatory landings, but still persists (Pálsson et al., 2010) and little evidence of more selective fishing is available in the literature. The shifting of targeting to haddock by cod fishers (ICES, 2011) highlights the importance of ensuring that fishing mortality of all target species within a mixed fishery is constrained to appropriate levels, and that any changes in fishing behaviour are monitored and accounted for.

2.5 Norwegian fisheries

A discard ban has been in force in Norwegian fisheries since 1983 and has undergone a continual extension of the species to which it applies (Dingsør, 2001, Graham et al., 2007, MRAG, 2007). Under this policy discarding of all significant commercial species is prohibited onboard all Norwegian registered vessels and vessels inside the Norwegian EEZ (Diamond and Beukers-Stewart, 2011, Gezelius, 2006). These commercial species are managed under TACs subdivided into ITQs or group quotas (Dingsør, 2001, Eliasen et al., 2009). Catch is counted against quotas and all fishing activity that runs the risk of catching that species must stop when the quota is fulfilled (Johnsen and Eliasen, 2011). Small overruns of quota or non-target catch can be legally landed and retained by fishers (Johnsen and Eliasen, 2011). Larger catches that incidentally exceed quotas or catches of sub-legal length can be landed without prosecution or penalties but the catch is confiscated by the sales organisations or Directorate of Fisheries respectively. The catch value is forfeited, but vessels in the demersal fishery receive 20% to cover landing costs, incentivising compliance with the ban (Gezelius, 2006, Gezelius, 2008). This system of legal landings and forfeiture of sales values is designed to discourage discarding and the targeting of over quota catch (Diamond and Beukers-Stewart, 2011). Observation of discarding, direct or negligent targeting of non-mandated catch or falsifying sales notes and logbooks will result in fines and the confiscation of the catch, or revoking of fishing licences (Gezelius, 2006, Eliasen et al., 2009, Gezelius, 2008).

A system of area closures, similar to the Faroese and Icelandic systems, is designed to reduce the capture of undersized fish in the Barents Sea whitefish fisheries (Rejwan et al., 2001). Fishing grounds will be closed if more than 15% of the total catch of target species is undersized cod, haddock and saithe and will not be reopened until levels of juvenile fish reach acceptable limits (Dingsør, 2001, Rejwan et al., 2001, ICES, 2011). Similar restrictions are in place for bycatch in the *Pandalus* shrimp fishery (Graham et al., 2007, Rejwan et al., 2001). Observers onboard commercial fishing vessels (Graham et al., 2007), and survey vessels operating in areas where undersized fish are more likely to be abundant facilitate the rapid closing and opening of fishing areas (Johnsen and Eliasen, 2011). Coastguard inspections ensure that catch matches the composition regulations. If the level of undersized catch or non-target species is too high, vessels are required to move at least 5 nautical miles to different fishing grounds (Graham et al., 2007, Rejwan et al., 2001, Johnsen and Eliasen, 2011).

The lack of effective monitoring has complicated estimates of compliance and consequent efficacy of the discard ban (Diamond and Beukers-Stewart, 2011, Dingsør, 2001, Graham et al., 2007). Assessment of any link between changes in selectivity and the presence of this policy has not been made in the available literature. Discarding of saithe is known to occur in the cod and purse seine fisheries, and highgrading of haddock is also a problem in the Northeast Arctic longline and trawl fisheries, although this has not been quantified (ICES, 2011). However, the Norwegian Ministry of Fisheries and Coastal Affairs argues that the behaviour of fishers has changed in response to the policy's existence, reducing overall discards (MFCA, 2010). A reduction in the discarding of cod and haddock below the minimum legal catch size was observed in the Barents Sea between 1988-1998, however evidence suggests this occurred in response to the supporting system of area closures, rather than the ban (ICES, 2011). Other changes in selectivity have also been incentivised by area closures. The *Pandalus* shrimp fishery developed a type of sorting grid, the Nordmøre grid, to reduce the large catches of undersized fish, which had resulted in the closure of substantial areas of the Barents Sea (Graham et al., 2007). The grid consisted of an aluminium grid of variable size held at a 48˚ angle in front of the codend. The narrow bar spacing (19mm) guided larger fish to an escape whole in the top of the trawl, whilst smaller target shrimp passed through the bars into the codend (Isaksen et al., 1992). The voluntary uptake of the Nordmøre grid allowed participating vessels to gain access to closed fishing grounds, and it became mandated in 1993. Closures may still be implemented despite the success of this gear modification, incentivising continued research into improving the selectivity of shrimp fishing. Inspired by the success of the Nordmøre grid, the Barents Sea demersal trawl fleet developed fish grids, allowing access to closed fishing grounds (Graham et al., 2007). The grids were mandated in 1997 (Dingsør, 2001).

The effect of the Norwegian discard ban in incentivising more selective fishing is difficult to quantify due to a lack of data. However, ICES state that the Norwegian management system has been successful at reducing the capture of juvenile haddock, and the adult stock is currently exploited at sustainable levels (ICES, 2011). The system of area closures reducing fishing opportunities has also generated an economic incentive to avoid undersized fish of other species (Graham et al., 2007). However, the management system as a whole has failed to maintain all stocks at target levels. The Coastal Cod stock is currently exploited unsustainably, despite large reductions in bycatch limits and restrictions on allowable gear types (ICES, 2011). Golden redfish (*Sebastes marinus*) and beaked redfish (*Sebastes mentella*) stocks are also depleted and cannot support directed fisheries or the bycatch levels currently observed (ICES, 2011). Although some success has been seen in Norwegian fisheries, particularly in regard to the system of real time area closures, maintaining the catches of all species at sustainable levels remains a challenge that has not been met.

2.6 New Zealand fisheries

New Zealand fisheries have been managed under a discard ban incorporated within an ITQ system since 1986 (Hutton et al., 2010). Discarding of catch is only allowed for species with high survival rates (Sanchirico et al., 2006) or those below the legal MLS (MRAG, 2007). The landing of over quota, non-target or bycatch species is allowed, incentivising compliance (Hutton et al., 2010). To avoid the curtailment of fishing and loss of fishing permits, this catch must be covered through the purchase of additional quota or the payment of a tax, the “deemed value” (Peacey, 2002, Hutton et al., 2010). The deemed value is a penalty based on the market value and weight of catch, and is subtracted from catch profits. To discourage excessive overruns of quota, the deemed value will increase with the scale of the overage. A 20-40% overrun of an individual’s quota will incur 20% larger deemed values dependent upon the species in question (Sanchirico et al., 2006, MRAG, 2007). Subsequent purchase of quota to cover this catch will result in a refund of the deemed value (Peacey, 2002). This sliding scale is aimed at incentivising fishers to operate more selectively, avoiding the harvest of fish for which they have insufficient rights (Peacey, 2002). If set correctly this incentivises the landing of non-mandated catch, particularly if the quota for that species is constraining, but not its direct targeting (Hutton et al., 2010).

Despite the discard ban and deemed value system, discarding is seen as an increasing problem by the New Zealand Ministry of Fisheries (Peacey, 2002, MRAG, 2007). The current effect of the ban is difficult to evaluate as data on discarding are sparse (Davies et al., 2009). However, a lack of sufficient incentives for selective fishing or increased catch utilisation has been linked to an increase in illegal discarding of non-target or over quota catch (MRAG, 2007). Large quota overages resulting in high deemed values may incentivise fishers to discard catch before arriving into port. High deemed values may also encourage highgrading (Hutton et al., 2010). However, there is no direct evidence of increased discarding as a direct result of the deemed value system (Peacey, 2002).

The system as a whole is unlikely to incentivise the avoidance of juvenile fish; discarding of sub-legally sized individuals of certain commercially important species is required and is not documented or counted against quotas, providing little or no incentive for selective fishing (MRAG, 2007). Moreover, deemed values cannot be applied to non-commercial or catch below marketable size which have no market value, providing little incentive to avoid these individuals (Hutton et al., 2010, Sanchirico et al., 2006).

A lack of data has also reduced the effectiveness of the management system as a whole. In 2000-2001 fleet quotas were exceeded in 27% of quota stocks linked to many TACs being based on insufficient stock data (Sanchirico et al., 2006). However, in 2009, there was sufficient information to evaluate the status of 119 out of the 633 stocks now included under the quota system. 82 (69%) are at or above target stock sizes, whilst 14 (13%) are depleted or collapsed. New Zealand's Ministry of Fisheries considers these rates to compare favourably with other management systems employed globally (Ministry of Fisheries, 2010).

Evaluation of these fisheries shows that discard bans are not implemented in isolation, but as part of a much larger management system. A discard ban by itself will not reduce fishing mortality, although may allow improved data collection and closer observance of TACs (Clucas, 1997). It is the accompanying management measures that will incentivise fishers to operate more selectively in order to avoid undersized, over quota and non-target catch. Experience from North America and the Nordic countries show that effects will be greatest where high levels of non-mandated catch trigger a reduction in fishing opportunities (Gilman et al., 2006, Sigler and Lunsford, 2001, Graham et al., 2007, Grafton et al., 2005, Branch and Hilborn, 2008). Area closures can result in a shift in gear choice and the development of bycatch reduction tools, whilst bycatch limits can be effective at incentivising fishers to act collaboratively, as shown by the Alaskan and Norwegian case studies (Graham et al., 2007, Gilman et al., 2006). Experience from the New Zealand, Norwegian and Faroese fisheries show that a lack of accurate data complicates evaluation of the efficacy of any management measure in incentivising more selective fishing. Above all experience from these fisheries shows that selective fishing on its own will have little benefit unless fishing mortality is also set at a sustainable level (Fargo et al., 2007, ICES, 2011).

3. Incentivising selective fishing – lessons from UK fisheries

A number of schemes and pilot studies have concluded that more selective fishing can be incentivised in UK fisheries. Project 50%, a collaborative project between English Channel beam trawlers and scientists, gave fishers the freedom to design their own gear based on their knowledge and experiences (Armstrong and Revill, 2010). Changes in structure and mesh size resulted in an average reduction in discards of 52%. This project concluded that there is "no one size fits all" gear modification, any attempt to improve selectivity must be appropriate for the season, the area of fishing, and the individual vessel (Armstrong and Revill, 2010).

Eliminating discards through catch quotas has been proposed under the reformed CFP (European Commission, 2011a). Pilot schemes have been initiated for North Sea cod and English Channel sole (*Solea solea*). All catch of the managed species is deducted from a vessel's catch quota independent of marketability, including those that were formerly discarded. Exhaustion of quota will require fishing activities that risk the capture of that species to stop. The total catch is monitored via Remote Electronic Monitoring (REM) including CCTV cameras and sensors (Course et al., 2011). Selective fishing is incentivised in order to maximise the value of quota and prevent the curtailment of fishing (Marine Scotland, 2011). Fishers have the freedom to choose how they operate allowing the adaption of fishing methods to suit particular vessels (Course et al., 2011). In the Scottish North Sea cod pilot, changes in fishing behaviour in order to reduce the capture of the constraining cod were observed. Fishers switched to more selective gear, and relocated to different fishing grounds where they could target other species and avoid high concentrations of cod (Marine Scotland, 2011). Similar behaviour was observed in the English North Sea cod pilot, where the average length of cod in the catch increased above that observed before the trial

(Course et al., 2011). During the schemes REM showed promise as a monitoring tool, potentially supplementing observer coverage.

REM could also be used as a catch data collection tool to facilitate a system of real time closures designed to protect vulnerable species, juvenile and spawning fish (Marine Scotland, 2010). Stakeholder consultation identified that many UK fishers would support such a system, on the proviso that effective systems were put in place to ensure both the rapid closure and reopening of areas (Paramor et al., 2005). Defining areas where different gear types could be used was also favoured, with gears that are less selective being designated to areas where bycatch rates are lower (Paramor et al., 2005).

4. Discussion - Advice for European fisheries

A number of lessons can be drawn from the fisheries discussed in this paper which could influence the design of any incentives schemes that are implemented under the reformed CFP.

4.1 Reducing Discards

4.1.1 Discard Bans

As shown by the North American and Icelandic case studies, if compliance is high discard bans can result in a reduction in discards and more accurate catch data (MRAG, 2007). Compliance is more likely if the level of surveillance is high, as total fishing mortality can be accounted for, removing the incentive to highgrade (Grafton et al., 2005, Branch and Hilborn, 2008). However implementing an observer programme similar to that of British Columbia in EU fisheries may be impractical. 100% observer coverage is expensive (Vestergaard, 1996), and is unlikely to be cost-effective in EU fisheries which are dominated by vessels of 10m and under (Graham et al., 2007). Experience from the UK catch quota pilots suggests that this problem may be addressed at least in part by REM (Marine Scotland, 2010, Course et al., 2011).

4.1.2 Accompanying Measures

In the absence of high levels of monitoring discarding under a discard ban will continue unless the accompanying management measures create strong enough incentives to encourage landing of catch or selective fishing (MRAG, 2007). Implementing gear restrictions or area closures may reduce the need to discard, through a reduction in the capture of unwanted catch (MRAG, 2007). In addition increased flexibility in management systems that allow the transfer, purchase or leasing of quota to match the catch composition of vessels will reduce the incentive to discard non-mandated catch (MRAG, 2007). Allowable quota overages and economic landing incentives will reduce the cost of landing formerly discarded catch (Hutton et al., 2010, Sanchirico et al., 2006). However, EU fisheries managers will have to implement sufficient restrictions to ensure that selective fishing results in a greater economic benefit to fishers than landing unwanted catch, thereby preventing continued capture of over quota catch or the direct targeting of formerly low value sizes or species of fish (MRAG, 2007).

4.2 Incentivising Selective Fishing

4.2.1 Discard Bans

Anecdotal evidence from Norway and Iceland suggests that discard bans and accompanying measures can generate social or economic incentives for more selective fishing. However, very little data are available from the case studies to suggest that a discard ban in itself directly results in the avoidance of non-mandated, non-commercial or undersized catch. Moreover, encouraging compliance with a discard ban through landing incentives may reduce the benefit of avoiding this unwanted catch (Hutton et al., 2010, Sanchirico et al., 2006, MRAG, 2007).

4.2.2 Accompanying Measures

The case studies highlight the need for additional management measures to encourage a change in fishing behaviour. The strongest incentives are generated by measures that place a constraint on fishing in response to quota overages and incidental catch, such as the UK catch quota schemes (Course et al., 2011, Marine Scotland, 2011), the Norwegian area closure system or the restrictive bycatch limits implemented in the Alaskan walleye pollock fishery (Graham et al., 2007). These result in a shift in gear choice, target species or fishing area (Gilman et al., 2006, Branch and Hilborn, 2008). These measures rely on the detailed monitoring of catches or catch compositions (Graham et al., 2007, Johnsen and Eliasen, 2011, Course et al., 2011). As noted above, an extensive observer programme may be unfeasible in EU fisheries, but the catch quota pilot schemes have highlighted the potential use of REM as an enforcement tool (Marine Scotland, 2010, Course et al., 2011). Any management measure implemented in EU fisheries will be particularly powerful if they can utilise the experience and knowledge of fishers, highlighted by the success of Project 50% and the catch quota pilot schemes (Armstrong and Revill, 2010, Course et al., 2011, Marine Scotland, 2011). However, Iceland’s experience with the unsustainable harvest of haddock highlights the need for EU fisheries managers to ensure that any change in fishing behaviour will not shift effort onto species or a size range of fish that are unable to support the increase in exploitation (ICES, 2011).

4.3 Sustainable fisheries

Perhaps the most important lesson to draw from these experiences is that selective fishing will not be a panacea for the state of EU fisheries. Despite a reduction in discards and evidence of more selective fishing, unsustainable exploitation of fish stocks is still occurring in a number of stocks managed under a discard ban (Fargo et al., 2007, ICES, 2011, Ministry of Fisheries, 2010). A policy of mandatory landings can be a useful tool in the management of fisheries, reducing waste and improving data collection, especially when combined with management measures that incentivise selective fishing. But it must be embedded in a wider management system that constrains catches to a long term sustainable level (ICES, 2011).

5. Conclusions

The reformed CFP seeks to eliminate discards through a discard ban and/or catch quotas (European Commission, 2011a). Additional management measures are likely to be needed under any discard ban to incentivise more selective fishing. Experiences from fisheries in the UK and around the world show that choosing the right measures is not a simple process. Different regulations will be required for different fisheries, dependent upon distribution of activities, the gear in use, the scale of enforcement that is available, and the species that are targeted and incidentally caught (Hutton et al., 2010). These measures will mean little unless fishing mortality is constrained to a sustainable level, whether that is through quotas or effort controls. These challenges will be faced by fisheries managers throughout Europe if the proposed changes to the Common Fisheries Policy are implemented.

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Chapter 3.

Does banning discards in an otter trawler fishery create incentives for more selective fishing?

Condie, H. M., Grant, A., and Catchpole, T. L. 2013. Does banning discards in an otter trawler fishery create incentives for more selective fishing? Fisheries Research, 148: 137-146.

Abstract

Reforms of the European Union Common Fisheries Policy (CFP) will implement an EU wide ban on discarding phased in from 2015, requiring the landing of unwanted small and unmarketable fish. The Commission argues that this will create strong incentives for more selective fishing practices; however, there is little information to allow us to predict likely changes in fishing behaviour. Using detailed historic observer and logbook data from English North Sea otter trawlers and information on fish prices and landing costs, we examine the potential impact of a discard ban combined with either effort controls or catch quotas on the landings of an average trip. We calculate fishing incomes based on the assumption that existing fishing behaviour and catch compositions are maintained and compare this with incomes calculated on the assumption that all unwanted catch can be avoided. The difference provides an estimate of the maximum possible financial incentive for fishers to adopt more selective fishing practices. The calculations suggest that a discard ban in isolation will generate little economic incentive to operate more selectively. When combined with effort controls, a reduction in fishing effort may result in a proportional reduction in unwanted catches, but an incentive to actively avoid this catch is unlikely to be generated. Catch quotas would generate much stronger economic incentives, but only for the avoidance of the five quota species. So, contrary to the aims of the reformed CFP, a discard ban may not result in a dramatic reduction in unmarketable catches of all species.

Keywords: Discards, discard ban, Common Fisheries Policy reform, catch quotas, selective fishing

1. Introduction

Discarding, the act of throwing catch back into the sea (Kelleher, 2005), wastes food and economic resources. It represents a major source of undocumented mortality, contributing to the overfishing of European fish stocks (European Commission, 2011d, European Commission, 2007a). However, the focus of management under the existing European Union Common Fisheries Policy (CFP) is on landings rather than catches. It is illegal to land catch that does not match prescribed catch compositions, legal Minimum Landing Sizes (MLS) or TACs (European Commission, 2002). Discarding represents a legitimate means for fishers to comply with these regulations by disposing of catch which cannot be legally landed, as well as fish with a low economic value (Gezelius, 2008). So there is little incentive for fishers to operate more selectively and avoid this "unwanted catch" in the first place. However, discarding is perceived as unethical and a waste of resources (European Commission, 2011b). Moreover, permitting discarding can result in total catches far exceeding the recommended level of removals from stocks, threatening the sustainability of fisheries (Kindt-Larsen et al., 2011). If fishers were to operate more selectively, avoiding capturing unwanted fish, whether through the adoption of more selective gear, a change of target species, or a change in temporal or geographical distribution of fishing, fishing mortality could fall if marketable catches were unchanged. This would allow a greater number of individuals to survive and reproduce (Sigler and Lunsford, 2001), with a subsequent growth in the size of stocks and exploitable catch (Valdemarsen, 2003, European Commission, 2007b). The European Commission (CEC) has proposed reforms of the CFP that seek to reduce these unwanted catches and eliminate discards by 2019 (European Commission, 2012). Central to the reforms is a discard ban, supported by fishing effort controls or catch quotas (European Commission, 2011a, European Commission, 2011d, European Commission, 2011c). Fishing effort controls aim to constrain exploitation of stocks through restricting the time vessels may spend fishing (Cotter, 2010), whilst catch quotas place a direct cap on fishing mortality, requiring all catches to be deducted from quota (Kindt-Larsen et al., 2011). Once the quota is exhausted fishers must halt any activities that risk the capture of the regulated species within the designated fishing grounds (Course et al., 2011). The Commission argues that these measures will create strong incentives for the avoidance of unwanted catch through the adoption or development of more selective fishing gears and or other changes to fishing practices (European Commission, 2007a).

If effort controls or catch quotas are combined with a discard ban, having to retain and land unwanted catches may result in additional costs that lead to a fall in income, generating economic incentives to avoid unwanted catches. If hold capacity is limited, the obligation to retain and store unwanted catches may result in full holds (MRAG, 2007), with fish that would previously have been discarded displacing additional valuable landings. When operating under catch quotas, additional trips might have to be undertaken in order to maintain existing marketable landings, with an associated increase in costs. Under effort controls, where additional trips are not possible, fishers may be able to improve the efficiency of operations through gear modifications, investment in technology, or fisher knowledge and skill. This would increase the catches of valuable species per trip and reduce the loss in income generated by a reduction in fishing time (van Oostenbrugge et al., 2008, Kraak et al., 2013, Catchpole et al., 2006). However, an increase in target catches per trip may not be possible if hold space is exhausted by the retention of unwanted catch. As well as occupying hold space, retaining unwanted catch will require additional storage boxes and ice, and will incur additional landings charges (European Commission, 2007a, MRAG, 2007). Sales need to cover both landing charges and the cost of additional boxes and ice, or fishers will see a fall in income. Therefore, a rational fisher should act to avoid these costs and maximise revenue through more selective fishing, reducing the unwanted catch in the first instance (Johnsen and Eliasen, 2011, Vestergaard, 1996, Valdemarsen, 2003, European Commission, 2007a).

Two additional incentives may be generated by a discard ban combined with catch quotas. Unsalable or low value catch of the regulated species will be deducted from a vessel's quota, reducing the amount of quota available for fishers to catch more marketable individuals, and reducing the value of a catch quota. In addition, catching unwanted fish will result in catch quotas being fulfilled more rapidly. This will reduce the duration of the fishing season and prevent continued fishing for other valuable species, reducing fishing income. Operating more selectively to avoid unwanted catch should increase profits (Kindt-Larsen et al., 2011).

These arguments that a discard ban will incentivise more selective fishing seem plausible. However, there is little information to allow us to predict the likely magnitude of changes in fishing behaviour that will result from a discard ban combined with either catch quotas or effort controls. Here, we use extensive observer, logbook and economic data from the English North Sea otter trawler fleet to predict the economic incentives for selective fishing that will be created. This is an important EU fleet where discarding is currently high (Enever et al., 2009). We also determine how the economic consequences of a discard ban are likely to be distributed across different fleet segments.

2. Materials and Methods

2.1 Mean landings per trip under a discard ban

2.1.1 Landings weight and value

The reformed CFP (European Commission, 2012) includes a discard ban applied to all regulated fish species and Norway lobster (*Nephrops norvegicus,* hereafter referred to as *Nephrops*)*.* Mean landings per trip were estimated, assuming 100% compliance with this ban. Trip data on the weight, size and species composition of discards from English North Sea otter trawlers under 24m in length between 2008-2010, were extracted from the Centre for Environment, Fisheries and Aquaculture Science's (Cefas) Observer Programme (COP). These vessels include otter trawlers of varying size primarily targeting *Nephrops* or whitefish (mainly cod, *Gadus morhua*; haddock, *Melanogrammus aeglefinus*; and whiting, *Merlangius merlangus*). The discard data comprised of 78 trips in which 424 hauls (approximately 90% of the total number of hauls) were sampled by on board fisheries observers. Discard rates, and therefore the impact of any discards policies, are known to vary between different sections of a fleet (STECF, 2008). So data were grouped into 6 vessel segments based on gear type, vessel length and engine power (Table 1), in line with the segment designations used by Seafish, the UK fishing industry authority. Landings data for vessels matching these segment designations were extracted from statistics for 2008-2010, held by the UK Department for Environment, Food and Rural Affairs (Defra) Fishing Activities Database (FAD). We assume that the behaviour of fishers was not altered by the presence of an observer, and that data from the COP is representative of similar unobserved vessels. In particular, for each segment of the fleet, we assume that the mean weight and size composition of the discarded catch of each species is the same as that in the observer programme. This may not be the case in reality (Benoît and Allard, 2009), however, as the focus of this analysis is the generation of economic incentives and the likely spread of economic impacts between vessel segments, rather than an attempt to forecast the actual economic consequences of implementing a discard ban combined with other measures, valid conclusions can still be drawn from the model. We assume that fish that are currently below marketable size, i.e. are below the minimum conservation reference size (MCRS) as referenced in CFP reform documentation, (European Commission, 2012) or are below the minimum size that is currently landed (minimum marketable size, MMS), cannot be sold, except for fishmeal and that the MCRS is set at existing MLS.

Table 1 Characteristics of English North Sea otter trawler vessel segments in the Cefas Observer Programme from 2008-2010. Standard errors are shown in parenthesises.

Vessel segment	Mean vessel length (m)	Mean engine power (KW)	Mean mesh size (mm)	Mean hold capacity (50kg boxes)	Trips (2008-2010)	Observed trips (2008-2010)
<10m trawlers	9.6	140	86	100	16984	18
Nephrops trawlers <300KW	11.4	167	83	225 (29)	5042	12
Nephrops trawlers >300KW	16.5	353	85	710 (182)	474	9
Whitefish trawlers <300KW <15m	12.2	169	90	162 (23)	3256	15
Whitefish trawlers <300KW >15m	16.2	245	98	275 (42)	1898	9
Whitefish trawlers >300KW	18.5	381	106	710 (182)	1268	15

The mean weight in tonnes of marketable catch per trip for each segment and species,C_{vs}, is given by:

$$C_{vs} = \frac{\sum_s L_{vs}}{n_{FAD_v}} + \frac{\sum_s M_{vs}}{n_{COP_v}}$$

L_{vs} is the weight in tonnes of landings per species and segment; M_{vs} is the weight in tonnes of discards per species and segment that are of marketable size; n_{FAD_v} is the number of trips per segment documented in the FAD and n_{COP_v} is the number of trips per segment extracted from the COP. The subscripts v and s refer to vessel segment and species, respectively. In both management scenarios it is assumed that existing landings quota are removed and any catch of a quota species and marketable size could be sold for human consumption. The value of the mean marketable landings per trip for each segment, V_v, was calculated as:

$$V_v = \sum_s (C_{vs} \times V_s)$$

where V_s is the average first sale value per tonne of each species landed by the English North Sea otter trawler fleet in the FAD over the period 2008-2010. It was assumed that the marketable discards component of the marketable catch would attain the same price as individuals of the species that had been retained, and that an increase in catch entering markets would not alter sales values.

The mean weight in tonnes of unmarketable landings per trip for each segment, U_v, defined as discards that fall below MCRS or MMS, were calculated as:

$$U_v = \frac{\sum_s U_{vs}}{n_{COP_v}}$$

Where U_{vs} is the weight in tonnes of undersized fish of species s caught by all COP trips on vessel segment v.

A value of £60-£100 per tonne of whole fish sold for fish meal production was supplied by a commercial fish meal plant. Both the minimum and maximum values were applied to the mean weight of unwanted landings per trip, as below:

$$W_v = U_v \times W$$

where W_v is the value that could be attained by the unwanted catch, based on the minimum or maximum value of raw products for fish meal production, W, assuming that this is the same for all species.

2.1.2 Landings volume

The volume of total landings per segment, defined here as the number of fish boxes required to land the total catch, was calculated as:

$$B_v = \frac{\sum_s C_{vs}}{0.05} + \frac{U_v}{0.05}$$

Each fish box contains 50kg and it is assumed that marketable catch would be sorted into separate boxes based on species, whilst unwanted catch would be stored in multi-species boxes. B_v, the total number of boxes per trip, was then compared with estimates of vessel hold capacity, or the maximum number of boxes that could be stored, supplied by skippers in the fleet, in order to gauge available hold space.

2.1.3 Landing costs

Landing costs will vary dependent upon the port, but a mean estimate was calculated and applied to the landings per trip of each vessel segment. The cost of hiring boxes (65p/box) and ice (mean value of £48.75/tonne), and an estimate on the mean use of ice of 0.2 tonnes to every 1 tonne of fish were based on information from the industry. It was assumed that fishers would hire all fish boxes. Sales commission charges of 4% of the sales value were supplied by Seafish, and were applied only to the marketable fraction of the catch. Landing charges were supplied on the websites of 16 major UK ports, giving a mean cost of 2.5% of the sales value. Landing charges were applied to the mean marketable catch value per trip, and the mean unwanted landings per trip. Accordingly, total landing costs for each segment, A_v, were calculated as:

$$A_v = B_v \times 0.65 + \frac{\sum_s C_{vs} + U_v}{5} \times 48.75 + (V_v + W_v) \times 0.025 + V_v \times 0.04$$

The influence of an increase in each individual cost on overall landings costs of unmarketable catch is shown in Figure S1 (supplementary information, Appendix 8.1).

To calculate the economic incentive to avoid unwanted landings, the above estimates of mean landings volume, costs and value per trip were also calculated based on a scenario where knife-edged selectivity was implemented and 100% of unwanted catch was avoided, i.e. unwanted landings were set to zero. In addition, the uncertainty (standard error) around mean catch and hold capacity estimates was included and propagated through the model.

2.2 Management scenario 1- a discard ban with effort controls

If fisher behaviour remains unchanged, a reduction in effort will lead to a pro-rata reduction in catches and therefore fishing mortality. To examine the potential impact of a discard ban combined with effort controls, the annual landings volume, costs and income of each segment were estimated based on the mean segment effort levels of 2008-2010, and on a 30% reduction from this level. A 30% reduction in effort was chosen to reflect an extreme change in effort. Mean landings volume, costs and value per trip were estimated using the methods outlined in section 2.1 and multiplied by the mean annual number of trips undertaken by each segment, as documented in the FAD for 2008-2010. This was repeated with the annual number of trips undertaken reduced by 30%, giving an estimate of the impact of a 30% reduction in allowable effort. For the purpose of this scenario, it was assumed that a 30% reduction in the number of trips would produce a 30% reduction in days-at-sea; that fishers did not alter their behaviour and that catchability of all species was unchanged, i.e. those trips no longer undertaken due to the reduction in allowable effort would be chosen at random by fishers. Additionally it was assumed that effort reductions were uniform across segments. The annual costs of each segment, under each effort level, were then subtracted from the annual value of landings, providing an estimate of annual fishing income for each segment. The mean hold capacity of vessels in each segment was multiplied by the existing and reduced effort levels, giving an estimate of the maximum volume of landings that could be landed in a year under each effort level, and compared to the above estimate of annual landings volume indicating the degree of hold utilisation under each effort scenario. As mentioned above, under a system of restricted effort fishers may alter their behaviour to increase catch rates per trip. To investigate whether hold capacity would restrict this behaviour in the case study fleet, the annual hold capacity under a 30% reduction in effort was compared to the annual volume of catches achieved under the existing effort levels. This indicates whether fishers would have sufficient storage space to maintain annual marketable landings by increasing catch rates per trip of target species. The above analysis was performed based on the per trip estimates of landings including unwanted catch or excluding 100% of unwanted catch, indicating the economic benefit that might be generated by implementing more selective fishing practices.

2.3 Management scenario 2 - a discard ban with a catch quota

Single species catch quotas were calculated for each segment, for 5 species: cod, haddock, plaice (*Pleuronectes platessa*), sole (*Solea solea*) and whiting. Under catch quotas, the full documentation of catches allows a part of the TAC that is usually set aside to account for discards to be added to existing landings quotas (Eliasen et al., 2009). Under the current UK Marine Management Organisation's catch quota scheme protocols, the percentage of this extra quota should not exceed 75% of the stock percentage discard rate. The catch quotas in this analysis were set accordingly using the 2009 stock discard rates estimated by the International Council for the Exploration of the Sea (ICES) (32% for cod, 24% for haddock, 45% for plaice and 26.6% for whiting). Annual statistics from the MMO show that UK North Sea landings quota for the 5 chosen species were almost completely utilised in 2008-2010 (97-100% of cod quota, 86%-99% of haddock quota, 95-99% of plaice quota, 78-97% of sole quota and 98-100% of whiting quota); consequently it was assumed that mean annual landings documented in the FAD represented the mean landings quota available to each segment in 2008-2010. The extra quota, calculated using the ICES stock discard rates, was then added to the existing landings quota to give estimated catch quotas for each of the chosen species. For sole, no ICES stock discard rate exists, so catch quotas were instead set in line with the 2011 MMO protocols which cap the uplift in existing landings quota at 30%.

Assuming no change in the existing fishing behaviour, the number of trips that could be undertaken by each vessel segment before the catch quota was fulfilled was calculated based on the above estimates of the mean landings weight per trip of the 5 catch quota species.

$$E_{qv} = \frac{Q_v}{(C_{qv} + U_{qv})}$$

E_{qv} is the number of trips that can be taken under each catch quota, Q_v, by each segment, and C_{qv} and U_{qv} are the weight of marketable and unwanted landings of the catch quota species. The number of trips that can be undertaken provides a proxy for fishing season duration under each of the catch quotas and a discard ban, based on the existing catch composition or avoidance of all unmarketable catch, and assuming no restriction on allowable effort; the fewer trips that can be undertaken, the shorter the fishing season. It was assumed that a catch quota for one species only would be implemented for each segment at any one time.

The per trip estimates were raised by E_{qv} to give annual landings volume and weight in tonnes, landings costs and income, based on existing catch compositions or avoidance of unmarketable catch. These estimates were based on all 50 species caught by the case study in 2008-2010, including the 5 regulated species, providing an insight into the impact of catch quotas in a mixed fishery. The annual landings volume was compared to mean vessel hold capacity to examine if there would be sufficient hold space to land all catches under a discard ban and a catch quota.

The value of each catch quota for each segment, Y_{qv}, based on existing catch compositions or avoidance of unwanted catch was calculated as:

$$Y_{qv} = E_{qv}(V_{qv} + W_{qv} - A_{qv})$$

where V_{qv} and W_{qv} are the value of marketable and unwanted landings of the catch quota species, whilst A_{qv} are the costs associated with the catch quota species landings.

For the purposes of this analysis it was assumed that quotas were not transferable.

2.4 Summary of Assumptions

The model is built upon a number of assumptions as stated above. As the intention of the model is to evaluate whether an economic incentive is created for more selective fishing practices, the avoidance of unmarketable catch is the only behaviour change investigated here. Consequently it is assumed that the catch volume and composition of marketable fish per unit effort will remain unchanged despite the introduction of either management scenario. The avoidance of unmarketable catch will also not affect the volume and composition of marketable fish per unit effort. Under management scenario 1 it is assumed that existing landings quotas are removed, but that effort is constrained to its current level. By contrast, under management scenario 2, all effort restrictions are lifted. This allows us to evaluate the potential impact of a discard ban combined with effort controls *or* catch quotas in the absence of any other management tools. Under both management scenarios 100% compliance is assumed, and it is also assumed that hold capacity will vary proportionately with fishing effort (i.e. that the lengths of trips remain the same as at present).

3. Results

3.1 North Sea otter trawler discards, 2008-2010

During 2008-2010 English North Sea otter trawlers discarded close to 19% of their total catch by weight on trips sampled in the COP (Figure 1a). 87% of discards were of quotas species, and 27% of all discards were of an unmarketable size or species. The discards were dominated by whiting, dab (*Limanda limanda,* Pleuronectidae), plaice, saithe (*Pollachius virens*, Gadidae), cod and haddock (Figure 1b). Dab does not have a specified MLS and quota uptake was low, suggesting that this species may have been discarded due to its low market value (MMO, 2010). Only 3% (by number) of discarded saithe were below the legal MLS, however the discard rate for this species was close to 7%, indicating that quota restrictions may have been a primary driver in the decision to discard fish of a marketable size (Figure 1f).

The five species managed under catch quotas in this model represented 32% of discards by weight (Figure 1b). The high percentage by number of individuals below the MLS suggest that landing size restrictions were a primary driver in the discarding of cod (Figure 1c, 68%), haddock (Figure 1d, 60%), plaice (Figure 1e, 73%), and sole (Figure 1f, 99%). The discarding of some marketable individuals also occurred, possibly in response to quota limitations or quality (Figure 1c and e). 51% of whiting discards were over the MLS, suggesting that the influence of landing size restrictions on discarding is weaker for this species. Much of the whiting catch may have been returned to the sea in response to quota restrictions, or fluctuations in catch composition and price (Figure 1g).

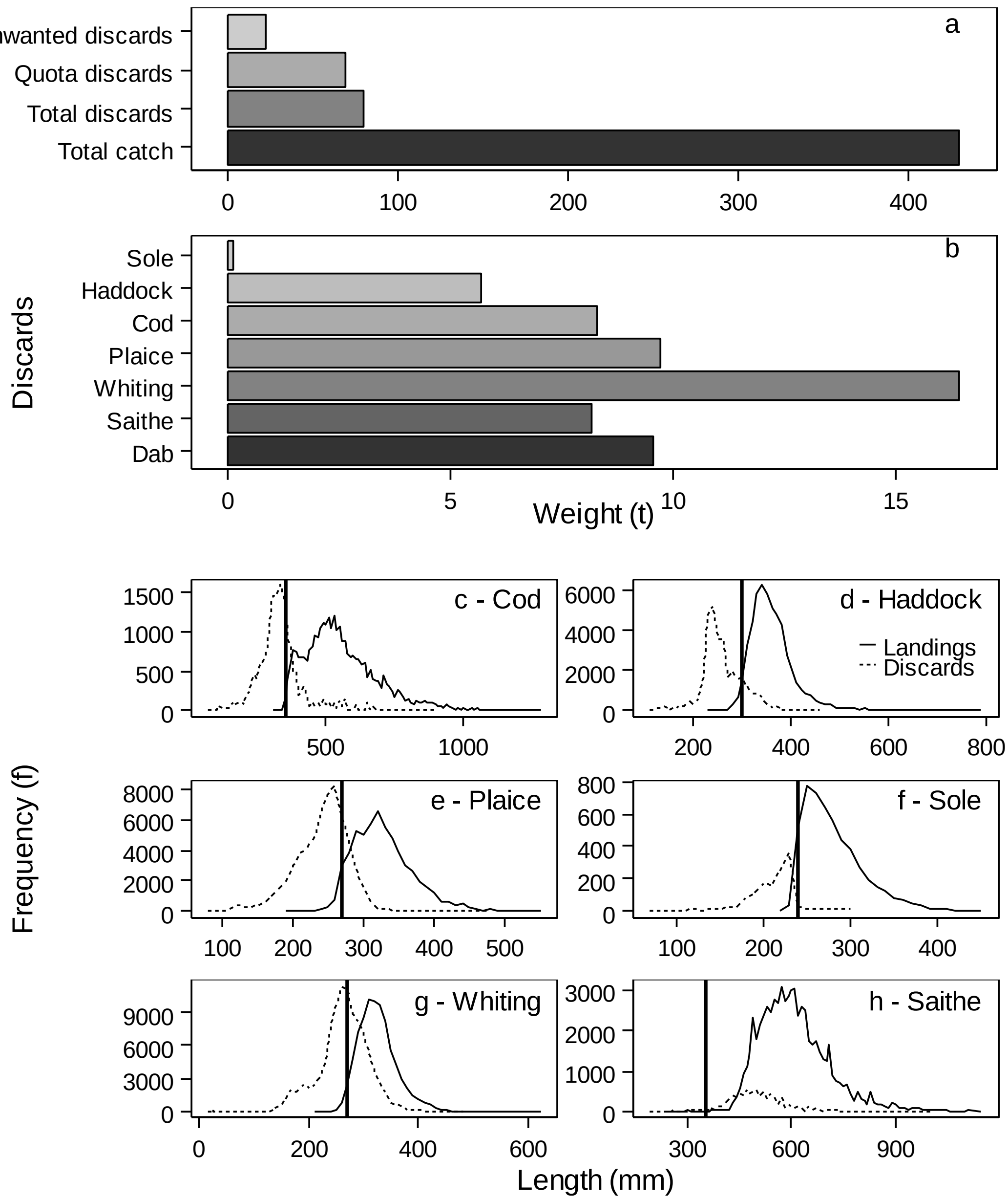

Figure 1 Discards of the English North Sea otter trawler fleet documented in the Cefas observer programme between 2008 and 2010. (a) The scale of discards by weight (tonnes, t). (b) Discards of the 5 catch quota species, and 2 high discarding species, dab and saithe. The length-frequency distributions of retained (solid line) and discarded catch (dotted line) of catch quota species (c-g) and saithe (h), a major component of discards, in comparison to legal MLS (vertical line).

3.2 Management Scenario 1 - a discard ban combined with effort controls

Removing existing landings quota and introducing a discard ban under existing effort levels would have resulted in a 13-68% increase in marketable landings (Figure 2a) and an 8-30% increase in fishing income (Figure 2b) compared to mean annual landings and income of 2008 to 2010. The <10m segment would have seen the greatest increase in landings, however *Nephrops* trawlers over 300kW in engine power would have seen the greatest increase in fishing income. Whitefish trawlers with engine power over 300kW would have observed the smallest change in both income and landings. Implementing knife-edged selectivity would have resulted in a very small decrease in fishing income of up to 1% (Figure 2b). The total landings under a discard ban and existing effort levels would have utilised between 12 and 49% of available hold space, dependent upon the vessel segment (Figure 3a). This estimate of used hold space is based on a mean value of the total landings per trip under a discards ban. However, in reality the volume of landings varies between trips (Figures S2 and S3, supplementary information, Appendix 8.1), and a vessel may undertake a trip where a much higher percentage of the hold space is utilised than on average. Consequently, having to retain catch that would previously have been discarded may result in hold space being exceeded on a small number of individual trips.

A 30% reduction in effort levels, assuming no change in fishing behaviour, would have had varying impacts on different segments; <10m vessels would have seen an 18% increase in marketable landings compared to mean annual landings in 2008-2010, whilst whitefish trawlers over 300kW in engine power would have incurred a 21% reduction in marketable landings (Figure 2c). All segments would have seen a reduction in the income generated by landings, from 9% to 24% compared to mean annual incomes in 2008-2010 (Figure 2d). Avoidance of unwanted catch would once again have resulted in a maximum 1% reduction in income (Figure 2d). Under the assumptions of the model annual hold capacity would have been reduced by 30%, in line with effort reductions, however, as total landings would also have been reduced proportionately hold capacity would not have been exhausted; only 12-49% of hold space would have been utilised (Figure 3b). The surplus hold capacity would have allowed fishers to alter their behaviour, and maintain the level of marketable landings achieved under a discard ban and existing effort levels, despite the retention of associated unwanted catches (Figure 3c).

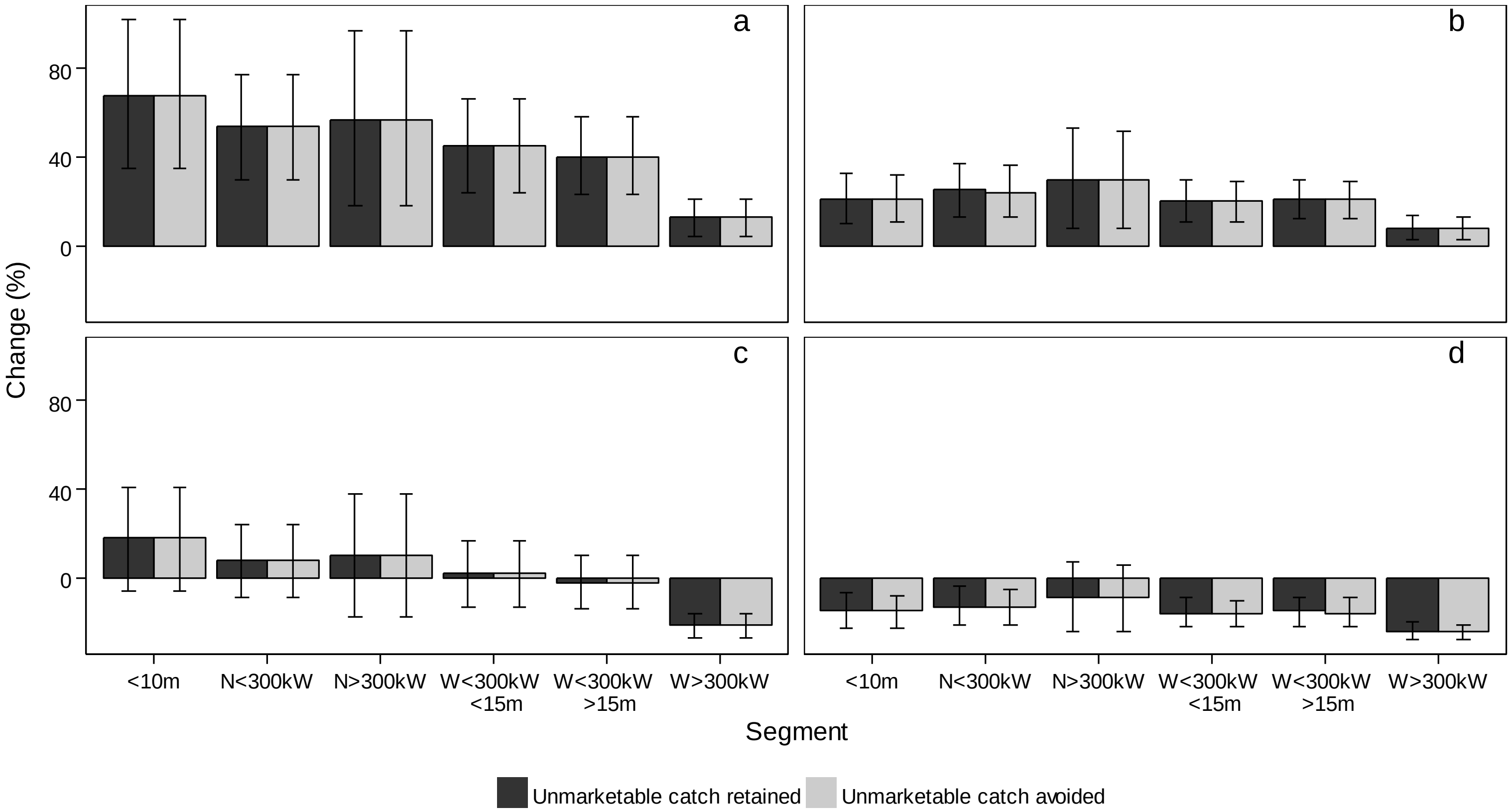

Figure 2 Percentage change in the a) annual marketable landings and b) fishing income of <10m, *Nephrops* (N<300kW, N>300kW) and whitefish (W<300kw<15m, W<300kW>15m, W>300kW) otter trawlers under a discard ban and effort controls restricted to the mean annual fishing effort of 2008-2010, compared to the mean marketable landings and income achieved in 2008-2010, if unmarketable catch is retained (dark grey) or avoided (light grey). Change in c) annual marketable landings and d) fishing income under a discard ban and effort controls compared to 2008-2010 if effort is reduced by 30%. Error bars show range of values due to uncertainty in mean catch estimates and variation in the value of unmarketable catch.

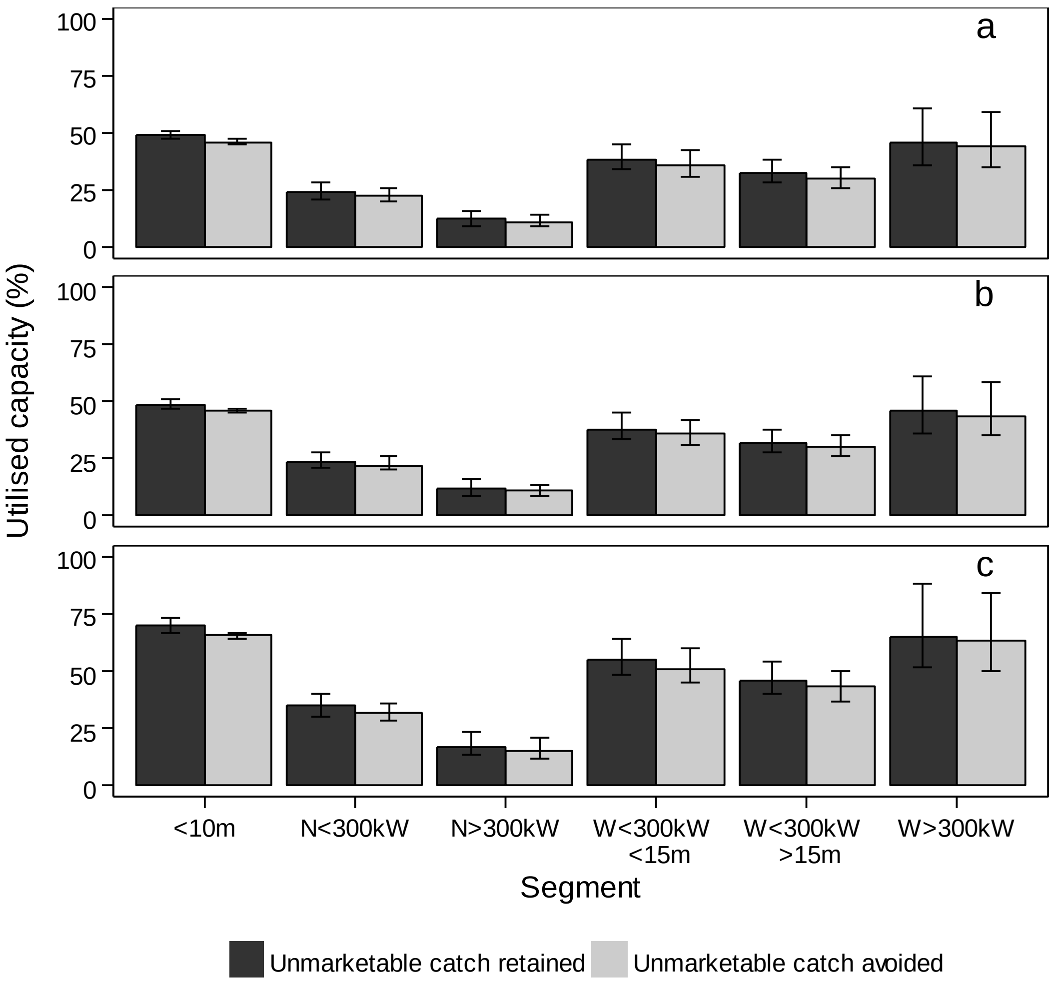

Figure 3 The percentage of <10m, *Nephrops* (N<300kW, N>300kW) and whitefish (W<300kw<15m, W<300kW>15m, W>300kW) otter trawler hold space that would be used annually by total landings if unmarketable catch is retained (dark grey) or avoided (light grey) under a discard ban and effort controls set at a) the existing mean annual fishing effort level of 2008-2010, or b) a 30% reduction in effort, assuming no change in fisher behaviour. c) The percentage of hold space used if fishers were to alter their behaviour and maintain catches achieved under existing effort levels, despite a 30% reduction in fishing effort. Error bars show range of hold utilisation values resulting from uncertainty in mean catch estimates and mean hold capacities.

3.3 Management Scenario 2 - a discard ban combined with a catch quota

The impact of introducing a catch quota and a discard ban into the otter trawler fleet would have varied dependent upon the regulated species and the segment (Table S1, supplementary information, Appendix 8.1). For example, under a cod catch quota *Nephrops* trawlers >300kW in engine power would have seen a 52% reduction in the number of trips that could be undertaken annually compared to 2008-2010 (Figure 4a), leading to a 25% reduction in marketable catches of all species (Figure 4c) and a 38% reduction in income (Figure 4e). Meanwhile, the annual number of trips by whitefish trawlers >300kW in engine power, would have increased by 14% (Figure 4a), leading to a 28% increase in marketable catches (Figure 4c) and a 23% rise in income (Figure 4e).

Avoiding unmarketable catches of the regulated species would have allowed more trips to be undertaken before the catch quota was fulfilled, allowing an increase in marketable catches and income (Table S1, supplementary information, Appendix 8.1). Avoiding the 86% of cod catches that were unmarketable would have allowed <10m trawlers to increase their annual number of trips by 65% above that achieved under a scenario where fishers continue to catch both marketable and unmarketable catch (Figure 4a). This would increase marketable catches by 108% (Fig, 4c) and income by 78% (Figure 4e). Avoiding unmarketable cod would also have increased the value of this segment's cod catch quota by 95% above that achieved when both marketable and unmarketable cod are caught (Table 2). Avoiding unmarketable catches of all species would have resulted in approximately 1% reduction in income compared to a scenario where only unmarketable cod are avoided. As mentioned above hold capacity would not be exhausted by the retention of the total catch including unmarketable fish of all species; with 51-88% of hold space unutilised on an average trip.

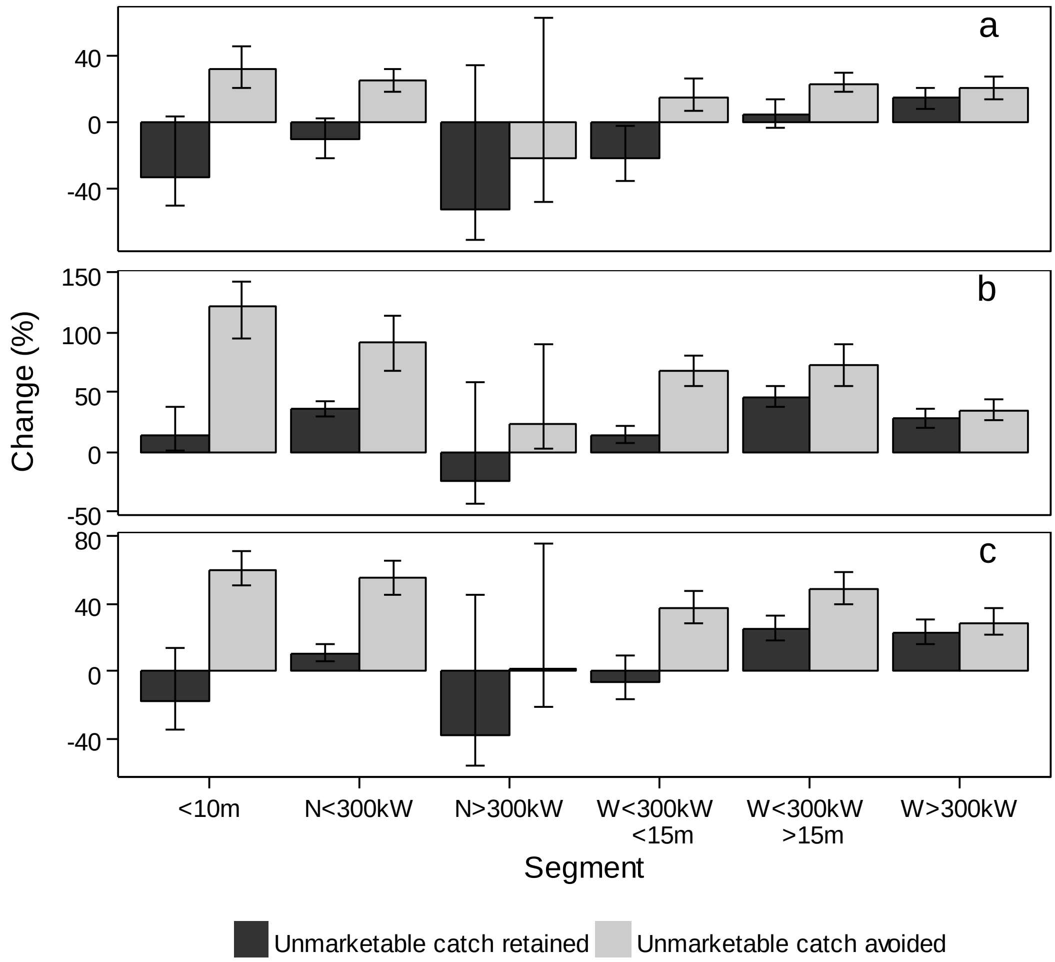

Figure 4 Percentage change in a) annual number of trips, b) annual marketable landings of all species and c) annual fishing income of <10m, *Nephrops* (N<300kW, N>300kW) and whitefish (W<300kw<15m, W<300kW>15m, W>300kW) otter trawlers when unmarketable cod is retained (dark grey) or avoided (light grey) under a discard ban and a cod catch quota, compared to under the management regime of 2008-2010. Error bars show range of values due to uncertainty in mean catch estimates and variation in the value of unmarketable catch.

Table 2 Change in the value of a catch quota if unmarketable catch of the regulated species (cod, haddock, plaice, sole or whiting) is avoided compared to under existing catch compositions. Parentheses show range due to uncertainty in catch estimates and value of unmarketable catch.

	Change in catch quota value (%)				
Vessel segment	Cod	Haddock	Plaice	Sole	Whiting
<10m trawlers	95 (41, 142)	18 (10, 26)	202 (120, 285)	13 (7, 19)	34 (25, 42)
Nephrops trawlers <300kW	39 (25, 53)	34 (21, 49)	97 (70, 122)	8 (1, 17)	65 (45, 91)
Nephrops trawlers >300kW	63 (20, 94)	35 (8, 50)	3 (2, 5)	2 (-1, 9)	20 (14, 25)
Whitefish trawlers <300kW <15m	46 (28, 62)	6 (3, 8)	74 (44, 97)	1 (1, 2)	21 (13, 28)
Whitefish trawlers <300kW >15m	18 (11, 26)	4 (2, 6)	25 (9, 39)	1 (0, 1)	9 (5, 14)
Whitefish trawlers >300kW	5 (4, 7)	4 (2, 5)	5 (1, 9)	0 (-1, 0)	9 (6, 12)

4. Discussion

4.1 Management scenario 1 - a discard ban combined with effort controls.

In the absence of existing landings quotas, implementing a discard ban in the otter trawler fleet under existing effort levels would have resulted in a large increase in income, as fishers could retain marketable fish that would previously have been discarded. However, the model shows that the rise in income is not proportional to the increase in marketable landings, suggesting that marketable discards are less valuable than catch that is currently landed and that discarding of some species may have been driven, at least in part, by a low market value. For fleets where discards are dominated by less valuable species, implementing a discard ban in the absence of landings quotas may not result in a large rise in income, despite an increase in marketable landings. In addition some marketable fish may have been discarded as they are close to the MMS or MLS (as shown by COP data), or of poor quality, and would achieve a lower market value; consequently the increase in income may not be as large as estimated by the model. Landing marketable discards may compensate for a reduction in marketable landings as a result of effort restrictions; however, as this catch is of a proportionally lower value than existing landings, fishing income may still be reduced.

Any reduction in fishing effort should benefit fish stocks that are currently overexploited (Murawski et al., 1999), but implementation of a discard ban offers little benefit in reducing unmarketable catches, beyond that which results from the effort controls alone. If there is no direct control on catches, the discard ban generated little economic incentive for the modelled fleet to avoid unmarketable catches as a result of increased landings costs or exhausted hold capacity. Independent of the level of effort and the behaviour of fishers, avoiding unmarketable catch would have resulted in a small reduction in fishing income as the value of the unmarketable catch sold for fish meal production exceeded the cost of its landing, generating a small profit. The cost of landing 1t of unmarketable catch (£13.50) is far exceeded by its value (£60-£100), and as the relationship between the weight and the costs and values of this catch is linear unmarketable catch should generate a profit independent of its weight and composition. However, the English Discard Ban scoping study highlighted potential impacts on shore based operations that could result in an increase in landing costs (Catchpole et al., 2011). More catch would have to be moved and a larger area of fish quays utilised, potentially increasing labour costs and leading to increased landing charges and harbour dues (Catchpole et al., 2011). If landing costs start to exceed the value of the unmarketable catch, increased selectivity may be incentivised (European Commission, 2007a).

Retaining unmarketable catches would not have exhausted the mean hold capacity of vessels under the existing effort levels. With the majority of hold capacity remaining unutilised there would have been little incentive for fishers to avoid unmarketable catches as valuable landings would not have been displaced. This finding is based on the volume of landings and discards that would have been landed on an average trip. However, the volume of landings and discards varied between trips (Figures S2 and S3, supplementary information, Appendix 8.1). In all segments the volume of landings was much higher than the mean on a small number of trips. On such trips much more of the hold space may be utilised than on average and having to retain previously discarded catch may result in a full hold, forcing vessels to stop fishing. The impact of a small number of curtailed trips will be dependent upon how important the landings of such trips are to the annual income of a vessel. Under a 30% reduction in effort, the model assumes that annual hold capacity of vessel segments would have been reduced by 30%, resulting in a proportional reduction in the volume of catch that could be landed annually. If fishers did not alter their behaviour in response to restrictions in fishing effort, and catch compositions were maintained, all else being equal, catches of both marketable and unmarketable fish would also have seen a proportional reduction. Consequently, the 30% decrease in total landings would have prevented hold capacity being exhausted despite the retention of unmarketable catch. If fishers had altered their behaviour to maximise catches per trip and maintain landings annual hold capacity would still not have been exhausted; there is sufficient available hold space for the total catch achieved under existing effort levels to be caught and retained despite a reduction in the number of trips that could be undertaken. If effort restrictions were more severe, hold capacity may have become more restrictive, particularly in the <10m segment and for whitefish trawlers >300kW in engine power. However, avoidance of unmarketable catches would offer little benefit due to their small volume compared to marketable catches. This finding is based on an assumption that catch compositions will remain the same even if effort is reduced, but in reality, in the absence of landings quotas, fishers can alter their target species to maximise income (Kraak et al., 2008, Kerrigan et al., 2004, Cotter, 2010). However, unless the volume of catch, particularly of unmarketable fish, increases dramatically the hold capacity of the modelled fleet is unlikely to be exhausted, generating little incentive for more selective fishing practices. Moreover, in reality, a 30% reduction in fishing effort may not result in a 30% reduction in annual hold capacity; dependent upon the duration of fishing trips, a 30% reduction in days-at-sea may not translate into a 30% reduction in the number of trips that can be undertaken annually, and the reduction in hold capacity may be less than estimated here. Consequently, annual hold capacity under effort restrictions may be even less restrictive for this fleet.

At present, some catch of a marketable size may be discarded because it is of poor quality. As a result, the amount of catch sold for fishmeal production may be higher, and the volume of marketable catch lower than estimated in the model. In addition the findings of the model are based on mean catches per trip, however discard compositions and volumes vary spatially and seasonally (Moranta et al., 2000, Batista et al., 2009, Feekings et al., 2012). So the discard ban may lead to more or less unwanted catch having to be landed than would be predicted from the mean totals, depending upon the timing and location of fishing operations. Nevertheless, as landing costs are recouped and hold capacity is not exhausted, little economic incentive will be generated to avoid unmarketable catches. In fleets where the majority of hold space is currently utilised, a discard ban combined with effort controls may have more of an impact. This suggests that the assumption of the model of 100% compliance with the discard ban is a valid one. Having to land unmarketable catch does not result in a loss in income providing little incentive for illegal discarding under this management scenario.

Other incentives to avoid unmarketable catches could be generated under a discard ban and effort controls, including an increase in the time and effort needed for catches to be sorted (European Commission, 2007a, MRAG, 2007). Avoiding unmarketable catches would allow fishers to use their time and effort more efficiently, and would reduce the time valuable species spend on deck before being processed (Morizur et al., 2004). Johnsen and Eliasen (2011) identify a reduction in sorting time as a strong incentive for fishers to aid in the development of more selective fishing gears and techniques. However, the strength of the incentive will be vessel-specific as the degree to which sorting times are increased will be dependent upon the nature of the catch, the efficiency of the crew and the sorting procedure of individual vessels. In reality, the use of large mixed-species boxes is likely to limit the additional time required to sort unmarketable catch, and reduce the benefit of its avoidance.

A discard ban combined with effort controls set at existing effort levels is synonymous with a discard ban implemented in isolation, suggesting that a discard ban alone will not incentivise more selective fishing by otter trawlers. This agrees with experience from other fisheries where there is little evidence that a partial or full discard ban in itself has resulted in the active avoidance of unwanted catch (Condie et al., 2014). In Faroese fisheries, where a discard ban and effort controls are in place there is little evidence that a change in the selectivity has occurred (Condie et al., 2014). It has been necessary to supplement the management system with additional output controls and technical measures, to limit the capture of juvenile fish (Eliasen et al., 2009).

Despite a lack of economic incentives generated by increased landings costs or exhausted hold capacity, unmarketable catches may still be reduced under effort controls and a discard ban. Restricting days at sea can reduce the fishing mortality imposed on both target and non-target species, through a reduction in catches (Rijnsdorp et al., 2006, Murawski et al., 1999). The relationship between fishing effort and catch is not linear and varies with changes in the behaviour of both fishers and fish (Rijnsdorp et al., 2006, Rochet and Trenkel, 2005, Kraak et al., 2013). Restricting fishing time creates an incentive for fishers to improve targeting of species that contribute the most to the value of landings, through fisher knowledge of the best places and time to fish, investment in technology and or gear modifications (Kraak et al., 2013, van Oostenbrugge et al., 2008, Rijnsdorp et al., 2006). Consequently reductions in catches of these valuable species may be less than reductions in fishing time (Rochet and Trenkel, 2005, Rijnsdorp et al., 2006). Changes in unmarketable catches could be more or less than the reductions in fishing effort, dependent upon the co-occurrence of these species and sizes of fish with targeted individuals, and any changes in their catchability due to the alterations in fishing practices (van Oostenbrugge et al., 2008, Kraak et al., 2013). Greater reductions in unmarketable catches could be encouraged by issuing enhanced fishing opportunities, such as additional days at sea, to those vessels using more selective gear or avoiding areas where a high proportion of the catch is contributed by juvenile fish (Catchpole et al., 2005).

4.2 Management scenario 2 - a discard ban combined with a catch quota

A catch quota, but no effort controls, would create stronger incentives to avoid unmarketable catches, but only of the catch quota regulated species. Once again implementation of a discard ban offers little benefit in incentivising avoidance of unmarketable catches, beyond that which results from the catch quotas alone. The current cost of landing unmarketable catch is less than its value as fishmeal, so avoiding unmarketable catch of all species would result in a very small decline in income under a catch quota. Hold capacity is not exhausted by the retention of total catches, providing no incentive to avoid unmarketable catch. However, by avoiding unmarketable individuals of the catch quota regulated species fishers can increase the number of trips that can be undertaken before the catch quota is exhausted, increasing marketable catches of all species and fishing income.

The impact of implementing catch quotas on the modelled fleet is determined by the magnitudes of the current actual discard rates of a vessel segment relative to the ICES estimated stock discard rate used to set the catch quota. If the discard rate of a vessel segment is high and exceeds the ICES estimate then the catch quota will be insufficient to cover the usual total catches of the vessels. Under a cod catch quota, *Nephrops* trawlers >300kW in engine power saw a large drop in the number of trips that could be undertaken, with a subsequent decline in income, as these vessels discard 76% of cod catches, substantially higher than the ICES estimate of 32% (Figure 5). Loss of income is particularly severe for these vessels as cod catches contribute only a small proportion of total landings by value (Figure 5); having to stop fishing as a result of a fulfilled cod catch quota results in a large decline in catches of other marketable species. This could be alleviated to some degree by acquiring additional quota through swaps, leases or pools. Where discard rates are substantially less than the ICES estimate, catch quotas will exceed usual catches, allowing vessels to increase the number of trips they undertake. Marketable catches and income will increase, but so might the fishing mortality generated by these vessels. Under a sole catch quota fishers receive a 30% increase in existing quota in line with MMO catch quota protocol as an ICES stock discard rate is not available for this species. However, existing discards of the fleet are substantially less than the 30% additional sole quota given to vessels. Fishers are able to increase the number of trips they undertake, and their catches of both quota species and other marketable fish, provided there are no catch restrictions for other species (Table S1 supplementary information, Appendix 8.1; Figure 5). The greater the discrepancy between actual and ICES estimated discard rates, the larger the mismatch between catch quotas and actual catches, and the greater the impact on income. By avoiding unmarketable individuals of the regulated species fishers can lower their total catch per trip, allowing more trips to be undertaken before the catch quota is fulfilled. The strength of the incentive for such a behaviour change will depend upon the proportion and scale of catches that are unmarketable, and is strongest when discard rates are high and the majority of discards are unmarketable. This also applies to catch quota value. By avoiding unmarketable catches fishers can allow the catch quota to be fulfilled by marketable fish, increasing the quota's value. The more fish that are unmarketable, the greater the economic benefit of avoiding them and the stronger the incentive to do so. This agrees with experience from the Labrador and northeast Newfoundland Shelves Cod fishery, and the British Columbia groundfish fishery. If all catch is counted against a vessel's quota, catching unmarketable or over-quota fish results in a loss of revenue incurred directly by fishers (Kraak et al., 2013), and an incentive is created to avoid these individuals (Kulka, 1997), particularly if the cost of leasing additional quota is high (Branch et al., 2006b). This incentive for more selective fishing is reliant upon all fish being documented; a high level of monitoring will be required to ensure that all catches are documented and that fishers will not reduce the economic cost of catching unwanted fish through illegal discarding, as has been observed in other fisheries where individual transferable quotas have been implemented (Harrington et al., 2005, Branch et al., 2006a, Branch et al., 2006b).

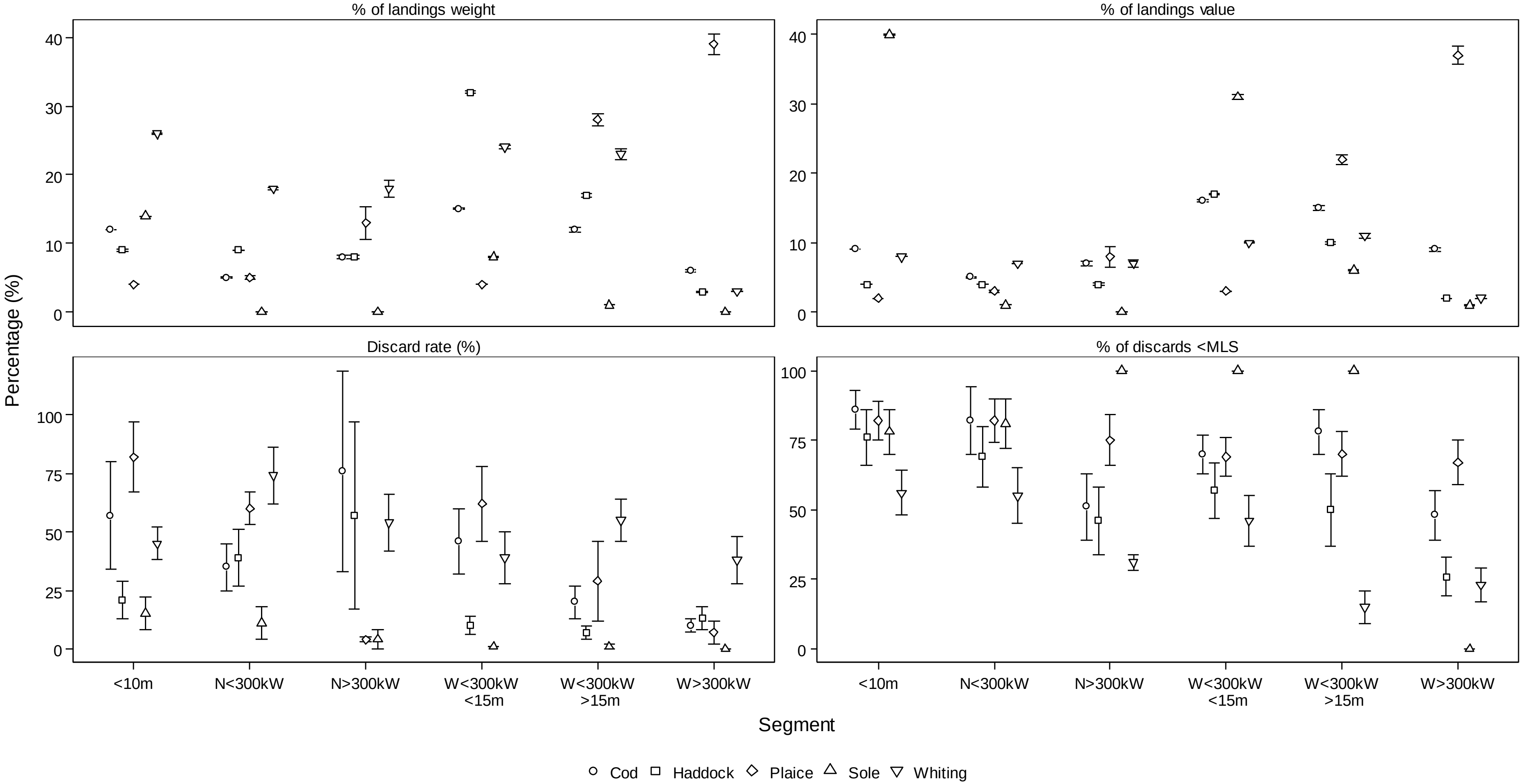

Figure 5 The percentage of mean landings per trip between 2008 and 2010 of <10m, *Nephrops* and whitefish otter trawlers contributed cod (circle), haddock (square), plaice (diamond), sole (triangle) and whiting (inverted triangle), by weight and value. The percentage of the mean total catch per trip discarded by weight and the percentage of discards that are unmarketable. Error bars show ± variation in estimates due to uncertainty in catch estimates.

The relative gain in fishing income associated with avoiding unmarketable catch of quota species will be lower than estimated by the model, as avoiding all unmarketable individuals is unlikely to occur. However, a large reduction in their capture is achievable (Graham et al., 2007, Gezelius, 2008, Johnsen and Eliasen, 2011), and the incentive to do so will still be strong. Changes in fishing practices have already been observed in a number of catch quota pilot schemes. Facilitated by the elimination of micromanagement, participating vessels have adopted more selective gear, or changed fishing grounds, and the average size of the regulated species in the catch has increased (Course et al., 2011, Marine Scotland, 2011).

Despite the strong incentives generated by this system, catch quotas must be implemented with caution. A large discrepancy between actual discard rates and the ICES stock discard rate used to limit the additional quota will result in catch quotas that do not reflect existing catches, and fishing may become either unprofitable due to a decline in the length of the fishing season or unsustainable in the long term due to an increase in fishing mortality. In addition, under a scenario of multiple catch quotas, fishing will be driven by the most constraining quota, potentially underutilising some stocks. Consequently, it will be important to ensure that catch quotas match catch compositions. This could be achieved through setting catch quotas in line with the actual discard rates of vessel segments, rather than the ICES estimate, or through ensuring high levels of catch quota flexibility and transferability. In addition, the CFP proposals include the provision for a de minimis exemption that can be applied to up to 9% of the total allowable catch under certain conditions (European Commission, 2012). However, providing fishers with more flexibility to match their quota allocations with their catch composition will reduce the incentive to avoid unmarketable catches.

5. Conclusion

Contrary to the aims of the reformed CFP, a discard ban in the absence of limits on catch may not incentivise a dramatic reduction in unmarketable catch. A discard ban can reduce discards, cutting waste and improving data collection (MRAG, 2007, European Commission, 2002). However, a discard ban in isolation generates little or no economic incentive for more selective fishing (Condie et al., 2014). Limiting fishing effort could result in a reduction in unwanted catches, but is unlikely to actively incentivise fishers to change their behaviour to avoid unwanted fish. A discard ban combined with catch quotas has the greatest potential to incentivise more selective fishing, but only for the regulated species, and unless quotas are set appropriately and with flexibility, could increase the fishing mortality imposed by some vessel segments while rendering fishing unprofitable in others. No one discard management measure will be appropriate for all EU fisheries, or all vessel segments within a single fishery. Additional technical measures or incentive programmes tailored to different fleets or fleet segments may be needed to encourage fishers to adopt more selective fishing practices and avoid unwanted catches of all species. Understanding the economic consequences of management policies and the most likely behavioural response of a rational fisher will allow the most appropriate management tools to be implemented, in order for the CFP objective of eliminating discards and reducing unwanted catches to be achieved.

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Chapter 4.

The short term impacts of implementing catch quotas and a discard ban on English North Sea otter trawlers

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Abstract

A key objective of the European Union's Common Fisheries Policy reforms is the elimination of discards and a reduction in unwanted catches. Combining a discard ban with catch quotas, where all fish, independent of size, count towards quotas could create economic incentives for more selective fishing, reducing unwanted catches. We use fishing activities data from English North Sea otter trawlers to examine the impact of these measures on this fleet. Initial impacts depend on the scale of increase and distribution of quotas and are unevenly distributed, depending on the catch and discard characteristics of vessels. Selective fishing will be rewarded as vessels that currently have low discards could increase catches and profits. Fishing by less selective vessels will be curtailed, reducing profits by 1-14%. This could be partially mitigated through reducing regulated catches but will require changes to fishing patterns as using currently available selective fishing gears may impact on profitability. So, catch quotas and a discard ban create strong incentives for more selective fishing practices, but also for non-compliance with full documentation of catches. A high level of monitoring and enforcement will be required to ensure that fishers improve profitability through more selective fishing practices rather than illegal discarding.

Keywords: Catch quotas, economic impact, fishing mortality, North Sea otter trawlers

1. Introduction

Non-governmental organisations, such as the Fish Fight campaign (Fish Fight, 2011), have drawn public attention to the scale of discarding in marine fisheries. Non-target species, undersized fish and over quota catch are returned to the sea in large quantities, often dead (Alverson *et al.*, 1994). Such discards not only represent a waste of food and economic resources but also limit the accuracy of stock assessments. Much of the discarded catch will go undocumented, representing unaccounted mortality and making it difficult to set appropriate limits on fishing activities (European Commission, 2011a). This has contributed to the overfishing of European fish stocks (European Commission, 2011c). Currently, under the European Union's Common Fisheries Policy (CFP) it is illegal to land catch that does not match prescribed catch compositions, legal Minimum Landing Sizes (MLS) or TACs (European Commission, 2002). Instead this catch may be legally discarded. Fishers can also choose to discard any catch with a low market value. The European Commission is implementing a discard ban as part of the latest reform of the CFP, seeking to reduce these unwanted catches and eliminate this wasteful practice (European Commission, 2011c, European Commission, 2011a, European Commission, 2011b).

However, a discard ban itself creates little economic incentive to reduce unwanted catches. Supporting measures are required (Condie et al., 2014). A more promising approach is to manage fisheries through a combination of catch quotas and a discard ban (European Commission, 2011b). As outlined in the CFP proposals, this seeks to encourage more selective fishing practices by creating economic incentives to avoid catches that would formerly have been discarded (European Commission, 2012). Under catch quotas the total catch of a regulated species, independent of quality or size, will be documented, and counted against a vessel's quota by weight (Marine Scotland, 2011). Full documentation of catches allows a part of the TAC currently set aside to account for discards to be added to current landing quotas (Eliasen et al., 2009). However, all activities that risk the capture of the regulated species within the designated fishing ground must stop once the catch quota is fulfilled (Course et al., 2011). Lowering the total catch of regulated species per trip will delay the fulfilment of the quota and allow fishing for other species to continue for longer, whilst avoiding juvenile fish will allow the quota to be fulfilled by more valuable individuals of marketable size (Course et al., 2011). Vessels involved in catch quota pilot schemes have adopted more selective gear, or changed fishing grounds, and the average size of the regulated species in the catch has increased (Course et al., 2011, Marine Scotland, 2011).

So, catch quota management has shown promise in reducing catches of previously discarded individuals and capping fishing mortality, but the impact of changing to such a management measure for an entire fleet is unknown. If we have good data on the fishing activities of individual vessels, it is possible to construct a model that estimates the initial impact of catch quotas and the resulting strength of any economic incentives for more selective fishing. Here we do this using observer and logbook data for a European case study fleet, English North Sea otter trawlers. Potential changes in fishing effort, landings and profits are calculated under the assumptions that fishers make no attempt to alter the selectivity of fishing or, alternatively that fishers change their behaviour to maximise profits. Data on changes in catch composition achieved in published gear trials can be used to calculate the potential economic benefit of adopting more selective gear, giving an indication of whether such a shift in fishing behaviour is likely to be seen under catch quotas. By identifying the trips that maximise profits when operating under catch quotas, it is also possible to examine the likelihood of other changes in fishing behaviour occurring, such as changes in target species or seasonality of fishing.

2. Materials and Methods

2.1 Data

The model uses logbook data detailing landings, income and fishing effort by trip extracted from the UK Department of Environment, Food and Rural Affairs' (Defra) Fisheries Activities Database (FAD), and data on discards from the Centre for Environment, Fisheries and Aquaculture Sciences (Cefas) observer programme (COP) database (described in (Enever et al., 2007). Data were extracted for a single year 2010, a year in which landings by English vessels are similar to those of preceding years, allowing the outputs of the analysis to be generally applicable to future years (MMO, 2011).

2.2 Trip catches and profits

Logbook data on the weight and value of landings on all 9031 trips undertaken in 2010 by English North Sea otter trawlers less than 24 meters in length were extracted from the FAD. Trips were separated into six vessel segments (Table 1), in line with the segment designations used by Seafish, the UK fishing industry authority. Trips by vessels less than 10m in length were grouped together. Trips undertaken by larger vessels were subdivided by gear type (trawls mainly targeting Norway lobster (*Nephrops norvegicus*, hereafter referred to as *Nephrops*) or whitefish (mainly cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*)), and subdivided again by engine power (under 300kW, over 300kW). Trips undertaken by whitefish trawlers were finally subdivided by length of vessel (10m-15m, 15-24m).

Table 1 Landings weight and value, percentage of the total catch discarded by weight, and percentage of discards <MLS for vessel segments within the English North Sea otter trawler fleet in 2010. Discard proportions and percentage of discards <MLS are estimated from observer data, landings data are extracted from logbook data. Numbers in parenthesis indicate the lower and upper 95% confidence values.

Segment	Species	Landings (t)	Landings value (£)	Discard proportion (%)	Discards <MLS (%)
Mixed trawlers <10m length overall (LOA) and <300kW engine power					
	Cod	162	221 970	58 (25, 82)	38 (9, 94)
	Haddock	128	92 944	10 (6, 20)	72 (42, 93)
	Plaice	49	35 796	66 (51, 80)	82 (77, 89)
	Whiting	339	260 198	27 (21, 38)	57 (38, 72)
	Other	777	2 250 660		
Nephrops trawlers <300kW engine power					
	Cod	38	52 318	46 (20, 69)	39 (12,87)
	Haddock	50	42 355	13 (8, 23)	59 (35, 82)
	Plaice	35	25 382	65 (53, 77)	82(78, 87)
	Whiting	94	69 932	38 (28, 52)	47 (29, 66)
	Other	458	933 060		
Nephrops trawlers >300kW engine power					
	Cod	9	14 996	50 (27, 69)	33 (14, 67)
	Haddock	11	8 586	16 (9, 28)	51 (34, 73)
	Plaice	5	5 492	64 (52, 76)	82 (78, 87)
	Whiting	35	29 772	38 (50, 45)	45 (29, 62)
	Other	111	213 216		
Whitefish trawlers <15m LOA and <300kW engine power					
	Cod	126	206 122	36 (19, 55)	38 (20, 66)
	Haddock	204	206 108	11 (6, 18)	51 (37, 69)
	Plaice	31	22 850	60 (48, 71)	81 (78, 85)
	Whiting	122	90 957	38 (49, 45)	45 (30, 60)
	Other	205	577 907		
Whitefish trawlers >15m LOA and <300kW engine power					
	Cod	115	199 188	31 (17, 46)	41 (23, 68)
	Haddock	134	135 933	11 (7, 17)	54 (39, 70)
	Plaice	397	428 141	56 (47, 65)	83 (79, 87)
	Whiting	140	106 992	40 (32, 49)	38 (27, 49)
	Other	351	670 863		
Whitefish trawlers >300kW engine power					
	Cod	265	531 185	16 (8, 26)	43 (25, 67)
	Haddock	145	142 279	10 (7, 15)	51 (40, 64))
	Plaice	2 620	3 030 563	40 (31, 52)	73 (60, 84)
	Whiting	103	77 618	39 (32, 47)	37 (27, 47)
	Other	2 617	3 700 777		
Fleet					
	Cod	715	1 225 779	38 (7, 74)	39 (16, 85)
	Haddock	672	628 205	11 (4, 23)	56 (39, 75)
	Plaice	3 137	3 548 224	44 (30, 60)	76 (65, 85)
	Whiting	833	635 469	34 (21, 52)	46 (31, 61)
	Other	4 519	8 346 483		

Catch quotas regulate total catches of a species, rather than landings. This required the total catch of the regulated species produced on each trip to be calculated, using mean segment specific discard proportions, estimated from COP data (Table 1). Mean discard proportions, the percentage of the total catch discarded by weight, and 95% confidence intervals (CI) were estimated for each segment using bootstrap analysis (Table 1), as were the percentage of discards by weight over or under the MLS. The variable nature of discarding means that the 95% CIs are wide, suggesting that the discards of the fleet could be higher or lower than estimated from the small number of observed trips. The impact of this uncertainty was estimated by recalculating the total catches generated on each trip using the upper or lower limits of the 95% CIs of discards and <MLS catch proportions, and applying the data to the model.

The value of the >MLS, or marketable catch, of both regulated and non-regulated species was calculated based on values from the FAD. Data from the COP shows that most >MLS fish discarded in 2010 were smaller than individuals in the retained catch, (Condie et al., 2013), and consequently may have been of a lower market grade, achieving a lower market value than the catch landed in 2010. To account for this discrepancy a reduced value was applied to this fraction of the catch, based on the difference in value between fish grades, using COP data and information from UK fish markets. The profits of each trip, the cost of operating subtracted from fishing income, were then calculated, using segment specific percentage operating profits taken from the 2009 Economic Survey of the UK Fishing Fleet (Curtis and Brodie, 2011).

The CFP reforms propose that all species regulated by catch quotas will be subject to a discard ban and the total catch including <MLS fish must be landed (European Commission, 2012). <MLS catch cannot be sold for human consumption, but may be directed to other processes such as fish meal production (European Commission, 2012). So the value of <MLS fish of the regulated species as a raw material for fish meal production was calculated based on an estimate from the UK fish meal industry of £100 per tonne. The costs of landing this catch, C_t, including increased landings charges, and use of additional ice and fish boxes was calculated as:

$$C_t = \frac{W_t}{0.05} \times 0.65 + \frac{W_t}{5} \times 48.75 + U_t \times 0.025$$

Landing charges were supplied on the websites of 16 major UK ports giving a mean cost of 2.5% of the value of the catch, U_t. Based on information supplied by the industry, it was assumed that fishers would hire additional fish boxes, each storing 50kg of catch, at a cost of £0.65 per box; and use ice at a rate of 0.2 tonnes of ice to every 1 tonne of fish, at an average cost of £48.75/tonne. The weight of <MLS catch in tonnes from each trip, t, is represented by W_t. Mean landing costs do

not include additional costs that may be incurred at particular ports, such as transportation costs if ports are not in close proximity to fish markets, or the use of chill rooms or other areas for the storage of catch before sale. These costs were subtracted from the value of the <MLS catch and the net profit was added to the operating profit of each trip as:

$$P_t = \left(\sum_{s} V_{st} \times p_v \right) + (U_t - C_t)$$

P_t is the operating profit generated on each trip; $V_{s\,t}$ is the value of marketable catch of each species, *s*, generated on the trip; p_v is the percentage operating profit for each vessel segment, *v*.

2.3 Calculating catch quotas

Fleet catch quotas were set for 4 species for which extensive landings and discard data were available, cod, haddock, plaice (*Pleuronectes platessa*) and whiting. Under the reforms of the CFP, catch quotas, in the form of TACs, may replace existing total allowable landings (European Commission, 2012). As mentioned above, full documentation of catches allows part of the TAC set aside to account for discards to be allocated as additional quota (Eliasen et al., 2009). To account for any uncertainty in discard estimates, this uplift in quota could be limited to 75% of the estimated stock discards; a protocol that has been followed in UK catch quota pilot schemes (Course et al., 2011). The catch quota TAC will then be distributed to member states based on the principle of relative stability (European Commission, 2012), and further divided between national fleets and metiers. It was assumed in this analysis that the catch quota would be equally divided amongst fleets based on their existing landings quota share. Consequently, in this analysis, the fleet catch quotas were set by increasing estimated landings quotas by a portion of the fleet's discards, in line with 75% of the 2009 stock discard rate estimated by the International Council for the Exploration of the Sea (ICES) (32% for cod, 24% for haddock, 45% for plaice and 26.6% for whiting). The UK utilised 98-100% of the quota available for cod, haddock, plaice and whiting in the North Sea in 2010 (MMO, 2011). So the single species landing quotas available to the fleet for these species were assumed to be equal to the landings of the case study fleet in 2010, as documented in the FAD. Accordingly fleet catch quotas were set at 992 tonnes of cod, 807 tonnes of haddock, 5 026 tonnes of plaice and 1 087 tonnes of whiting. It was assumed that effort would be restricted to the days at sea set in 2010.

Eight catch quota combinations were examined in the model: catch quotas for cod, haddock, plaice or whiting alone, and 4 combinations in which 3 or 4 of the single species catch quotas were applied to the fleet simultaneously (cod, haddock and plaice; cod, haddock, plaice and whiting; cod, haddock and whiting; and cod, plaice and whiting). Fulfilment of any one of the catch quotas would stop fishing.

2.4 The model

Individual trips were inputted into the model using the R programming environment (R Development Core Team, 2008) based on 4 different fishing behaviour scenarios, as described in Table 2 and below. When the cumulative catch weight of each regulated species from the trips inputted into the model matched the catch quota for that species no more trips were inputted, simulating the closure of a fishery when a catch quota is exhausted. Fleet and segment fishing effort, operating profits and marketable landings of all species generated under each behaviour scenario and catch quota combination were then calculated and compared.

Table 2 Selectivity changes implemented in the model, and their impact on catches of regulated species and other commercial catch.

Selectivity change – Affected Vessels	Examples of changes to Gear	References	Mean % change in catch weight								
			Cod		Haddock		Plaice		Whiting		Other spp.
			<MLS	>MLS	<MLS	>MLS	<MLS	>MLS	<MLS	>MLS	
Nephrops trawlers – Change 1	Cutaway trawl Increase mesh size to 120mm Inclined Seperator Panel	(Revill *et al.*, 2006) (Krag *et al.*, 2008) (Rihan and McDonnell, 2003)	-8%	-8%	-11%	-11%	-21%		-17%	-39%	-11% *Nephrops*
Nephrops trawlers – Change 2	Modified square mesh panel Swedish grid and Swedish grid combined with square mesh codend Swedish grid	(Madsen et al., 1999) (Valentinsson and Ulmestrand, 2008) (Ulmestrand and Valentinsson, 2003)	-53%	-73%	-62%	-68%	-23%	-39%	-54%	-78%	-6% *Nephrops*
Whitefish trawlers – Change 3	Orkney trawl Eliminator trawl	(Campbell *et al.*, 2010) (Kynoch *et al.*, 2010) (Revill and Doran, 2008)	-58%	-58%	+20%	+20%			-8%	-8%	-47% Commercial Species
Nephrops and Whitefish trawlers – Change 4	Above changes of Senarios 1 and 3 applied simultaneously										
Nephrops and Whitefish trawlers – Change 5	Above changes of Senarios 2 and 3 applied simultaneously										

2.5 Fishing behaviour scenarios

The first behaviour scenario, "no behaviour change," examined the potential impact if the fleet had transitioned to catch quotas in 2010 and fishers did *not* change their behaviour to try and optimise profits. Under this assumption, any reduction in fishing effort caused by exhaustion of a catch quota could be spread evenly across the year, or trips could be forgone in a particular month; fishers make no active effort to avoid trips that may be less profitable when operating under a catch quota(s). This was reflected by randomly inputting trips into the model without replacement until the catch quota(s) was exhausted. The second behaviour scenario, "adopting selective gear," examined the benefit of adopting more selective fishing gear to avoid low value small fish or constraining species, an action that can be encouraged under catch quotas (Course et al., 2011). Using the mean results of 3 groups of recent gear trials, the catch weight of unregulated species (species not managed under a catch quota) and regulated species of each trip was adjusted to reflect the use of more selective gear by different segments under 5 selectivity changes (Table 3). Where possible, changes in the catch weight above and below MLS were applied. Where such estimates were absent it was assumed that there was a uniform change in the catch weight of fish across the whole size range. The modified trip data was then applied to the model, as described in Table 2. Comparing the outputs to those of the no behaviour change scenario indicated the strength of any incentive to adopt the selective gears examined. The gear trials examined are not an exhaustive list of available selective gears; other options are available which may have different results. In addition the selective gears included may have differing effects on the catches of the different vessel segments, but this information was not available in the reports. However, the estimated changes in gear selectivity shown in Table 3 are indicative of the improvements that can currently be made in otter trawls. The third behaviour scenario, "optimal trips," examined the impact of catch quotas if fishers were to undertake only trips that would maximise the operating profit of the fleet. Rijnsdorp et al. argue that, when faced with a reduction in fishing effort, fishers should be able to use their experience to pick which trips to undertake in order to maximise revenue, and the same principle was operated here (Rijnsdorp et al., 2006). A number of factors will affect the operating profit achieved by the fleet under catch quotas; the number of trips that can be undertaken, and so the catch of other valuable species, will be determined by the catches per trip of the regulated species; whilst the value of landings will be determined by the weight, species and sizes present. So each trip was assigned a rank from 1-9031 based on the operating profit of the trip, the total weight of regulated species caught, the weight of regulated species catch below the MLS, and or the value of unregulated species catch, relative to all other trips. Each trip was then inputted into the model in order of rank until a catch quota was exhausted. The ranking that produced the maximum fleet operating profit was identified and the characteristics of included trips were examined, providing insight into fishing behaviour that could be incentivised in order to optimise fleet operating profits within the constraints of the allowable fishing effort and existing catch patterns. The fourth behaviour scenario, “least optimal trips,” examined the impact of catch quotas if fishers were to undertake only trips that would minimise the operating profit of the fleet, giving a worst case scenario of the short term impacts of transitioning to catch quotas. The rankings of the third scenario above were reversed and the ranking that resulted in the minimum fleet operating profit was identified.

Table 3 The steps involved in each of the four fishing behaviour scenarios examining the potential impact of a transition to catch quotas by the English North Sea otter trawler fleet.

Scenario	Step
No behaviour change	
Fishers continue to operate as they did in 2010 with no attempt to optimise profits – any foregone effort could occur during any month.	
1	Trips are randomly drawn from the pool of all trips undertaken by the fleet in 2010 without replacement.
2	Each trip selected in step 1 is inputted into the model and the cumulative catch weight of each of the regulated species is calculated.
3	Steps 1 and 2 are repeated until the cumulative catch weight of any of the regulated species is equal to the catch quota for that species.
4	The cumulative catch weight and cumulative operating profits of the fleet and fleet segments are calculated based on the trips included in the model.
5	Steps 1 to 4 are repeated for each catch quota and catch quota combination.
6	50 replicates of the model are completed and mean operating profits and catches of the fleet and each fleet segment are calculated. This number of replicates was chosen as the maximum coefficient of variation was only 1.8% of mean catches and operating profits.
Adopting selective gear	
Fishers alter catch compositions through adoption of more selective gear. No other change in behaviour occurs – any foregone effort could occur during any month.	
1	Catch composition of each trip is altered based on one of 5 selectivity scenarios (Table 2).
2	Trips are randomly drawn from the pool of altered trips without replacement and steps 2 to 6 of the above process are completed.
3	Steps 1 to 2 are repeated for each selectivity scenarios.
Optimal trips	
Fishers undertake trips that will maximise the operating profit of the fleet– catches are not altered.	
1	Each trip in the pool of all trips undertaken by the fleet in 2010 is assigned a rank (1-9031) based on: **maximum** trip operating profit and or, **maximum** value of non-CQ catches on each trip and or, **minimum** catch weight of each regulated species on each trip relative to the species catch quota and or, **minimum** weight of <MLS catch of catch quota species on each trip.
2	Each trip is inputted into the model in order of rank, and the cumulative catch weight of each of the catch quota species is calculated.
3	Step 2 is repeated until the cumulative catch weight of any of the regulated species is equal to the catch quota for that species
4	The cumulative catch weight and cumulative operating profits of the fleet and fleet segments are calculated based on the trips included in the model.
5	The model is run for all of the rankings described above, under each catch quota or catch quota combination.
6	The ranking that produces the highest total fleet operating profit is identified and segment operating profits, marketable landings and effort are calculated.
Least optimal trips	
Fishers undertake trips that will minimise the operating profit of the fleet – catches are not altered.	
1	The trip rankings of the above scenario are reversed.
2	Steps 2 to 5 of the above model.

2.6 Fishing mortality changes

We can make an approximate estimate of how fishing mortality may change under a system of catch quotas by assuming that quotas will be fully utilised and comparing them with the weight of fish actually caught in 2010. Equating this to changes in (numbers based) fishing mortality assumes that there is no change in the size selectivity of the fleet and that selectivity of other fleets remained unchanged. The change in fishing mortality that might have occurred if all fleets exploiting the stocks had operated under a catch quota was also estimated. The fishing mortality associated with fully utilising a catch quota was compared to the fishing mortality generated by total removals from the stock in 2010.

3. Results

3.1 Behaviour Scenario 1: no behaviour change

If fishers had not altered their behaviour, the short term impacts of catch quotas and a discard ban would have varied dependent upon the regulated species and the existing catch and discard characteristics of vessels. When discard proportions exceeded 75% of the ICES estimate, the existing total catch of the regulated species would not have been covered by the catch quota. Without any change in behaviour, the catch quota would have been utilised before all trips could be undertaken, leading to a fall in fishing effort relative to that which occurred under landings quotas. The greatest discrepancies between fleet and ICES discard proportions occurred for cod and whiting. Fleet discard proportions of cod and whiting were 19% and 28% higher than the ICES estimate, resulting in 2010 total catches of cod (1 153t), and whiting (1 272t) exceeding catch quotas by 16% and 17% respectively. Consequently the largest reductions in fishing effort, of up to 16%, occurred under catch quotas for cod and whiting (Figure 1, Table S1 supplementary material, Appendix 8.2). These catch quotas were also exhausted before those for haddock and plaice, so were the main factor restricting catches of both unregulated and other regulated species when multiple catch quotas were implemented. A reduction in fishing effort would have had knock on effects on marketable landings and operating profits. Total marketable landings of all species would have been reduced for the majority of segments, despite the additional >MLS catch of regulated species available under catch quotas. Reductions were greatest for most segments under a whiting catch quota, and would have resulted in a fall in operating profits of up to 15% (Figure 1, Table S1 supplementary material, Appendix 8.2).

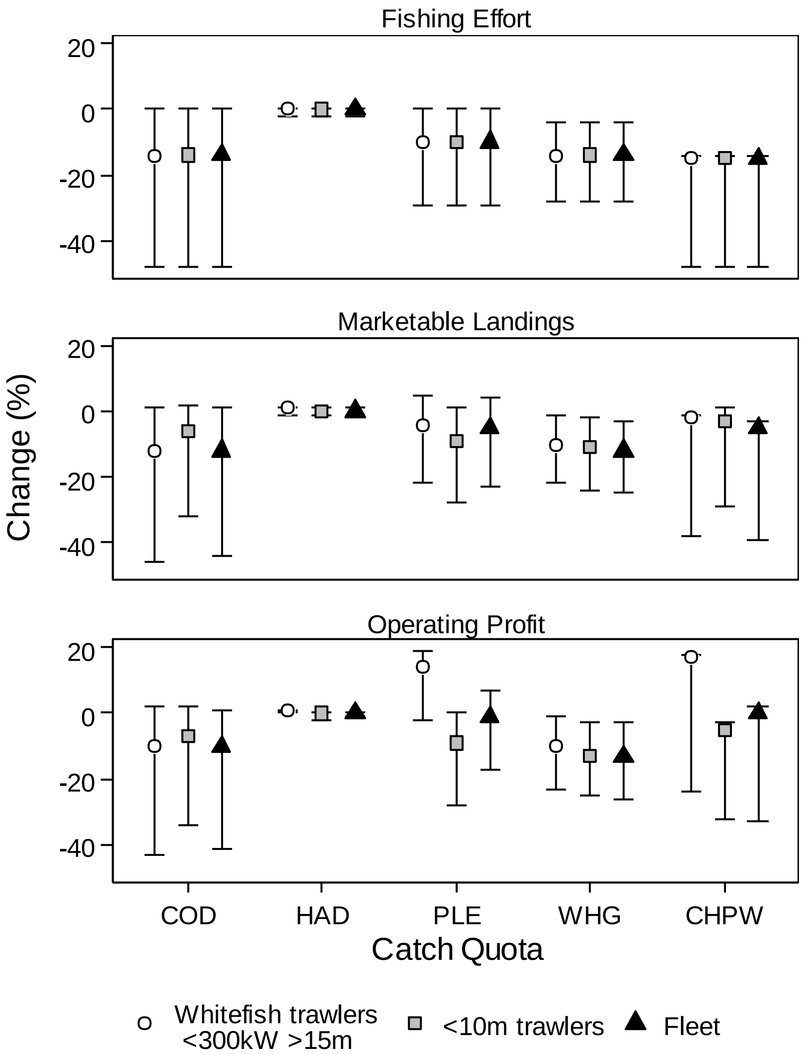

Figure 1 Fishing effort, marketable(>MLS) landings and operating profits of 2 English North Sea otter trawler segments and the fleet as a whole under a cod (COD), haddock (HAD), plaice (PLE), or whiting (WHG) catch quota, or a combination of all four (CHPW), compared to under the existing landings quotas of 2010, assuming no change in fishing behaviour. Segments are whitefish trawlers under 300kW and above 15m LOA (open circle), <10m vessels (grey square), and the fleet as a whole (filled triangle). Error bars show estimates derived using the lower (upper limit of error bars) and upper (lower limit of error bars) limits of the 95% confidence intervals of the mean discard and <MLS catch proportions.

Discards of haddock by the fleet were less than 75% of the ICES estimate, resulting in the catch quota exceeding the 2010 total catch of this species. Vessels would have benefited through landing >MLS haddock that would previously have been discarded, whilst maintaining other landings (Figure 1, Table S1 supplementary material, Appendix 8.2). Increases in operating profit would have been higher if effort had not been restricted to 2010 levels and fishers had been able to fully exploit the haddock catch quota.

Variations in the impact of catch quotas on the different vessel segments were apparent. For example, in 2010 <10m vessels discarded a higher percentage of plaice than whitefish vessels under 300kW in engine power and over 15m in length (Table 1). Under a plaice catch quota, landing the >MLS plaice that would previously have been discarded would have allowed <10m vessels to increase their marketable landings by 22%, compared with a 9% increase by these larger whitefish trawlers (Figure 1). However, <10m vessels saw a larger reduction in total marketable landings; plaice catches contributed only 3% of 2010 landings by weight (Table 1) and additional >MLS plaice catches would not have compensated for the reduction in other unregulated species, resulting in a 9% reduction in operating profits (Figure 1). Plaice was a more valuable species to the above whitefish trawlers, contributing 30% by weight of 2010 landings (Table 1). Although the percentage increases in marketable plaice would have been smaller than for <10m vessels, the additional catches would have partially compensated for the loss of other unregulated species, resulting in only a minimal reduction in total marketable landings. The large scale of plaice catches by this segment would have resulted in a high volume of <MLS plaice, relative to other segments; selling this catch for fishmeal would have compensated for the small reduction in total marketable landings, resulting in a 14% increase in operating profits (Figure 1).

The impact of discard and <MLS catch levels that differ from the mean values used here is examined by using the upper and lower limits of the 95% CI of estimated discard and <MLS proportions to calculate the total catches of each trip, as mentioned above. The lower limit of the error bars shows the impact of catch quotas if discard and <MLS catch proportions were *higher* than estimated. More discards results in a higher total catch per trip, reducing the level of effort that can be exerted before a catch quota is exhausted, with knock on effects on total marketable landings and operating profits, whilst a higher proportion of <MLS fish will reduce the value of the catch (Figure 1). The opposite occurs if discard and <MLS proportions are lower than estimated, and is shown by the upper limit of error bars (Figure 1). So, when discards or <MLS proportions are higher the impact of catch quotas are greater.

3.2 Behaviour scenario 2: adopting selective gear

Vessels adopting the more selective gear with the characteristics analysed would not have increased profits relative to the no behaviour change scenario, as operating with the more selective gear would have resulted in a reduction in the marketable landings of all species (Figure 2, Table S2 supplementary material, Appendix 8.2). The reduction in regulated catches by fishers using more selective gear would have left more of the catch quota(s) available for those vessels excluded from the selectivity changes, whitefish trawlers under selectivity changes 1 and 2 and *Nephrops* trawlers under change 3, resulting in an increase in marketable landings, and a subsequent rise in operating profits for these vessels (Figure 2, Table S2 supplementary material, Appendix 8.2). So the implementation of catch quotas does not create an incentive for vessels to adopt any of the selective gears investigated here. However, the lower limit of the error bars indicate that if discard proportions were higher than estimated whitefish trawlers would have benefitted through the adoption of more selective gear (selectivity change 3) under a catch quota for cod, implemented in isolation or in combination with others. Reducing the total catch of cod on each trip would have delayed the exhaustion of the cod catch quota, allowing whitefish trawlers to continue fishing for other species for longer, increasing total marketable landings and operating profits, relative to the no behaviour change scenario (Figure 2, Table S2 supplementary material, Appendix 8.2). So, dependent upon the regulated species and the vessels under management, catch quotas *would* incentivise the use of the more selective gear described in selectivity change 3 if discard proportions were higher than estimated.

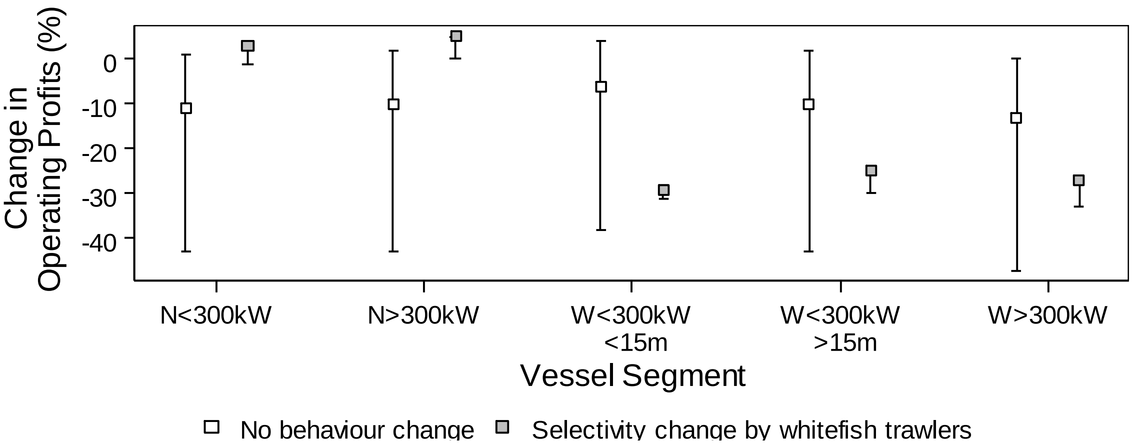

Figure 2 Percentage change in operating profits of some English North Sea otter trawler segments operating under a catch quota for cod, based on a scenario of no change in fishing behaviour (open square) or adoption of more selective gear by whitefish trawlers(closed square) (Selectivity change 3, Table 2), compared to under the existing landings quotas of 2010. Segments shown are *Nephrops* trawlers above (N>300kW) and below 300kW engine power (N<300kW), whitefish

trawlers under 300kW and above (W<300kW>15m) or below 15m in length (W<300kW<15m), and whitefish trawlers over 300kW. Other details as Figure 1.

3.3 Behaviour scenario 3:optimal combination of trips

Under single catch quotas the highest fleet operating profits were achieved when trips were ranked based on the level of <MLS catches (as described in Table 3). Trips with the highest <MLS catches were excluded. These were also trips with the highest total catches of the regulated species, so the total catch of the regulated species *per trip* was reduced, allowing a greater level of effort to be exerted before the catch quota was exhausted. This allowed fishing for other species to continue for longer resulting in higher total marketable landings by the fleet than under the no behaviour change scenario (Figure 3, Table S3 supplementary material, Appendix 8.2). Similarly, under a combination of catch quotas the optimum fleet operating profits were achieved when trips were ranked based on the scale of catches of the regulated species with the most constraining catch quotas and the level of <MLS catch. By excluding trips with the highest catches of regulated species more trips could be undertaken before any of the catch quotas were fully utilised. This allowed fishing for other species to continue for longer, with a subsequent rise in marketable landings and operating profits, compared to the no behaviour change scenario (Figure 3, Table S3 supplementary material, Appendix 8.2). Under all catch quota scenarios, fleet operating profits matched or exceeded the fleet operating profits generated under the 2010 landings quotas (Table S3 supplementary material, Appendix 8.2). But a reduction in operating profits was still incurred by some segments. However, this reduction was generally less than under the no behaviour change scenario. If discard proportions had been higher than estimated in reality, the benefits of excluding trips with the highest catches of the regulated species would have been much greater, as catch quotas would have been more constraining (Figures 3). So, catch quotas create a strong incentive for vessels to avoid both marketable and <MLS catches of regulated species; the more constraining the quota(s) the greater the incentive for more selective fishing.

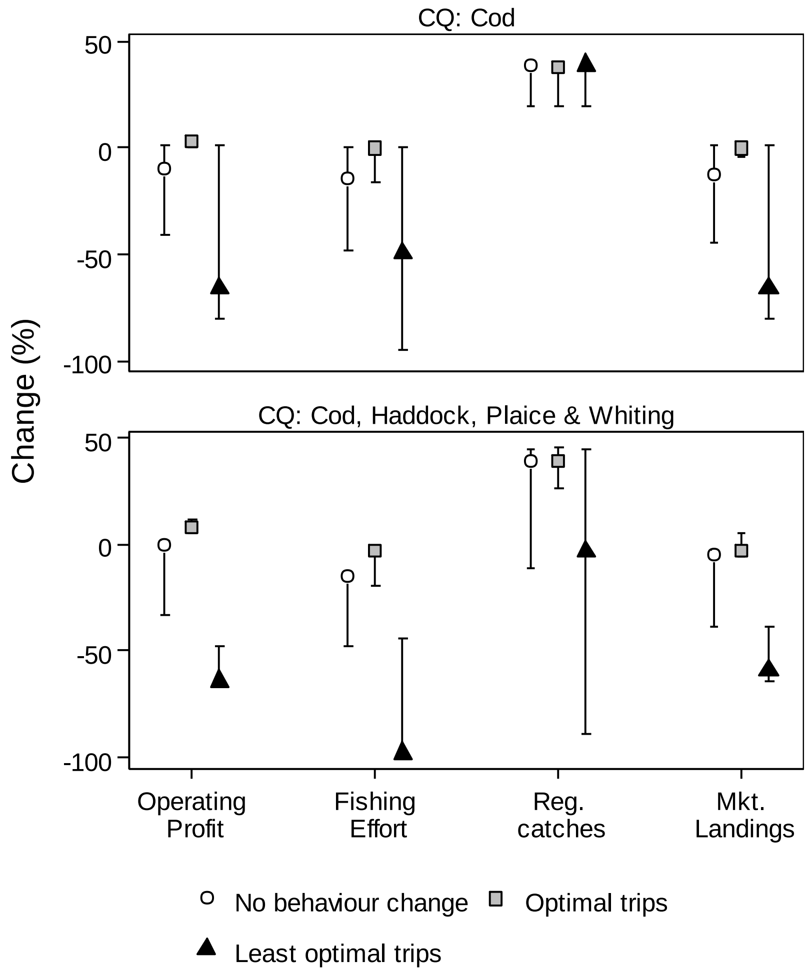

Figure 3 Percentage change in operating profits, fishing effort, regulated catches and marketable landings of the English North Sea otter trawler fleet when transitioning to a catch quota for cod, or a combination of catch quotas for cod, haddock, plaice and whiting, compared to under the existing landings quotas of 2010. Changes are based on the assumption of no change in fishing behaviour (open circle), an assumption that fishers will be able to select the trips that will maximise fleet operating profit (optimal trips, grey square, see Table 3), or the worst case scenario in which only trips that minimise fleet operating profits are selected (least optimal trips, closed triangle). Other details as Figure 1.

There may be some seasonality to the exclusion of trips. Under a combination of cod, haddock, plaice and whiting catch quotas, seasonal peaks in the exclusion of trips match peaks in catches of plaice and whiting. For *Nephrops* trawlers over 300kW in engine power operating under a combination of cod, haddock, plaice and whiting catch catches, the majority of excluded trips occurred in months where catches per trip of the most constraining species were highest (Figure 4).

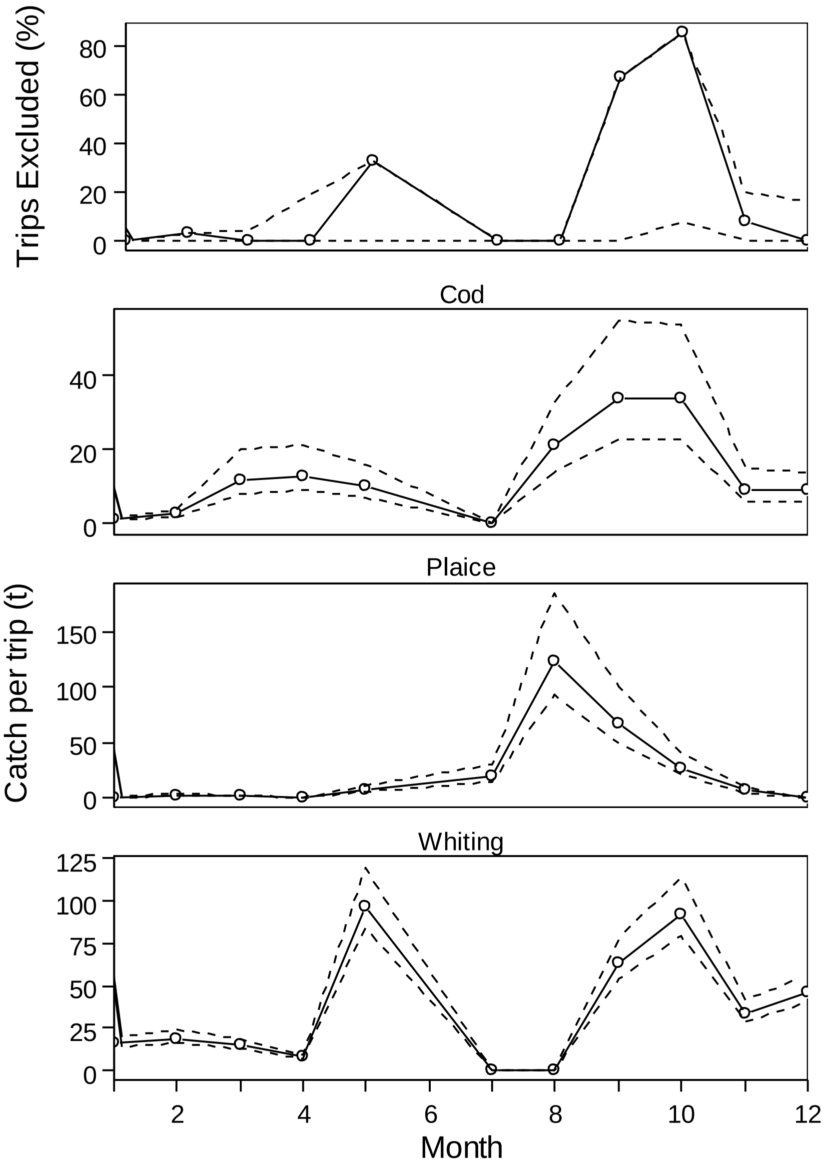

Figure 4 Seasonal variation in the percentage of trips undertaken by *Nephrops* trawlers over 300kW in engine power excluded from the optimal combination of trips that maximises fleet operating profit (Table 3) under a combination of cod, haddock, plaice and whiting catch quotas, based on the effort undertaken under 2010 landings quotas. Total catches of cod, plaice and

whiting per trip in the same months of 2010. Dashed lines represent propagation of the lower and upper limits of the 95% confidence intervals around the percentage of total regulated catch discarded and percentage of regulated catch <MLS.

3.4 Behaviour Scenario 4: least optimal trips

The least optimal trips scenario shows the impact of catch quotas if fishers were to adopt tactics that minimised fleet operating profits, providing a worst case scenario. Under all catch quotas the lowest fleet operating profit occurred when trips were ranked based on a combination of high catches of the regulated species, a high proportion of which was <MLS, and low catches of other marketable species (Figure 3), as described in Table 3. Fleet operating profits were reduced by as much as 82% compared to those achieved under existing landings quotas, much larger than the 13% reduction seen under the no behaviour change scenario. This confirms the finding of the optimal trips scenario, catch quotas generate strong incentives to minimise catches of the regulated species on individual trips. If discard proportions had been higher than estimated, fleet operating profits would have been reduced further as the total catch of trips would have been higher, reducing the level of effort that could have been exerted before the catch quota(s) was exhausted (Table S4 supplementary material, Appendix 8.2).

3.5 Fishing mortality

If the case study fleet alone had operated under and fully utilised a haddock catch quota total stock removals would have increased, but only by approximately 50t. Fishing mortality for this species would not have changed, assuming that the behaviour and catches of other fleets remained the same as in 2010 (Table 4). However if all fleets exploiting the North Sea haddock stock operated under a catch quota, stock fishing mortality would have been reduced. Under the assumptions of the model, the additional quota available will be limited to 75% of the stock discards and total removals would be capped at a lower level than 2010 catches. So, in contrast to the case study fleet, the catches of haddock by some or all other fleets exploiting the stock would have been reduced compared to 2010. The impact of cod, plaice and whiting catch quotas on the case study fleet would have been more severe; the 2010 catches of these species exceed the catch quotas and catches by the fleet would have been reduced, resulting in a reduction in the partial fishing mortality generated by vessels (Table 4). Once again, the reduction in total removals if all fleets exploiting these stocks had operated under a catch quota would have resulted in a reduction in fishing mortality (Table 4).

Table 4 Changes in stock fishing mortality under a catch quota based on catch quota weight and catch weight in 2010, assuming full utilisation of catch quota for the English North Sea otter trawlers or all fleets exploiting the stock. The total catch of the English North Sea otter trawlers is estimated from observer and logbook data. 2010 Fs and catch of all fleets are supplied by ICES (ICES, 2010).

		English North Sea otter trawlers			All Fleets		
Species	2010 F	CQ (t)	Catch (t)	Projected F	CQ TAC (t)	Catch (t)	Projected F
Cod	0.67	992	1 153	0.67	63 743	69 286	0.60
Haddock	0.23	807	753	0.23	37 262	39 640	0.21
Plaice	0.24	5 026	5 602	0.23	94 519	106 500	0.21
Whiting	0.27	1 087	1 272	0.27	29 499	31 600	0.25

4. Discussion

The results show that the short term economic impact of transitioning to catch quotas on the English North Sea otter trawler fleet in 2010 would have been dependent upon the species regulated, the level and composition of catches and discards, the scale of additional quota, and any change in fishing behaviour. Where discard proportions were lower than 75% of the ICES estimate the catch quota would have exceeded the existing catches of the fleet, allowing fishers to maintain their existing fishing effort and benefit through the landing of >MLS catch of the regulated species. In contrast, declines in operating profit would have occurred where fleet discard proportions were larger than 75% of the ICES estimate. Assuming no change in fishing behaviour, 2010 catches by the fleet would have exceeded the available catch quota, resulting in a decline in fishing effort. The greater the discrepancy between the estimates the greater the fall in operating profits. So, if the distribution of quota is uniform and no change in behaviour is observed, fleets that currently discard less than average will benefit through an increase in allowable catches, whilst high discarding fleets will see a curtailment of fishing and a fall in operating profits. If the uplift in quota is less than 75% of stock discards the impact on high discarding fleets will be more severe.

The impact of implementing catch quotas varied between fleet segments. If no change in behaviour occurred segments with higher discard proportions would have seen a greater percentage increase in marketable landings of the regulated species. However, for an increase in operating profits to occur, the larger regulated catches had to be sufficient to compensate for the loss of other valuable catches when fishing was curtailed. So, the impact of catch quotas on different fleet segments is likely to be determined by the scale and rate at which the regulated species are discarded by each segment, and the relative importance of those species to each segment.

By reducing catches of the regulated species vessels would have been able to delay the fulfilment of the catch quota(s), increasing fishing effort and operating profits. So a strong economic incentive is created for vessels to avoid both marketable and <MLS catches of regulated species. The more constraining a quota, the greater the incentive for more selective fishing. The incentive to avoid regulated catches also creates an incentive for non-compliance with the discard ban and full documentation of catches. Sufficient levels of surveillance and enforcement will be required to ensure that fishers do not avoid the economic burden of high regulated catches through illegal and unmonitored discarding. Assuming that compliance is high, fishers could reduce catches through the adoption of more selective gear. Such changes in fishing gear have been observed in vessels involved in catch quota pilot schemes (Course et al., 2011). However, the adoption of selective gear with the characteristics analysed here would not have been incentivised. This gear reduces catches of not only the regulated species, but also valuable unregulated species. Reductions in regulated catches would have delayed the fulfilment of the catch quota(s), allowing an increase in fishing effort, but, as marketable landings of all species were lower on each trip, a small increase in effort would not have resulted in an increase in operating profits, compared to the no behaviour change scenario. However, the incentive to adopt the more selective gear would have increased if discard proportions had been higher. If discards had been higher than estimated, the percentage reduction in regulated catches resulting from adopting more selective gear would have resulted in a greater reduction in the catch weight of regulated species than if discards had been at the lower level estimated by the mean. The larger reduction in catches would have delayed the exhaustion of the cod catch quota allowing more trips to be undertaken. With a much higher level of effort being exerted by vessels, cumulative marketable landings would have increased, compared to the no behaviour change scenario. In addition, implementing more selective gear may be more beneficial than suggested, the data used were derived from gear trials of experimental designs; encouraged by the economic benefit of reduced regulated catches, the fishing industry may be able to refine these gears to better match catches to their quota allocations. A lower catch per haul could also increase the value of catch (Wade et al., 2009) and reduce fuel costs (Campbell et al., 2010). Implementing other selective gear not explored in this study may be more beneficial for the fleet, provided that the retention of the regulated species is reduced and any fall in landings of other valuable species is minimal. More

selective fishing could also be implemented through a change in the timing of fishing trips, as suggested by the optimal trips scenario. Avoiding fishing during periods of high abundance of regulated species, particularly of species with the most constraining catch quotas, could help prolong the fishing season. Fishers have been observed avoiding fishing during periods of high abundance of <MLS cod when taking part in a UK cod catch quota trial (Course et al., 2011). Fishers have also been observed switching fishing grounds or target species during these periods (Course et al., 2011). As the current system provides little incentive for fishers to operate more selectively and does not make use of a fisher's technical ingenuity, it is unknown as to what extent in reality the selectivity of fishing could be improved to maximise revenue from allocated quotas.

Catch quotas should also reduce stock fishing mortality compared to under the existing landings quotas, dependent upon the accuracy of the stock discard estimates and the percentage of discards that can be allocated as additional quota. In this analysis the additional quota of which fleets receive a share is limited to 75% of the stock discards; fishing mortality would fall even if all fleets exploiting a stock were to fully utilise the catch quota TAC, as total catches are capped at a lower level than under the existing system of total allowable landings. If the additional quota was not limited, but instead all the TAC currently set aside to account for discards was allocated as quota, any change in fishing mortality would be dependent upon the accuracy of the estimated stock discards. If discard estimates are accurate catch quotas would match existing catches and fishing mortality should be maintained. If however discards were lower than estimated, full utilisation of a catch quota set in line with the TAC would result in an increase in catches, potentially resulting in a rise in the fishing mortality of the regulated stock.

5. Conclusions

Catch quotas in combination with a discard ban, are a management measure that could help realise the European Commission's aim of low discarding fisheries with minimal waste. Stock fishing mortalities will be capped, providing all fleets exploiting a stock operate under the catch quota and any uplift in quota is less than the previous stock discards. A long term economic benefit may result as reduced fishing mortality may aid the building of stocks, allowing larger quotas in the future (Sigler and Lunsford, 2001, Valdemarsen, 2003). Incentives for more selective fishing and the reduction of unwanted catches will be created, in line with the objectives of the reformed CFP. Reducing catches of the regulated species will delay the fulfilment of catch quotas, allowing continued fishing for other valuable species. This will be reliant upon the effective management of total catches. The initial economic impact of catch quotas, dependent upon the existing catch and discard characteristic of vessels and the uplift and distribution of additional quota, will determine the strength of the incentive. Fleets with high discards are more likely to see declining operating profits, particularly if the uplift in quota is small. Fishing could become unprofitable for some vessels, increasing the need for catches to be better aligned with the available quota and creating a strong incentive for more selective fishing. Adopting more selective gear could help to reduce unwanted catches. However, as highlighted in this study, the selective gears currently available may require refinement to improve their efficacy and economic performance. Catch quotas will provide the incentive and freedom for fisher-led development of such gears, but this will take time and economic investment. Fishers may have to find other means to improve selectivity, such as changing the timing of fishing trips, fishing grounds or target species. The ability and speed with which fishers can adapt and develop selective fishing techniques will ultimately determine what the economic impact of catch quotas is likely to be.

So catch quota management provides a simple and transparent framework in which fishers can be incentivised to develop more selective fishing practices, whilst also placing a cap on fishing mortality. Transitioning to such a system will not be without challenges, especially as the benefits of selective fishing practices are currently in debate. The initial setting and allocation of catch quotas will need to be carefully undertaken. The need for strong incentives for the improvement in practices by the least selective vessels must be balanced against the actual ability of fishers to rapidly refine and adopt more selective fishing methods, if catch quotas are not to drive some vessels out of business. Applying the model and scenarios constructed in this study to data from other fisheries will help predict the impacts of different catch quotas and resultant changes in fishing behaviour, and provide an indication of how additional quota could be appropriately set and distributed.

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Chapter 5.

Incentivising selective fishing under catch quotas: using an Fcube modelling approach to evaluate management options for North Sea mixed fisheries

Harriet M. Condie, Paul Dolder, Thomas L. Catchpole, Alastair Grant and Clara Ulrich

Abstract

Reforms of EU Common Fisheries Policy agreed in 2013 will make fundamental changes to European fisheries management. These include a discard ban, catch quotas for regulated species and management to achieve MSY. Here, the Fcube (Fleet and Fisheries Forecast) model is used to evaluate its impact on revenue and behaviour of North Sea demersal finfish fleets. With no change in behaviour, revenue is reduced by a mean of 19% compared to 2012, but with substantial variation between years, catch quota setting protocols and fleets. Revenue will reduce by 27% in the first year, rising to -9% in year 3, as fishing mortality is reduced and stocks rebuild. Impacts will be greatest if catch quotas are set equal to current landings quotas and reduce as the uplift allowed to reflect current discarding is increased. The greatest differences are between individual fleets, varying from -99% to +34% as a function of catch characteristics. The change depends upon whether the limiting species is a target and the rate at which it is caught relative to other species. Large reductions in revenue create a strong incentive to avoid catching the limiting species, particularly if it is not a primary target. A 30% reduction in the CPUE of cod increases revenue by up to 42% for fleets limited by this species. However, a change in selectivity may not prevent a decline in revenue for all fleets, and increased quota transfer, exemptions and substitutions will be important in maintaining the profitability of fishing.

Keywords: North Sea demersal fisheries, catch quotas, discard ban, selective fishing, cod.

1. Introduction

Eliminating discards and reducing unwanted catches by 2019 is a key objective of the reformed European Union's (EU) Common Fisheries Policy (CFP) (European Commission, 2013). These reforms will introduce a discard ban for regulated species combined with catch quotas, where total catches rather than just landings are documented and counted against an allocated quota (European Commission, 2013). Alongside this is a legally binding requirement to manage each fish stock in a way that achieves maximum sustainable yield (European Commission, 2013). At present, a total allowable catch (TAC) is set for regulated fish stocks to achieve a fishing mortality target. For some stocks a proportion of this TAC is set aside to account for discards, with the remainder being made available to the fishing fleet as landings quotas. If catches are fully documented, and estimated levels of discarding are accurate, then the same level of fishing mortality would be achieved by setting catch quotas equal to the quantity of discards plus existing landings quotas. Once this catch quota is exhausted, fishers must halt any activities that risk the capture of the regulated species within the designated fishing grounds (Course et al., 2011). Fish that are below the minimum landing size (MLS) must be returned to port, but cannot be sold for human consumption. This creates an incentive to reduce unwanted catches that would previously have been discarded. These catches now count towards the catch quota, so avoiding them will allow fishers to increase income by using a greater proportion of their quota on marketable catch. The potential incentives are even greater in mixed fisheries. Here, avoiding species where catch quotas are limiting allows fishing for other species to continue for longer (Condie et al., 2013b, Condie et al., 2013a). Pilot schemes have shown that catch quotas do indeed lead to changes in fishing behaviour, including avoidance of fish below MLS, reduced targeting of quota species (European Commission, 2013) and adoption of more selective gear and changes in the timing and location of fishing (Course et al., 2011).

Reliable estimates on the total annual catch from regulated stocks (landings plus discards) are required if fishing mortalities are to be maintained at current levels or reduced during this transition from landings quotas to catch quotas (Uhlmann et al., 2013). Fisheries observer programmes represent the most comprehensive source of information, but can be biased and may lack precision (Murawski, 1992, Cook, 2003, Rochet and Trenkel, 2005). This presents a problem. If *actual* discard rates differ from *estimated* rates the accuracy of stock assessments may be reduced (Alverson and Hughes, 1996, Branch et al., 2006) and the quotas set may not achieve the target fishing mortality in future years (Alverson et al., 1994). If catch quotas are set too high during the transition period, fishing mortalities could exceed management targets (Cotter, 2010, Chen et al., 2007, Cook, 2003). However, once catch quotas and a discard ban are introduced, the accuracy of catch data and stock assessments should improve as total catches will be fully documented, provided compliance is high (European Commission, 2002). To account for the uncertainty in discards data during the transition from landings quotas, catch quotas could be set at less than the estimated total catch, incorporating current landings quotas plus only a part of the estimated discards. However, the impact of the introduction of a discard ban combined with catch quotas, and the incentives for more selective fishing practices that this creates, could be dependent on the scale of this uplift in quota. Our previous work has shown that the strength of incentives and their distribution across fleet segments is substantially altered by the details of catch quota setting and distribution (Condie et al., 2013a, Condie et al., 2013b). When all vessels receive the same uplift, catch quotas create the strongest incentives for the least selective. Vessels discarding a high proportion of quota species benefit most from avoiding these regulated species and delaying the fulfilment of catch quotas. Avoiding <MLS fish also maximises the value of catch quotas (Condie et al., 2013a, Condie et al., 2013b). The incentive is strongest when the uplift in current landings quota is small in relation to total catch, particularly for vessels where the regulated species is not a primary target (Condie et al., 2013a).

Our previous work has examined the likely impact of the reformed CFP on the behaviour of a single North Sea fleet, without taking into account effects of changes in fishing activity on fish stocks in subsequent years. Here we extend this analysis to examine its impacts on the EU demersal fishery of the North Sea over the initial 3 years of implementation of the reformed CFP. Our analysis uses the Fcube (Fleet and Fisheries Forecast) model (Ulrich et al., 2011) to incorporate information on the population dynamics and current state of the most important commercial finfish stocks and data on the landings, discards, effort and revenue of 42 demersal fleets and technical interactions in the mixed fishery.

We estimate future catches and revenues for each fleet in the fishery under a range of possible catch quota protocols, allowing us to address four key questions:

1. What is the potential economic impact of transitioning to catch quotas if no change in fishing behaviour occurs?
2. Which catch quota protocol results in the highest revenue for fleets?
3. Are there relative economic winners and losers if no change in behaviour is made?
4. Will the modelled fleets be incentivised to change their behaviour and avoid catching "unwanted" fish, those that are undersized or with limited quotas?

2. Materials and Methods

2.1 Data

Data on EU North Sea fisheries, and their target fish stocks have been collated by the International Council for the Exploration of the Sea (ICES) working group on mixed fisheries (WGMIXFISH) (ICES, 2013c). Information is available on effort, capacity, catches, discards, landings and price of landings per tonne achieved by 42 different North Sea fleets between 2003 and 2012, encompassing 19 different metiers and 9 North Sea states. A fleet is defined as a group of vessels of the same length and using the same fishing gear for the majority of the year. A metier is defined as a group of vessels with a particular exploitation pattern, targeting similar species using similar gear in the same area and or during the same period (ICES, 2013c). A fleet may operate in multiple metiers during a year. This information is combined with biological data on the six most important target species of demersal finfish fisheries in the North Sea, namely cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), plaice (*Pleuronectes platessa*), saithe (*Pollachius virens*), sole (*Solea solea*) and whiting (*Merlangius merlangus*). Stock data were taken from the 2013 assessments by the ICES North Sea and Skagerrak working group (ICES, 2013d), and included time series of the total landings, discards, fishing mortality (F), stock size and spawning stock biomass (SSB), spanning decades. These stock and fleet data were converted into FLR (Fisheries Library for R, an open source framework that facilitates evaluation of fisheries management strategies) fleet and stock data objects (Kell et al., 2007) for input into FLR stock projection models and Fcube.

2.2 Fcube: projections of stocks, catches and revenues for 2012-2016

Fcube (described in detail by Ulrich et al, 2011) estimates the potential level of effort that could be exerted by each fleet in future years based on the available fishing opportunities (TACs and target fishing mortalities), the relative distribution of effort between a fleet's metiers and estimates of the past catchabilities of those metiers (Box 1). Here, Fcube was used to forecast fishing effort under different catch quota protocols, allowing evaluation of the potential change in fleet landings and revenue between 2012 and 2016 (Box 1). A summary of our assumptions is presented in Table 1. The fishing opportunities were defined by catch quotas, which were assumed to come into force in 2014. In reality, catch quotas may not be implemented in the North Sea until 2016 (European Commission, 2013). However, assuming that all catch quotas are introduced from 2014 allows their longer term impacts to be evaluated using a recent year of actual, rather than projected, fisheries data (2012). The catch quotas for each year were calculated by a FLR short-term stock forecasting model based on the total removals needed to achieve a target F for each stock in the following year. These in turn were defined by the long term management plan for each stock (European Commission, 2007, European Commission, 2008, ICES, 2013b). The proportion of target removals included in catch quotas were defined using the protocols described in section 2.3. 100 replicate projections were carried out, with values of recruitment drawn randomly from a normal distribution with the same mean and variance as in the historical data. Constant catchability was assumed in each year of all projections. It was also assumed that all fishers would fully comply with the discard ban modelled to come into force in 2014. The landings selectivity of each stock and fleet object, a measure of the proportion of catch that is landed rather than being discarded, was altered from 2014 onwards to reflect the assumption that all catch would be landed. Full documentation of catches was also assumed, so total catches will not exceed the catch quota.

Box 1 Summary of the modelling process using FLR projections (1-3, 9) and Fcube (4-8)

1. Target F is defined by the long term management plans for each stock. FLR short- term stock forecasting model uses stock data to estimate the level of catch (landings and discards) that would achieve a target F for each stock in the following year.

2. The catch quota is set based on the landings quota plus an uplift defined in the catch quota setting protocol described in Table 2.

3. The actual F of each stock is projected for the following year based on the catch quota for each species being achieved.

4. Fcube then uses the projected F of each stock, $F_{y+1\,s}$, and calculates each fleet's share of that F, F_{y+1sf}, based on the proportion of landings from each stock, $L_{y\text{-}1\,s}$ landed by the fleet, $L_{y\text{-}1\,sf}$ in a previous year, y-1. The discards of each fleet were not taken into account in this calculation. This results in a partial F for each stock by each fleet if the fleet were to fully utilise its share of the catch quota for each species.

$$F_{y+1\,sf} = \left(\frac{L_{y-1\,sf}}{L_{y-1\,s}} \times F_{y+1\,s}\right) \tag{1}$$

5. Fcube calculates the catchability of each stock for each fleet in the future year, $q_{y+1\text{sf}}$, based on the sum of the catchability of each metier, m, q_{y+1sfm}, and a metier's landing selectivity for each stock, l_{y+1sfm} relative to the amount of effort a fleet spends in each metier, e_{y+1fm};

$$q_{y+1\,sf} = \sum_{m} e_{y+1\,fm} \times \left(q_{y+1\,sfm} \times l_{y+1\,sfm}\right) \tag{2}$$

6. Using the partial F of each fleet calculated in equation 1 and the catchability of each fleet (equation 2), Fcube calculates the level of effort each fleet could exert if they were to fulfil their share of the catch quota for each stock, E_{y+1sf}:

$$E_{y+1\,sf} = F_{y+1\,sf} \div q_{y+1\,sf} \tag{3}$$

7. Under catch quotas a fleet must stop fishing if any of its quota allocations are exhausted, so Fcube calculates the level of effort each fleet could exert before any one of its six quota allocations are exhausted, $E_{y+1\,f}$;

$$E_{y+1\,f} = \min\left(E_{cod\,y+1f}, E_{haddock\,y+1f}, E_{plaice\,y+1f}, E_{saithe\,y+1f}, E_{sole\,y+1f}, E_{whiting\,y+1f}\right) \tag{4}$$

8. Fcube then calculates the partial F by each metier for each stock that results from this level of effort;

$$F_{y+1\,sfm} = \left(q_{y+1\,sfm} \times l_{y+1\,sfm}\right) \times \left(E_{y+1\,f} \times e_{y+1\,fm}\right) \tag{5}$$

9. The sum of partial Fs by stocks gives a new F for each species which is then used to estimate stock catches using the Baranov catch equation, implemented using the fwd procedure in FLR (Kell et al., 2007). Landings and revenue of each individual fleet can then be calculated (section 2.5).

Table 1 A summary of all assumptions made by Fcube and under the catch quota setting protocols and selectivity scenarios.

Assumptions in model projections

Assumptions of Fcube

- The share of the effort exerted by each fleet in a metier will be constant in all years of projections based on the effort shares of 2012.
- Recruitment for each year of a projection is a random variable drawn from a distribution with the same mean and variance as the historic recruitment of each stock.
- Catchability is constant in all years of the projections.
- Full compliance with the discard ban, all catches are landed.
- All catches are documented; total catches cannot exceed catch quotas unless defined overages are permitted.

Assumptions of catch quota setting protocols

- Catch quotas will be set for all six stocks.
- Catch quotas calculated in the forecast model under each catch quota setting protocol will be implemented without any change, for example from political negotiations.
- A uniform percentage of quota uplift will apply to all stocks.
- The proportion of catch quota allocated to fleets will be based on their past landings.
- This distribution of quota between fleets assumes that the level of quota transfer is constant in all years of the projections, and is equal to that of 2012.
- Catch quotas will apply to all fleets without exemptions.
- A 10% overage will only apply to the cod catch quota.
- Substitutions are not available; catches of each species may only be counted against the quota for that stock.

Assumptions of selectivity scenarios

- The catches of other species are not affected by any changes in selectivity towards cod.
- All fleets will adopt the behaviour described in each scenario.

Assumptions in estimating revenue

- All >MLS catch will achieve the same market value.
- Market values will not be affected by any change in supply, prices will be constant and equal to those achieved in 2012
- All <MLS catch will acquire a value of €93 independent of the size, species and quality of catch, and the fleet in which it is caught.

2.3 Catch quota setting protocols

Deterministic short-term stock forecasting models were used in each year of a projection to predict the total catch that would achieve a defined target fishing mortality for the following year. The target fishing mortalities were calculated in line with the existing long term management plans for each of the 6 stocks (European Commission, 2007, European Commission, 2008, ICES, 2013b). These plans detail how the annual TACs of a stock should be set, and if these should be supported by technical measures (Kraak et al., 2013). For example, the plan for cod (Council Regulation (EC) No 1342/2008) determines fishing effort for each year and changes in the TAC. These are based on the actual F level relative to a long term target of 0.4 and a comparison of predicted SSB for the beginning of the year in which the TAC will apply with defined reference targets (B_{pa} and B_{lim}) (European Commission, 2008). B_{lim} is defined as the SSB below which reproduction and recruitment may be reduced; B_{pa} is a precautionary reference that is larger than B_{lim} and is used as target for managers to account for uncertainty in data (ICES, 2013a). The management plans also include constraints that prevent dramatic changes in the size of the TAC relative to the previous year. For example, the TAC for cod cannot vary by more than 20% from that in the previous year (European Commission, 2008). These constraints were applied to the catch quotas.

Currently, the TAC recommended by ICES is set equal to the landings component of the total catch predicted to give the target F in the forecasting models. Consequently, TACs are actually landings quotas, rather than being the restriction on catch that the term implies. So, in the first year of the projections, catch quotas were set by increasing the landings quotas with a defined uplift to account for discards. The uplift that should be used in the first year of transition has not been defined in the CFP reforms. However, recent Danish and English cod catch quota pilot schemes have taken a conservative approach to deal with the possibility that there may be inaccuracies in existing catch or discards data. Catch quotas were limited to a 30% increase above existing landings quota (Dalskov et al., 2011, MMO, 2012) and the additional quota could not exceed 75% of the predicted discards (MMO, 2012). We used these examples in our protocols separately; the 30%c protocol described in Table 2 increases the 2014 landings quotas projected by the stock forecasting model by 30%, whilst the 75% protocol uplifts 2014 landings quotas by 75% of the estimated discards. We also examined the impact of two more extreme protocols. 0% where no uplift in landings quota is applied and 100% with an uplift equal to predicted 2014 discards (Table 2). Individual projections were performed for each of the protocols with the same level of uplift applied for all six species. Stock assessments for saithe and sole do not include discard data, so the 2014 catch quotas for these stocks were set at the same level under the 0%, 75% and 100% protocols. The different uplifts only apply in the first year of management. In subsequent years the total catch of vessels will be fully documented. So in 2015 and 2016 catch quotas were set so that total removals estimated from the TAC constraints combined with the estimated SSBs achieved the target Fs generated by the management plans. The same values of recruitment were used when comparing the results of projections across different protocol or behaviour scenarios to ensure the results were comparable.

Table 2 Catch quota setting protocols evaluated in the Fcube model. Under each protocol catch quotas are set at a defined level of the total removals estimated in the stock forecast model. In 2015 and 2016 catch quotas will be set equal to the total removals estimated in the stock forecasting models as the uncertainty in catch data will be reduced.

Protocol	2014 catch quota level
0%	Catch quotas are based on the estimated landings only: Landings quotas + 0% of estimated discards
75%	Catch quotas are based on landings and 75% of estimated discards: Landings quotas + 75% of estimated discards
100%	Catch quotas are based on the estimated total removals in the forecast model: Landings quotas + 100% of estimated discards
30%c	Catch quotas are set at 30% higher than the estimated landings: Landings quotas + 30% of landings quotas

Under the reformed CFP, 10% overages of quotas will be allowed but will be subtracted from the catch quota in the following year (European Commission, 2013). Each projection was repeated based on the assumption that fishers would fully utilise a 10% overage of cod in each year, and that this overage would be deducted for the cod catch quota in the following year. The 10% overage was applied only to cod as previous studies have indicated that cod catch quotas will be the most limiting (Condie et al., 2013b, Condie et al., 2013a). Other flexibilities in catch quotas have been included in the CFP reforms but were not investigated here. These include *de minimis* exemptions for certain fleets or exemptions for catch with high discard survival rates, and the ability to offset up to 9% of one catch quota against another.

2.4 Selectivity scenarios

Fish that are under minimum landing size cannot be sold for human consumption (European Commission, 2013), so improvements in selectivity of fishing that reduce catches of <MLS fish will increase profits. Where a quota allocation for one species is exhausted before allocations for others are fully utilised, profits can be increased by reducing catches of the limiting species. Such changes in fishing behaviour can be simulated within FLR/Fcube by setting the landings selectivity for a species to <1 while setting discards selectivity at 0. This produces a reduction in the CPUE of the species for which these parameters have been altered without altering the catches of other species. Landings selectivities of fleet objects were altered between 2014 and 2016 to reflect the following changes behaviour and selectivity;

i) ***No change in fishing selectivity*** - fishers make no attempt to alter how they fish. Landings selectivities are set to 1.

ii) ***Avoidance of all undersized catch*** - fishers alter how they operate to avoid all catches of <MLS fish. Landings selectivities are reduced by the proportion of catch estimated to be below MLS for each species. The proportion of catch estimated to be below <MLS was estimated through the following process; i) survey data were used to generate an Age-Length Key (ALK) for each species; ii) as catch-at-age was not available in the fleet data collected by ICES (section 2.1), this was approximated by using catch-at-age data for the same metier definitions as used in the model in the STECF catch database (STECF, 2013); then, iii) the ALK was used to allocate the numbers-at-age discarded into <MLS and >MLS based on the proportion of fish at a particular age above or below the MLS for that species; iv) length-weight relationships were then used to raise number-at-age to weight-at-age and the proportion of catch >MLS and <MLS approximated as the sum of the weight-at-age in each category across all ages. The proportion of catch <MLS was calculated for each species, metier, area, and member state.

iii) ***Avoidance of all undersized cod catch*** - fishers alter how they operate to avoid all catches of <MLS cod. Landings selectivities for cod were reduced by the proportion of the cod catch estimated to be below MLS; landings selectivities for the other five species were set to 1. As in section 2.3, cod was chosen as previous studies have indicated that cod catch quotas will be the most limiting (Condie et al., 2013b, Condie et al., 2013a).

iv) ***30% reduction in cod catches per unit of effort -*** fishers adopt selective practices to reduce the capture of cod including all <MLS catch by 30%; cod landing selectivities are set to 0.7, landings selectivities for the other five species were set to 1.

The knife-edged selectivity described in scenarios ii) and iii), where 100% of <MLS catch of all species or cod only is avoided is unlikely to be achievable, however, these scenarios give an indication of the strongest possible incentive to reduce catches of undersized fish. Under scenarios iii) and iv) it was assumed that the selectivity of fishing for other species was unaffected. The behaviour described in each scenario was also assumed to be adopted by all fleets included in the projections. The impact of each of the selectivity scenarios was assessed separately and a projection was performed for each, resulting in 32 projections in total, each with 100 replicates (Figure 1). The revenue generated from the six stocks by each fleet under scenarios ii) to iv) were compared with those estimated under scenario i) providing an indication of how each change in selectivity may or may not benefit each fleet in the model.

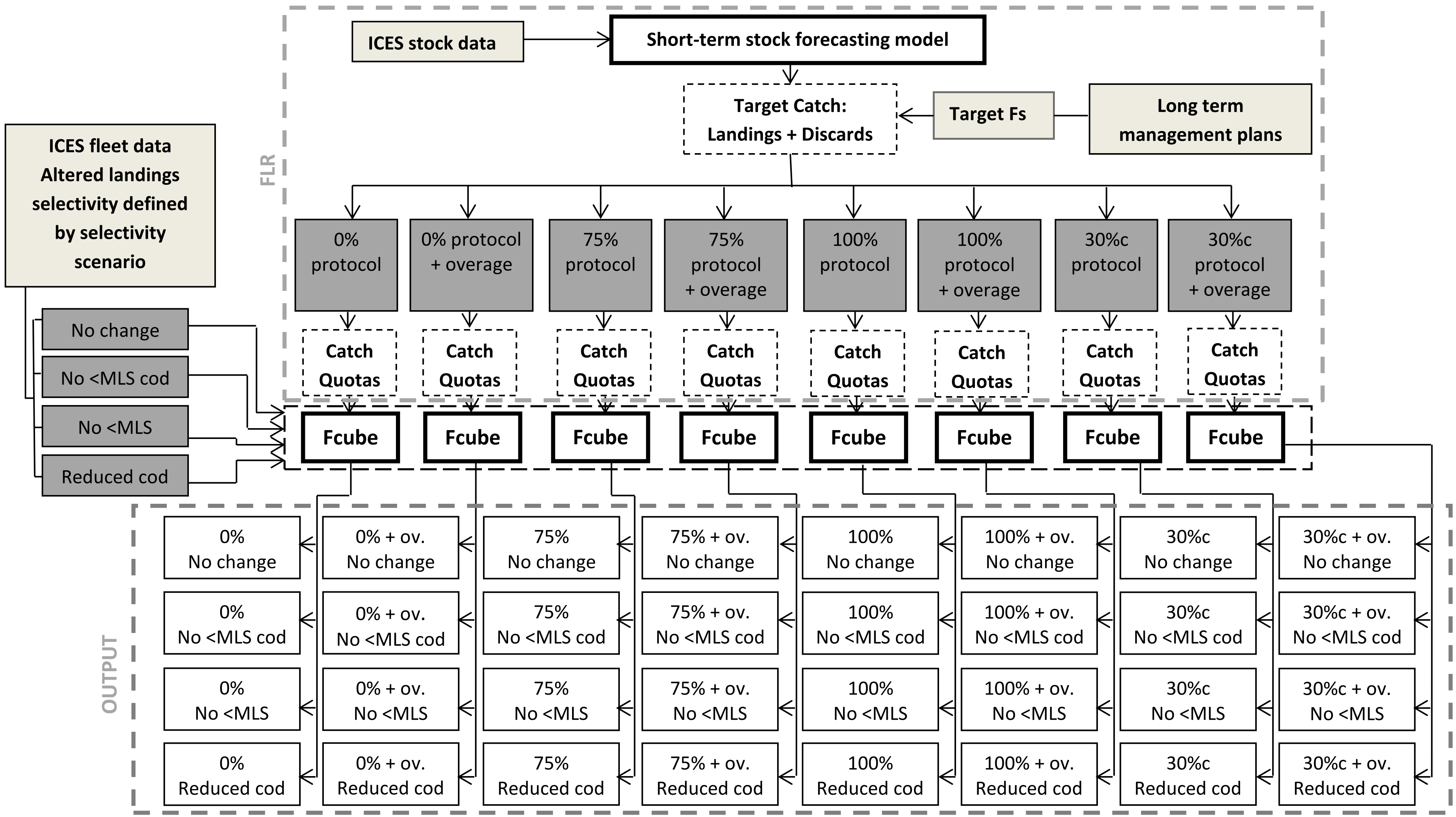

Figure 1. 32 projections using FLR forecasting models and Fcube were performed, each with a different protocol and selectivity scenario.

2.5 Fleet landings and revenues

The landings of each fleet were estimated from the projected total catch of each stock based on the partial fishing mortality generated by each fleet compared to the partial fishing mortality of all fleets;

$$C_{sf} = C_s \times F_{sf}/F_s$$

C_s is the total catch of a species s, F_{sf} and F_s are the partial fishing mortality of the fleet, f, and all fleets for that species, respectively, giving the catch of each species by each fleet, denoted by C_{sf}. Under selectivity scenarios i) and iii), no change in selectivity and avoidance of <MLS cod, fleet landings were divided into catch above or below MLS. The revenue generated from the >MLS, marketable landings was estimated using the data on the price of catch per tonne in 2011, included in the fleet objects. Full 2012 price information was not available, but prices have remained relatively stable in previous years. It was assumed that prices would remain the same in 2014-2016, and that any changes in supply would not affect prices. Price information was only available for 35 of the 42 fleets included in the model, and the analysis in section 3 is focused on these fleets. Under the CFP reforms the unmarketable landings cannot be sold for human consumption, but can be used as a raw material for production of other goods such as fish meal (European Commission, 2012). So, the revenue generated by <MLS landings was calculated based on a value of €93 per tonne, based on the mean of an estimate supplied by a British industrial fish meal plant of £60-£100 pounds per tonne. It was assumed that a similar value would be obtained by fleets in other states, and that this value was independent of the species, size and quality of unmarketable catch. The cost of processing and landing catch was not included in the estimated revenues.

3. Results

3.1 What is the potential economic impact of transitioning to catch quotas if no change in fishing behaviour occurs?

Taken over all fleets, protocols and years, a transition to catch quotas results in a median 19% reduction in the fleet revenue generated from the six stocks, compared to 2012. This reduction in revenue is not only due to the transition to catch quotas. For example, the management plan for cod requires a reduction in F. In 2014 the target F for cod is 0.22, compared to an actual F of 0.39 in 2012. This reduction in the target F would require a smaller cod TAC to be set in 2014 even if catch quotas were not introduced. Catch quotas set under the 0% protocol are set equal to estimated landings quotas, providing an indication of how TACs may have changed between 2012 and 2014 if catch quotas had not been introduced. The 2014 cod catch quota set under the 0% protocol is 5% smaller than cod landings in 2012, so the modelled fleets would have incurred a reduction in cod landings and revenue even if catch quotas had not been introduced.

A three way analysis of variance shows that the effects of fleet, protocol, year and all two way interactions between them are significant (Table 3). Only the three way interaction between the factors is not significant. The pooled standard error of the mean revenue change for each combination of fleet, scenario and year is 1.5%, so even rather small effects will be statistically significant. These factors and their interactions explain 81% of the variance in the results. Most of the variance (69%) is between fleets, a smaller amount is between protocols and between years (5% each) while the interactions between factors each account for less than 1% of the variation. We therefore focus on the differences between fleets, protocols and years, knowing that the marginal means for each level of these factors capture the most important features of the data, but will comment briefly on the largest components of the two-way interactions.

Table 3 ANOVA of the percentage change in revenue of the modelled North Sea demersal finfish fleets versus projection year, catch quota protocol and fleet.

Source	Sum of Squares	df	Mean Square	F	Sig.	Eta Squared
Corrected Model	82,884,050	839	98,789	426	0.00	0.81
Year	4,753,080	2	2,376,540	10,251	0.00	0.05
Fleet	70,594,461	34	2,076,308	8,956	0.00	0.69
Protocol	5,473,339	7	781,906	3,373	0.00	0.05
Year * Fleet	968,958	68	14,249	61	0.00	0.01
Year * Protocol	141,844	14	10,132	44	0.00	0.00
Fleet * Protocol	894,988	238	3,760	16	0.00	0.01
Year * Fleet * Protocol	57,379	476	121	0.5	1.00	0.00
Error	19,279,714	83,160	232			
Total	102,163,764	83,999				

a. R Squared = 0.811 (Adjusted R Squared = 0.809)

The greatest reduction in revenues (-27%) is in 2014, decreasing to -20% in 2015 and -9% in 2016 (Figure 2). This improvement in revenue over time is due to the impact of catch quotas on the F and SSB of the six stocks. Full documentation of catches results in the total F being capped at the level defined by the management plan. In addition, current landings quotas are set based on a target F assuming that fleets will discard catch at an estimated rate. However, under catch quotas no discarding occurs, so if the uplift applied to the landings quota in 2014 is less than current discards, the target F is undershot (Table S1). The target F of each stock can only be achieved if the landings quota is uplifted by 100% of the discards, and the resulting catch quota is fully utilised. However, none of the catch quotas set in 2014-2016 are fully utilised (Table S1), as not all fleets are limited by quota allocations for the same species. Consequently, fishing mortality is reduced well below 2012 levels and the target defined by the management plan for each stock. By 2016 the fishing mortality of all stocks will be below the F_{MSY} values, which are 0.19 for cod, 0.3 for haddock and saithe, 0.25 for plaice, and 0.22 for sole (Table S1). A lower F in 2014-2016 allows the SSB of stocks to increase, which allows progressively larger catch quotas to be set for cod, plaice and whiting, the three species which limit fleets if no change in behaviour occurs (Table S1). The cod catch quota increases from >39,600 t in 2014 to >57,000 t in 2016 under the 30%c protocol. Similarly, the plaice catch quota increases from >145,000 t in 2014 to >190,000 t in 2016, whilst the whiting catch quota increases form >37,000 t in 2014 to >49,000 t in 2016. A larger catch quota results in a larger quota allocation for fleets, leading to revenue increases from increased landings of the limiting species (Table S2).

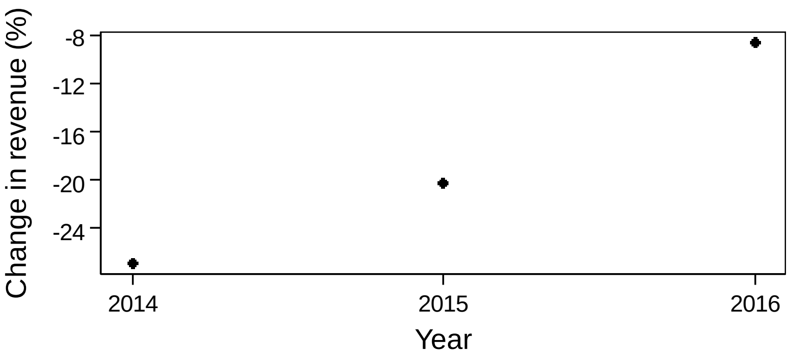

Figure 2 Mean percentage change in the revenue compared to 2012 of modelled North Sea demersal finfish fleets in 2014-2016 after transitioning to catch quota management, across all catch quota protocols. The pooled standard error is ± 0.1, so is not plotted.

Not all fleets will see the same trend in the increase in revenue between years, as indicated by the small but significant interaction between year and fleet (Table 3 and Figure 3). The increases of SSB in 2015 and 2016 results in higher CPUE for all species (Table S2). Fleets may potentially also see an increase in catches of non-limiting species. The largest relative increase in SSB is for cod and saithe (Table S1). So fleets will see relatively large increases in the CPUE of these species compared to 2014 (Table S2). Fleets limited by cod will see increased landings of both cod and saithe. If cod and saithe are target species, fleets could see a larger than average increase in revenue between 2014 and 2015 (Table S2). For example the increase in revenue of the Norwegian (NO) static fleet between 2014 and 2015 is slightly larger than the average for most fleets, increasing from a mean value of -1% in 2014 across all protocols, to an increase of 12% in 2015 (Figure 2). The Danish (DK) beam trawl fleet, the English (EN) beam, and 24-40m and 40m and over otter trawler fleets, the Belgian (BE) otter trawler fleet, and the German (GE) <24m otter and >24m beam trawl fleets do not see a large year on year increase in revenue (Figure 2). The limiting species of each of these fleets, cod or whiting, are not target species, so even a large percentage increase in landings of these species in 2015 and 2016 would only result in a small increase in revenue at best. The target species of these fleets is plaice, which contributed 81-99% of landings in 2012 (Table S2). The plaice stock gains only a relatively small increase in SSB in 2015 and 2016 (Table S1), and the increase in the CPUE is relatively small (Table S2). Moreover, although the cod and whiting quota allocations increase in size in 2015 and 2016, the increase in the CPUE of these species in these years means that the quota allocations will be utilised by a lower level of effort than in 2014. The lower level of effort combined with the relatively small increase in the CPUE of plaice results in fleets achieving only a small increase in plaice landings at best in 2015 and 2016, compared to 2014 (Table S2). Consequently the increase in revenue will be minimal between 2014 and 2016 (Figure 3).

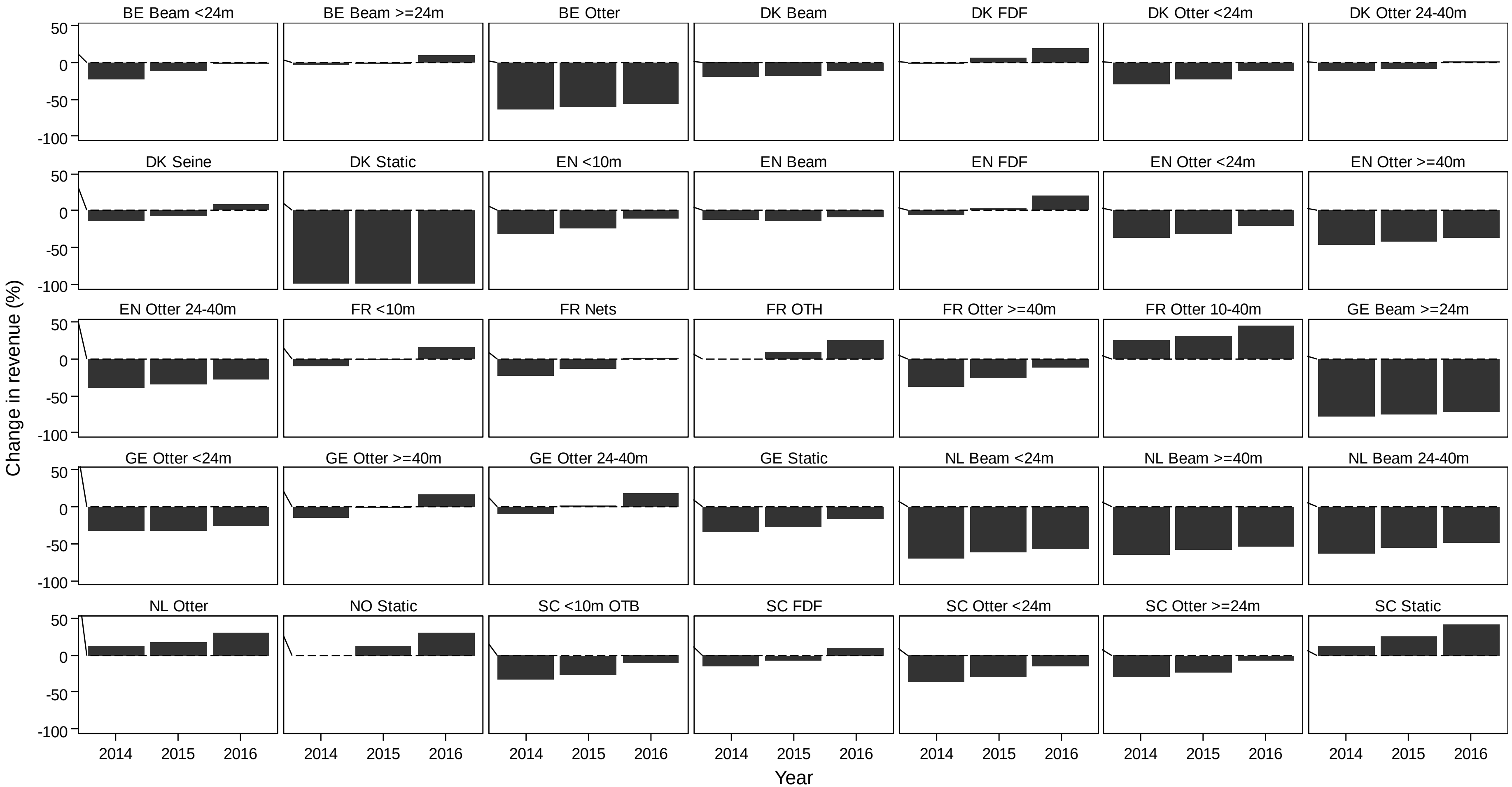

Figure 3 The mean percentage change in revenue of each of the modelled North Sea demersal finfish fleets operating across all protocols in 3 projected years, 2014-2016, compared to the revenue achieved in 2012 under landings quotas. The pooled standard error is small, ±0.5% and so is not plotted.

3.2 Which catch quota protocol results in the highest revenue for fleets?

Marginal means show that the 0% protocol with no cod overage results in a 33% reduction in average fleet revenue. The 75% protocol results in a much smaller reduction of 20% whilst the 100% and 30%c protocols result in 16% and 12% reductions respectively (Figure 4). So, not surprisingly, the larger uplift in quota under the 30%c and 100% protocol results in higher revenue for fleets relative to the other protocols.

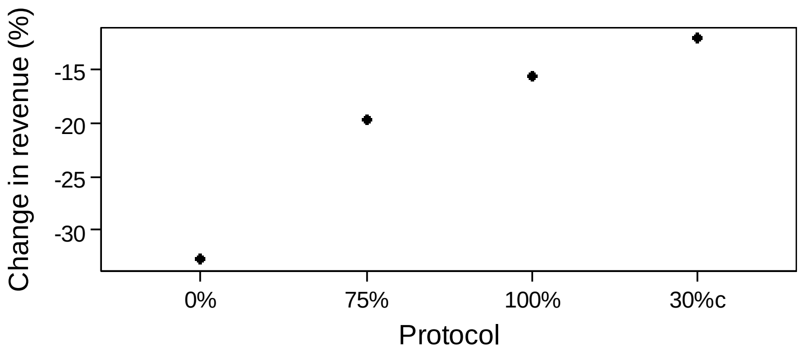

Figure 4 Mean percentage change in the revenue of all modelled North Sea demersal finfish fleets across 2014-2016 compared to 2012 under 4 different catch quota setting protocols with no cod overage allowed. The pooled standard error is only ± 0.1, so is not plotted.

The smaller reduction in revenue under the 30%c protocol with no cod overage is a consequence of the vast majority of fleets (27 out of 35) being limited by their cod quota allocations. The 30%c protocol results in the largest catch quota for cod, and thus the highest revenues for these fleets (Figure 5). A 30% increase in the cod landings quota exceeds estimated cod discards for 2014, so the 30% protocol results in a larger catch quota in 2014 than either the 75% or 100% protocols (see section 2.3, Figure 5). The larger quota allocations allow fishing to continue for longer in 2014, resulting in higher fleet revenues. The cod catch quota continues to be largest under the 30%c protocol in 2015 and 2016 (Figure 4). This is a result of the influence of the cod management plan. The relatively large catch quota in 2014 results in a higher F and smaller estimated cod SSB at the beginning of 2015 and 2016 than under the other protocols (Table S1). However the larger cod SSBs generated under the other protocols cannot result in a larger cod catch quota being set as the cod management plan (European Commission, 2008) prevents the catch quota changing by more than 20% relative to the previous year (Figure 5). If this constraint were not applied the cod catch quota would be smallest under the 30%c protocol in 2015 and 2016 and largest under the 0% protocol, as the latter results in larger SSB and lower F (Figure 5, Table S1). Moreover, the cod catch quota would be substantially larger in 2016 under all protocols if the constraints were removed (Figure 5). So, the impact of different catch quota setting protocols and catch quotas themselves will be heavily influenced by the quota constraints under management plan of each stock.

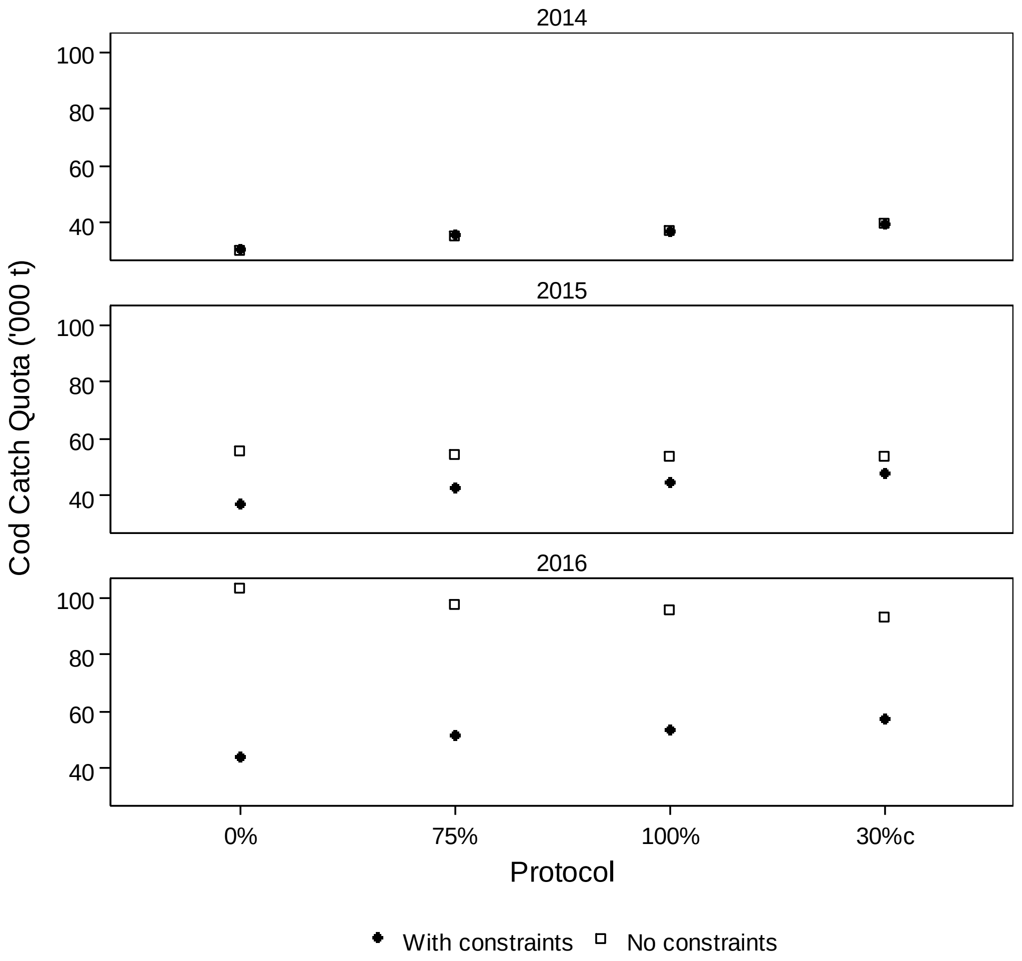

Figure 5 The size of the cod catch quota under 4 different catch quota setting protocols when no cod overage allowed, if existing constraints on change in quota size within the cod management plan are continued under catch quota management (closed diamonds) or removed (open squares).

For 7 fleets the 30%c protocol does not result in the highest revenues (Table 4). These fleets are the Dutch <24m, 24-40m, and 40m and over beam trawl fleets, the English 24-40m and 40m and over otter trawler fleets, the German >24m beam trawl fleet and the Danish static fleet. These fleets are all limited by whiting and revenues are highest under the 100% protocol. This protocol results in the largest whiting catch quotas being set in 2014 (Figure 6), as estimated discards of whiting exceed a 30% increase in the whiting landings quotas. The 100% protocol continues to result in the highest catch quotas being set in 2015 and 2016 (Figure 6) due to the whiting management plan limiting the year-on-year change in quota size to 15% (ICES, 2013a). As above, if the constraint was removed the whiting catch quota would be largest under the 0% protocol in 2015 and 2016 (Figure 6, Table S1).

Table 4 The mean percentage change in revenue across 2014-2016 of 7 of the modelled North Sea demersal finfish fleets which are limited by their whiting allocations compared to the revenue achieved in 2012 under landings quotas, based on if a 10% cod overage is allowed (+ ov.) or not allowed (- ov.) under 4 different catch quota setting protocol; 0%, 75%, 100% and 30%c.

	Change in revenue (%)							
	0%		75%		100%		30%c	
Fleet	- ov.	+ ov.	- ov.	+ ov.	- ov.	+ ov.	- ov.	+ ov.
DK Static	-99	-99	-98	-98	-98	-98	-98	-98
EN Otter >=40m	-55	-55	-37	-37	-32	-32	-41	-41
EN Otter 24-40m	-48	-48	-30	-29	-24	-24	-33	-33
GE Beam >=24m	-81	-81	-73	-73	-71	-71	-75	-75
NL Beam <24m	-72	-72	-60	-60	-57	-57	-63	-63
NL Beam >=40m	-69	-69	-56	-56	-52	-53	-59	-59
NL Beam 24-40m	-66	-66	-52	-52	-48	-48	-56	-56

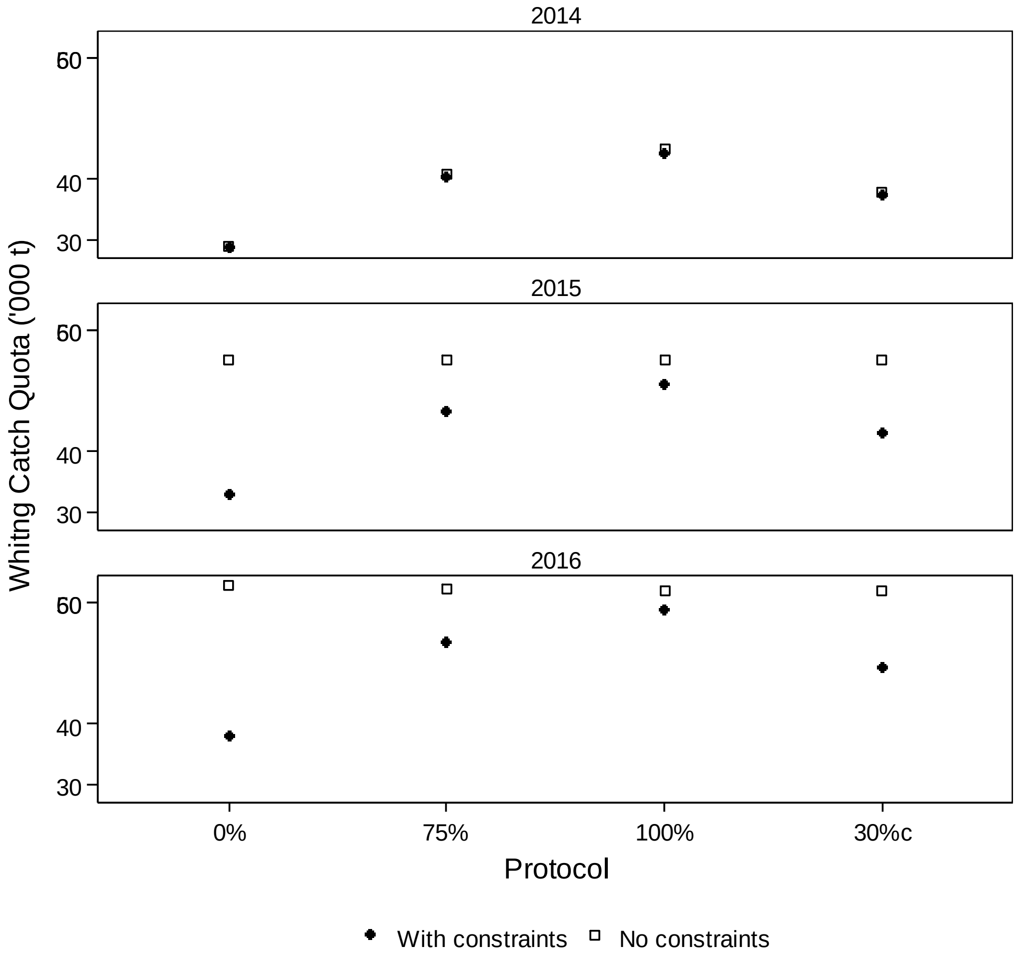

Figure 6 The size of the whiting catch quota under 4 different catch quota setting protocols, if existing constraints on quota size are continued under catch quota management (closed diamonds) or removed (open squares).

3.2.1 Impact of allowing a 10% cod overage

Allowing a 10% overage of a cod catch quota in 2014 increases the revenue of fleets. The marginal mean change in revenues is reduced to -30% under the 0% protocol, -17% under the 75% protocol, -13% under the 100% protocol and -9% under the 30%c protocol. However, the benefit of utilising a cod overage is not uniform across years (Figure 7). The increase in revenue is much smaller in 2015 and 2016. Applying an overage results in a higher F and a smaller cod SSB at the beginning of 2015 and 2016 (Table 5). This reduces the size of the catch quota that can be set compared to if no overage had been applied. The size of the catch quota is further reduced by deduction of the overage used in the previous year. Consequently, there is only a small increase in the amount of cod that can be landed in 2015 and 2016, even if an overage is also allowed in these years (Table 5). In addition there is no increase in revenue for fleets limited by plaice or whiting (Table 4).

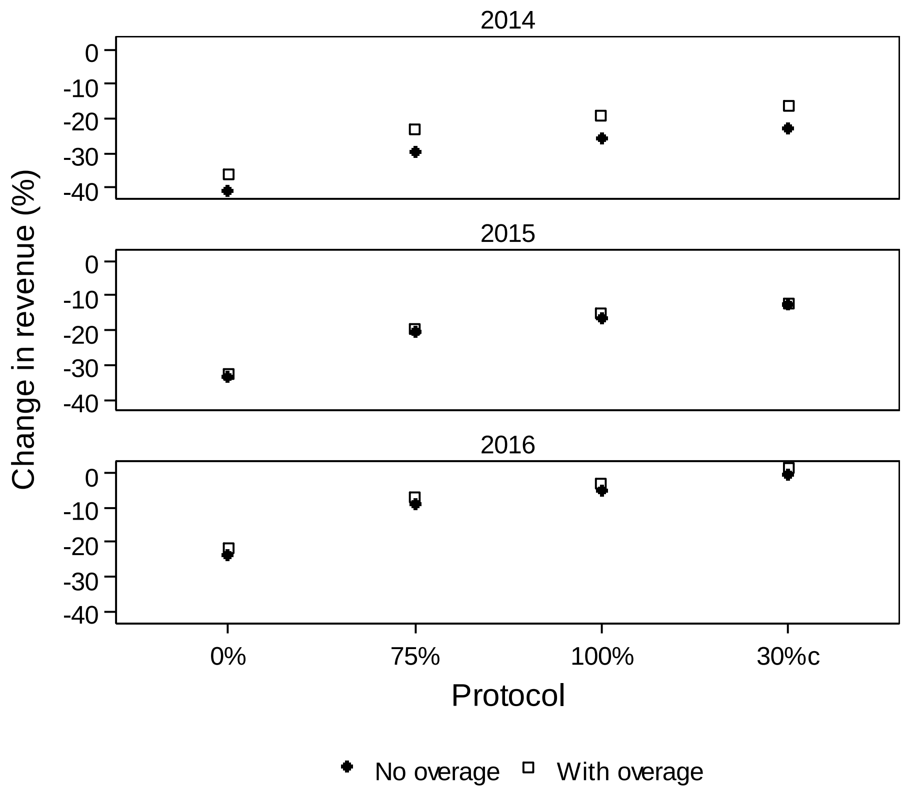

Figure 7 Mean percentage change in the revenue across 2014-2016 compared to 2012 of all modelled North Sea demersal finfish fleets after transitioning to catch quota management under 4 different catch quota setting protocols when no cod overage is allowed (closed disamond), and the influence of allowing an overage (open square). The pooled standard error is small ±0.9% and so is not plotted.

Table 5 Percentage change in SSB, F and cod catch quota size if a rolling 10% overage of the cod catch quota is allowed between 2014 and 2016, compared to if no overage is allowed, based on 4 different catch quota setting protocols.

Protocol	Year	Change in F (%)	Change in SSB (%)	Change in catch quota (%)
0%	2014	10	0	10
	2015	2	-2	1
	2016	4	-2	3
75%	2014	11	0	10
	2015	2	-2	1
	2016	4	-2	3
100%	2014	11	0	10
	2015	2	-2	1
	2016	4	-2	3
30%c	2014	11	0	10
	2015	2	-2	1
	2016	4	-2	3

3.3 Are there relative economic winners and losers if no change in behaviour is made?

The variation in change in revenue between fleets is much higher than that between years or protocols (Figure 8a). The mean change in revenue compared to 2012 varies from an increase of 34% for the French 10-40m otter trawler fleet to a reduction of 98% for the Danish static fleet (Figure 8a).

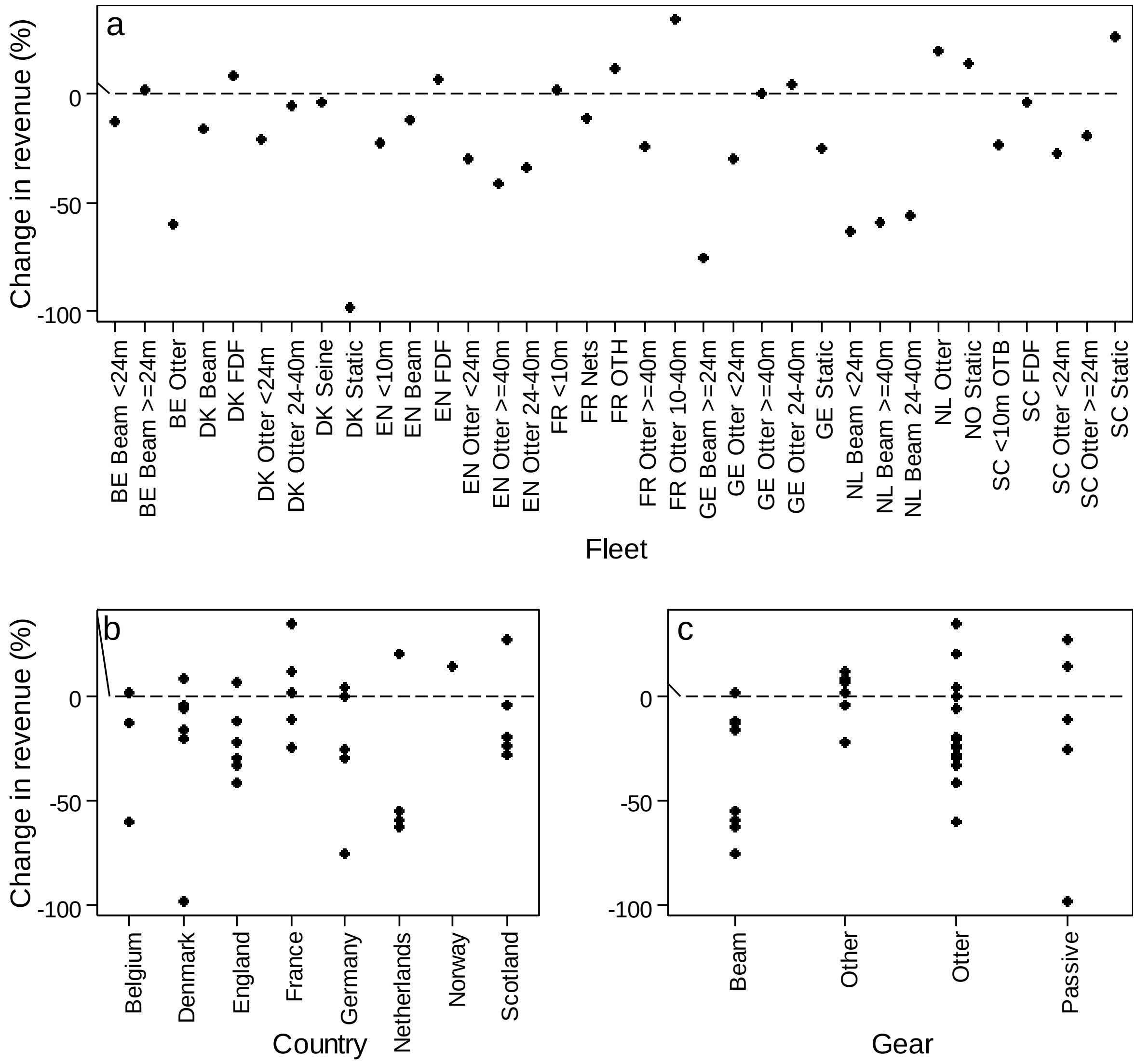

Figure 8 (a) Mean percentage change in fleet revenue of modelled North Sea demersal fleets between 2014 and 2016, compared to 2012. The pooled standard error is small, ±0.3%, so is not plotted. (b) Mean percentage changes grouped by country, and (c) by basic gear groups.

This high level of variation is not related to the Member State in which each fleet is registered (Figure 8b). For, example, English fleets see changes in revenue between -41% and +7% and French fleets see changes between -25% and +34%. Change in revenue is not linked to gear type (Figure 8c). Changes in revenue of beam trawler fleets vary from -75% to +1%. Otter trawler fleets see changes in revenue varying from -60% to +34%. The major determinant of the change in revenue is the catch characteristics of each fleet, with relative winners being those that are limited by a target species or have a high catching efficiency for their target species compared to the limiting species, preventing or reducing forgone catches. If forgone catches are small they could be compensated for by an increase in landings of the limiting species, allowing revenue to be maintained or increased compared to 2012. An increase in landings of the limiting species can occur as the catch quotas for all species are larger than landings in 2012, except for cod under the 0% protocol (31,987 t of cod, 46,941 t of haddock, 73,830 t of plaice, 77,100 t saithe, 11,610 t of sole and 17,105 t of whiting were landed in 2012, Table S1). A large absolute increase in the landings of the limiting species compared to foregone catches is more likely in fleets where the limiting species is an important target, contributing a large percentage of landings. Relative losers are those fleets that are limited by a non-target species and have a relatively high CPUE for the limiting species compared to their target species, resulting in relatively large foregone catches. This is more likely in high discarding fleets.

For example, amongst the relative winners is the French 10-40m otter trawler fleet, whose revenue increases by 34% in 2014 (Figure 8a). This fleet is limited by its cod quota allocation, and this is the second most important species for the fishery, contributing 32% of revenue and 14% of landings in 2012. However, 66% of revenue and 84% of landings in 2012 came from whiting (Table S2). Exhaustion of the cod quota allocation could result in a substantial reduction in landings of the more important target species. However, this fleet catches whiting with a higher efficiency than cod, catching 1.41 t and 0.1 t per unit of effort (1000 kW days) respectively. This allows the fleet to maintain its landings of whiting despite being limited by cod. Marketable landings of whiting are increased by 37% in 2014 under the 30%c protocol as whiting that would previously have been discarded is landed (Table S2). >MLS whiting may have been discarded for a number of reasons including poor quality, a lack of market or low prices, or because it exceeds the quota allowance of the fleet. As mentioned above, this fleet will also see an increase in cod landings under all but the 0% protocol; cod landings increase by 25% in 2014 under the 30%c protocol (Table S2). The combined increase in cod and whiting landings results in the 34% mean increase in revenue mentioned above. Another winner is the Scottish static fleet. Here, the mean revenue increases by 26% (Figure 8a). Cod contributed 90% of the revenue and 80% of the landings of this fleet in 2012 (Table S2). Therefore, the increase in cod under all but the 0% protocol results in an increase in the total landings and revenue of the fleet. This increase in cod compensates for the reduction in landings of haddock and saithe. For example, these are reduced by 37% and 11% respectively under the 30%c protocol (Table S2). The CPUE of haddock and saithe are both low, at <0.01 t per unit of effort, compared to 0.03 t of cod per unit of effort. Consequently the cod quota allocation is exhausted before enough haddock and saithe can be caught to match 2012 levels (Table S2). However, haddock and saithe together only contributed 10% of the revenue in 2012 and 19% of the landings (Table S2). So reductions in landings of these species do not represent substantial foregone catches. As cod dominates the landings of this fleet, the increase in cod landings will exceed the reduction in haddock and saithe landings and revenue will increase (Figure 8a, Table S2).

If the limiting species is not a main target, any increase in landings may not compensate for a reduction in non-limiting species, particularly if the CPUE of non-limiting species is relatively low. For example, the English 24-40m and >40m otter trawler fleets, the Danish static fleet, the German >24m beam trawler fleet, and the Dutch <24m, 24-40m and >40m beam trawler fleets are limited by their whiting allocation (Table S2). The whiting catch quotas exceed the amount landed in 2012 under all protocols, leading to an increase in whiting landings (Table S2). However, whiting is not a target species and contributed 1% or less of landings and revenue for the majority of these fleets in 2012. Even a large percentage increase in whiting landings will be of low value relative to landings of other species (Table S2). As whiting contributes so little to the landings of these fleets a relatively low CPUE could be expected for this species. However, these fleets discarded between 79% and 99% of their whiting catch in 2012, far exceeding the proportion of catch of the target species (plaice and sole) that was discarded (Table S2). So the CPUE of whiting for each of these fleets is relatively much higher than for their target species (Table S2). They exhaust their whiting quota allocation with a very low level of effort and landings of their target species cannot be maintained (Table S2), resulting in dramatic reductions in revenue between 34 and 98% (Figure 8a).

3.4 Will a change in fishing behaviour benefit the modelled fleets?

3.4.1 Avoidance of <MLS cod catch

Taken over all fleets, protocols and years, avoiding catching all <MLS cod results in a median 14% reduction in the fleet revenue generated from the six stocks, compared to -19% if no change in behaviour occurs. So higher revenue can be achieved if fishers change their behaviour to achieve this. As above when no change in behaviour is made, fleet revenue is significantly affected by fleet, protocol, year and all two way interactions between them. These factors and their interactions explain 80% of the variance in the results.

Variation in the change in revenue between fleets is the most important factor, explaining 68% of the overall variation. The impacts of the behaviour change will also vary between fleets (Figure 9). Avoiding <MLS cod results in a reduction in a fleet's cod CPUE (Figure 10). A lower CPUE results in a fleet having to exert a higher level of effort if they want to fulfil their cod quota allocation. So, avoiding <MLS cod could allow fleets limited by cod to operate for longer (Figure 10). With more

time to operate fleets can increase their landings of non-limiting species. In addition avoiding <MLS cod allows the cod quota allocation to be fulfilled by higher value >MLS catch. Together, the increase in landings of non-limiting species and marketable cod will increase revenue, compared to if no change in behaviour is made (Figure 10). The reduction in the cod CPUE, and the resulting increase in effort, landings and revenue will be largest for those fleets that currently catch relatively higher levels of <MLS cod (Figure 11). For example, in 2014 under the 30%c protocol the Belgian otter trawler fleet sees a 33% increase in revenue when all <MLS cod are avoided (Figure 10). The fleet is limited by cod, 25% of which is <MLS, more than any other fleet. However, if a fleet is not limited by cod, avoiding catching <MLS fish of this species will not offer any benefit (Figure 10). For example, the 40m and over English otter trawler fleet is limited by whiting. The limiting whiting quota allocation will still be exhausted by the same level of effort as when no change in behaviour occurs, as the CPUE of whiting is not affected by avoiding the 1% of the cod catch which is <MLS. If there is no increase in effort, the fleet cannot increase landings of non-limiting species. Instead the fleet will forgo the very small amount of revenue that could be generated from the <MLS cod if it is sold for fish meal. The impact on revenue will be minimal due to the low volume and value of the foregone <MLS cod catch (Figure 10).

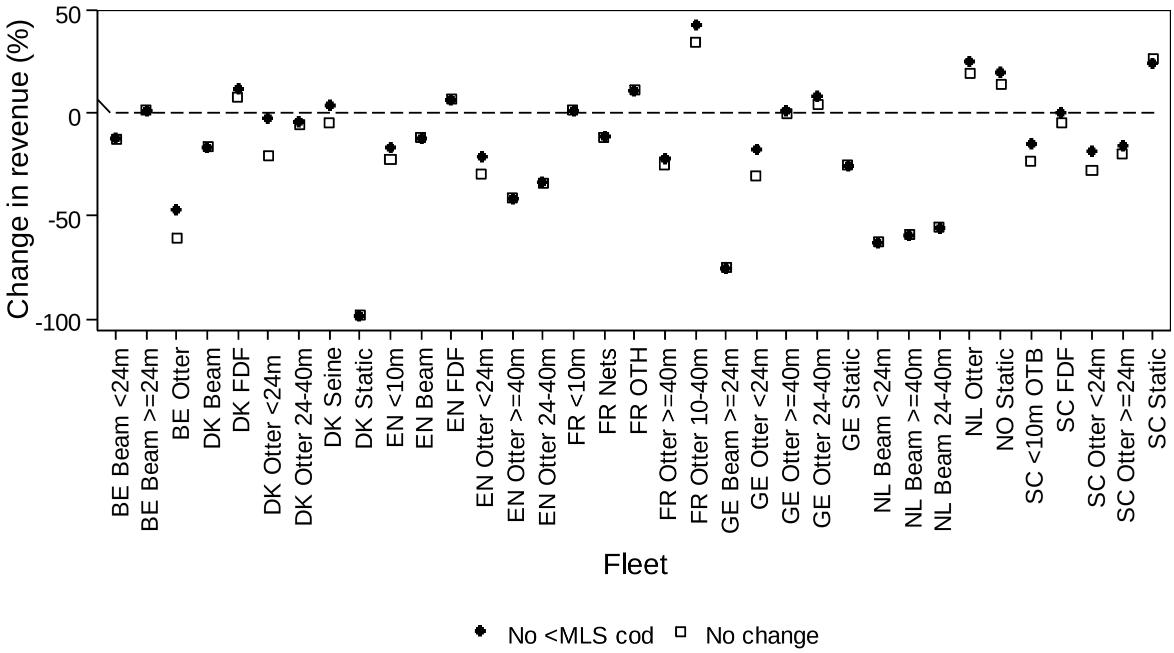

Figure 9 Mean percentage change in fleet revenue of modelled North Sea demersal fleets between 2014 and 2016, compared to 2012, if there is no change in behaviour (open squares) or if fishers change their behaviour to avoid all <MLS cod (closed diamonds). The pooled standard error of the behaviour change is small, ±0.3%.

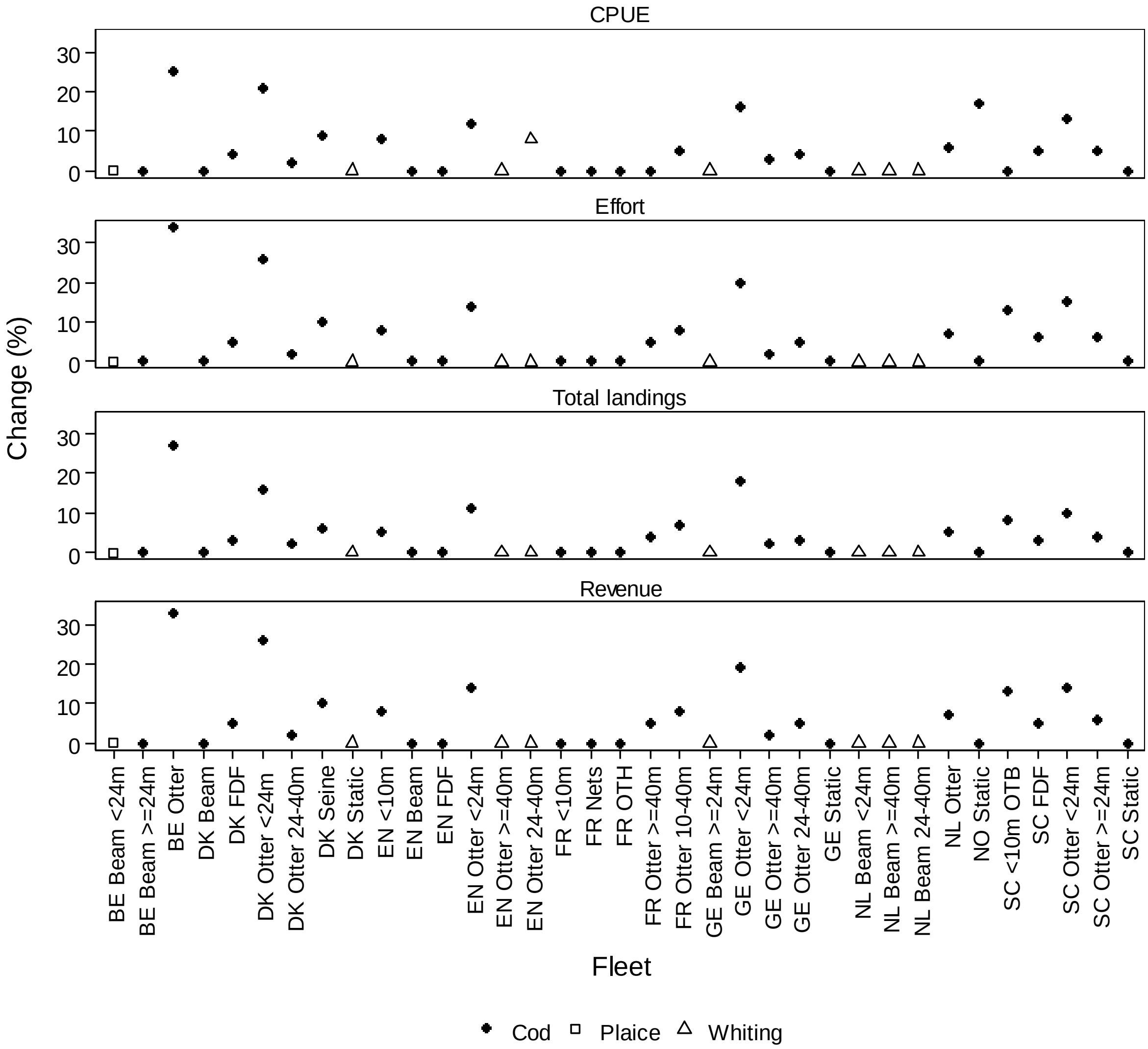

Figure 10 Median percentage change in the cod CPUE of modelled North Sea demersal finfish fleets and the resultant median percentage change in effort, total landings and revenue under the 30%c protocol in 2014 if fishers change their behaviour to avoid catching <MLS cod, compared to if no behaviour change is made. Fleets are limited by either their cod quota allocation (closed diamond), plaice (open square) or whiting (open triangle).

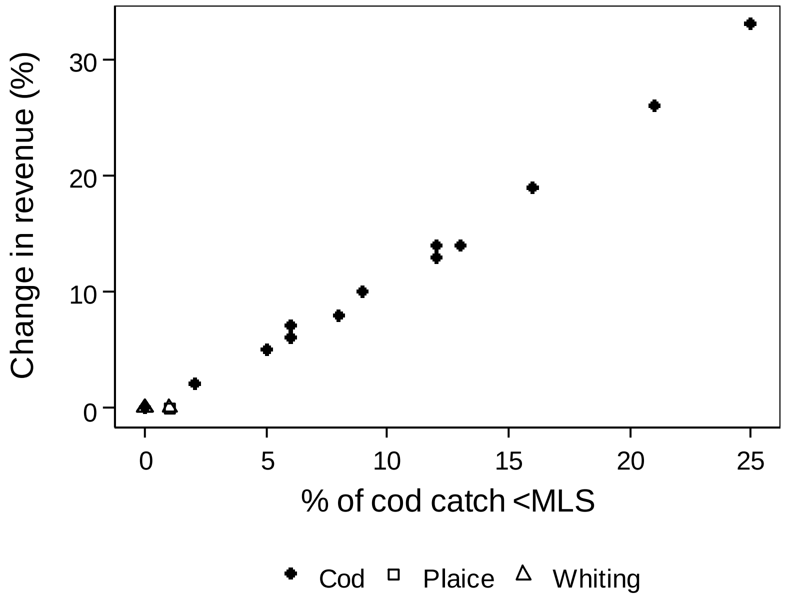

Figure 11 Percentage of the cod catch that is <MLS if no change in behaviour is made by the modelled North Sea demersal finfish fleets, compared to the percentage change in fleet revenue if this <MLS catch is avoided when operating under the 30%c protocol in 2014. Fleets are limited by either their cod quota allocation (closed diamond), plaice (open square) or whiting (open triangle).

Once again the fleet revenue will increase between 2014 and 2016 due to the influence of catch quotas on the F and SSB of stocks, allowing larger catch quotas to be set for limiting species (Figure 12a). Similarly, marginal mean change in revenue will continue to be highest under the 30%c protocol (Figure 12b). The year explains 4% of the variation in the change in fleet revenue whilst protocol explains 5%. The economic benefit of avoiding <MLS cod is uniform across years and protocols (Figure 12). The model assumes that the same proportion of a fleet's cod catch will be <MLS in all years, so avoiding <MLS cod results in the same relative reduction in the cod CPUE in all years. Consequently, the relative increase in effort, landings and revenue is also the same.

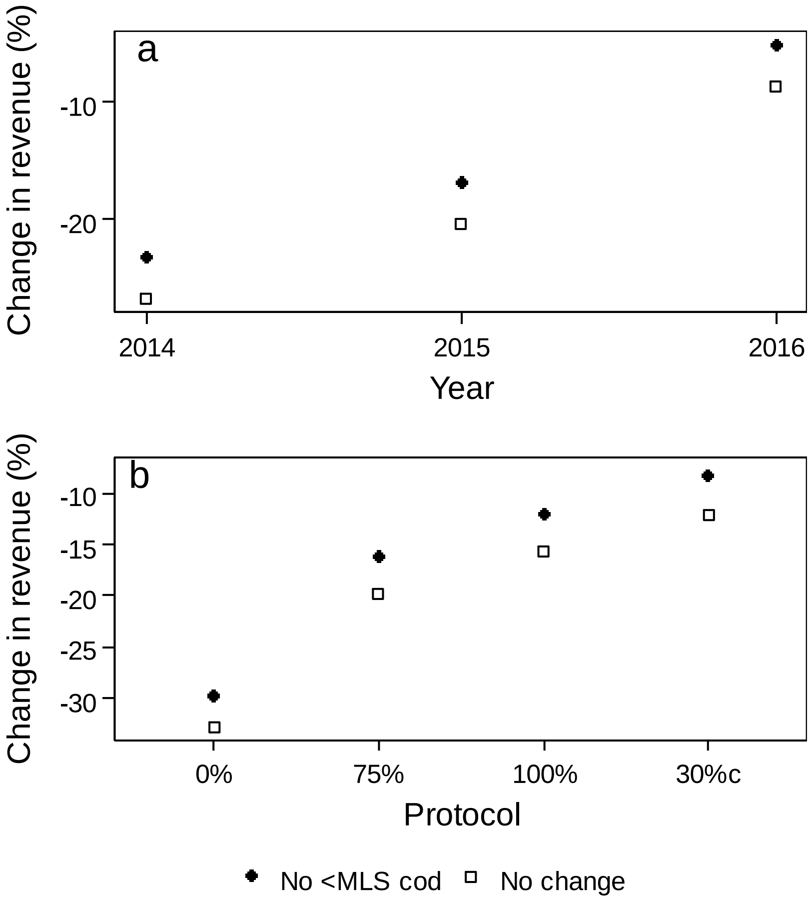

Figure 12 Marginal mean percentage change in revenue compared to 2012 of modelled North Sea demersal finfish fleets if no change in behaviour is made (open squares) or all <MLS cod is avoided (closed diamonds), (a) in 2014 to 2016, (b) under 4 different catch quota setting protocols where a cod overage has not been allowed. The pooled standard errors are ±0.1% for year and ±0.2% for protocol when a change in behaviour is made, so are not plotted.

3.4.2 Avoidance of all <MLS catch

When all <MLS catch of all 6 species is avoided, fleet revenue continues to be significantly affected by fleet, protocol, year and all two way interactions between them. In fact, avoiding all <MLS catch results in very similar effects to avoiding only <MLS cod. The model explains 81% of the variation in the change in revenue, year and protocol each explain 5% of the variation in results, fleet explains 69% and the two way interactions each explain 1%. Taken over all fleets, quota implementation protocols and the three years 2014 to 2016, avoiding catching all <MLS catch results in a median 14% reduction in the fleet revenue, compared to 2012, the same as when only <MLS cod is avoided. However, the impact of avoiding all <MLS catch opposed to only

<MLS cod may differ for some fleets that are limited by a species other than cod (Figure 13). For example, in 2014 under the 30%c protocol the Belgian <24m beam trawl fleet will see revenue increase by 12% if <MLS catch of all species is avoided, compared to when no change in behaviour is made; conversely if only <MLS cod is avoided revenue will be unchanged (Figure 13). This fleet is limited by its plaice allocation; avoiding the 11% of the plaice catch that is <MLS increases the level of effort this fleet can exert before the plaice allocation is exhausted, allowing the fleet to catch more non-limiting species, resulting in an increase in revenue of 12% (Figure 13). However, an increase in revenue will not be achieved by all fleets limited by a species other than cod. For example, the 3 Dutch beam trawl fleets, and the German >24m beam trawl fleet incur a small reduction in revenue if all <MLS catch relative to that when only <MLS cod is avoided. These fleets are limited by whiting but have no documented <MLS whiting catch included in the model. So, avoiding <MLS catch of all species will not affect the level of effort by these fleets. Instead the fleets will forgo <MLS catch of other species, particularly plaice, that could be sold for fish meal production. For these fleets the sheer scale of plaice landings means that forgoing <MLS plaice impacts on revenue, although only slightly (Figure 13). Some fleets that are limited by cod will also see a small reduction in revenue due to forgone catches of <MLS fish (Figure 13). These include the Danish <24m otter trawler and seine fleets, the English <24m otter trawler, the Dutch otter trawler fleet and the Scottish <24m otter trawler and <10m fleets.

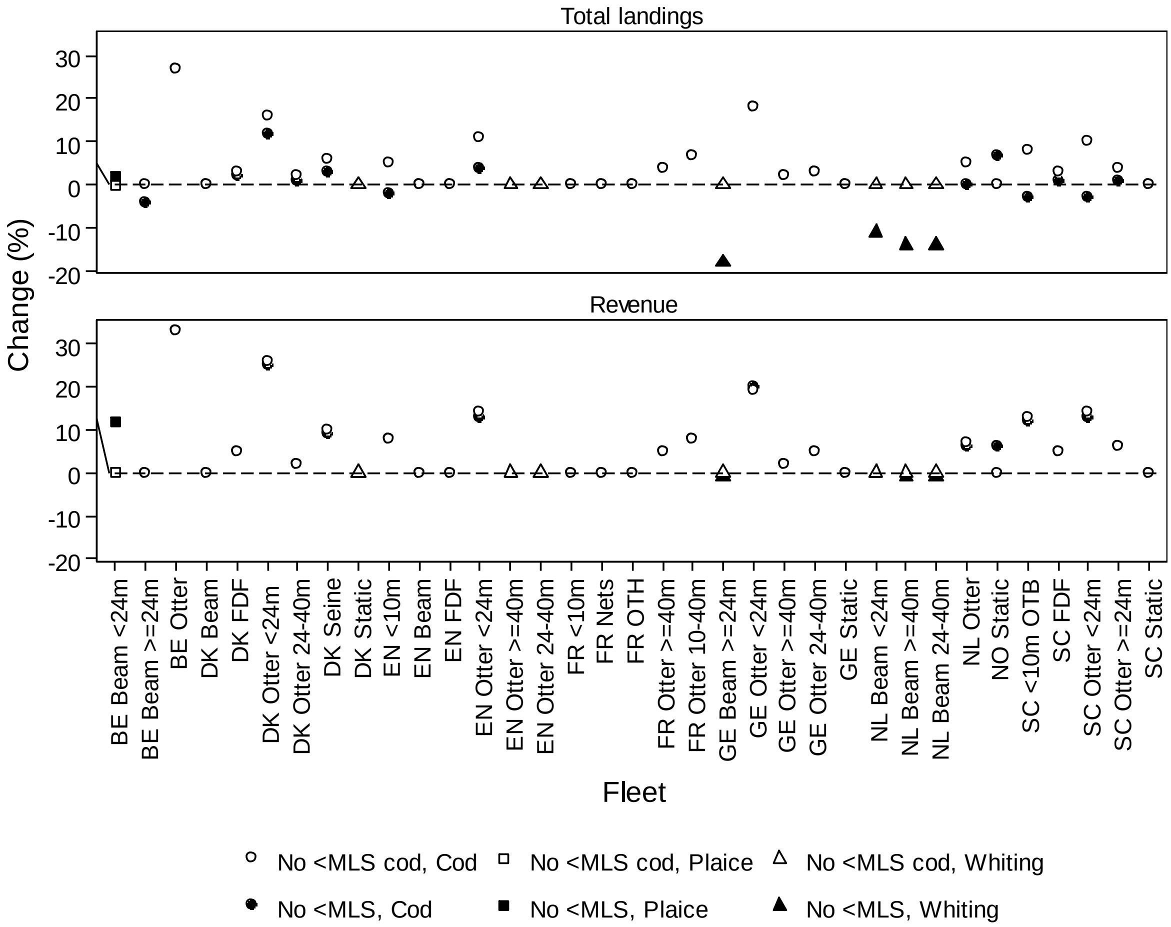

Figure 13 Median percentage change in the landings and revenue of modelled North Sea demersal finfish fleets under the 30%c protocol in 2014, if fishers change their behaviour to avoid catching <MLS cod (open shapes) or <MLS catch of all species (closed shapes), compared to if no behaviour change is made. Fleets are limited by either their cod quota allocation (circle), plaice (square) or whiting (triangle).

3.4.3 Reducing cod catch rates by 30%

Reducing cod catch rates by 30% results in the largest increases in revenue of all the selectivity change scenarios. Taken over all fleets, protocols and years, reducing the CPUE of cod by 30% results in a median 4% reduction in fleet revenue, compared to 2012. This reduction is much less than if no change in behaviour occurred, or if only <MLS catch of cod or all species is avoided. Once again fleet, year and protocol all significantly affect the change in fleet revenue, although the impact of year and protocol is less than if no behaviour change is made. The model explains 76% of the variation in results, year explains 2% and protocol explains 4%. Fleet continues to have the strongest impact on revenue, explaining 68% of the variance in the results. This is due to the

different catch compositions of the modelled fleets. Reducing the CPUE of cod by 30% will reduce the rate at which a cod quota allocation is exhausted, in the same way as avoiding only <MLS catch. This will allow fleets limited by cod to increase effort, and consequently landings of non-limiting species (Table S3). The resulting increase in revenue will be largest for fleets where cod is not a target species (Figure 14), as these fleets incur the highest levels of foregone catches if no change in fishing behaviour occurs. If cod is a target species, any increase in landings of non-limiting species is unlikely to result in a large increase in total landings and revenue (Figure 14). The increase in revenue will also be affected by the proportion of the cod catch that is <MLS if no change in behaviour is made. Under this selectivity scenario it is assumed that all <MLS cod are avoided. As above avoiding <MLS cod allows a fleet's cod quota allocation to be fulfilled by higher value >MLS catch. The increase in marketable cod is greatest for those fleets that are least size selective, where a high proportion of cod catches are currently <MLS. For example, the German <24m otter trawler fleet sees a 40% increase in total landings in 2014, whilst the Belgian otter trawler fleet sees a smaller 34% increase, and yet both fleets benefit from a 40% increase in revenue. 25% of the cod caught by the Belgian fleet would be <MLS if no change in behaviour were made, whilst 16% of the cod catch of the German fleet would be undersized. Consequently, marketable landings of cod increase by 34% for the Belgian fleet and only 20% for the German fleet. The greater increase in marketable cod landings gives the Belgian fleet the same increase in revenue as the German fleet (Table S3). For fleets not limited by cod, reducing the CPUE of this species offers no economic benefit (Figure 14) and reducing the CPUE of a non-limiting species results in foregone catches (Table S3). The scale of any reduction in revenue will be dependent upon whether cod is a target species or not.

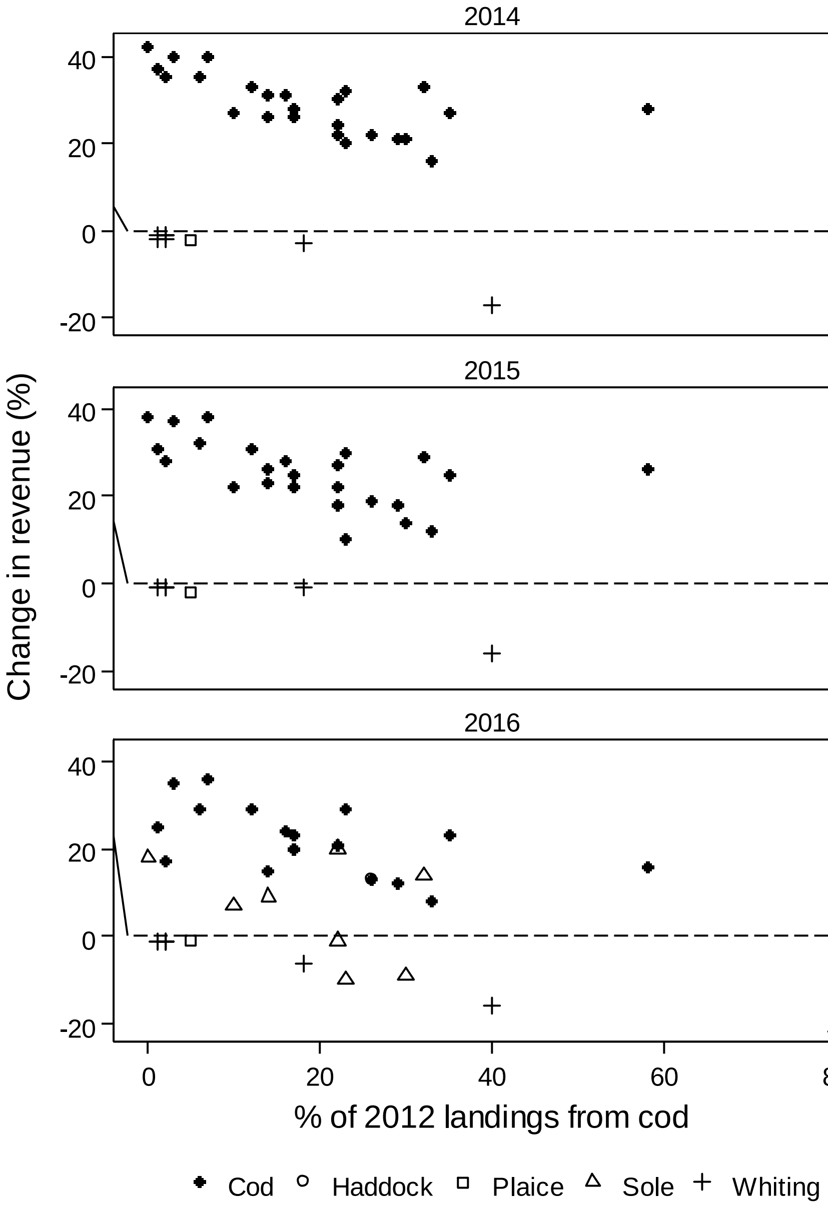

Figure 14 Percentage change in the revenue of modelled North Sea demersal finfish fleets under the 30%c protocol between 2014 and 2016 if the cod CPUE is reduced by 30% compared to that if no change in behaviour is made, plotted against the relative importance of cod as a target species. Fleets are limited by either their quota allocation for cod (closed diamond), haddock (open circle), plaice (open square), sole (open triangle) or whiting (cross).

As can be seen from the changes in revenue, the effect of the change in behaviour is relatively uniform across the different protocols (Figure 15a). However, the benefit of reducing the CPUE of cod does reduce across the years. The increase in revenue is lower in each year of the projection (Figure 15b). This occurs due to the combined influence of the behaviour change and the relatively large improvement in the SSB of cod compared to other stocks. As mentioned above, catch quotas result in an increase in stock size between 2014 and 2016 due to a reduction in F. However, the improvement in the cod stock far outweighs that of the other stocks (Table S1). Consequently, the increase in the size of the catch quota between 2014 and 2016 will also be largest for the cod stock. A larger cod catch quota results in relatively less limiting quota allocations. When the CPUE of cod is reduced by 30%, the likelihood that fleet will become limited by another species increases, particularly for haddock and sole which see the smallest increases in quota size (Table S1). This change in the limiting species is influenced by the level of recruitment in each stock. A relatively high level of recruitment in the previous year will increase a fleet's CPUE for that species reducing the amount of effort that will exhaust the associated quota allocation, increasing the likelihood that a fleet will become limited by this species (Table S4). For example, in 2014 under the 30%c protocol the English fully documented fleet is limited by cod in 70 of the 100 replicate runs in which recruitment is varied (see section 2.2). The fleet is limited by sole in only 4 runs. However, by 2016 the fleet is limited by cod in only 10 runs and sole in 54. Haddock is the limiting species on the majority of the remaining runs (Table S4). This change in the limiting species can result in a reduction in fleet revenue compared to that without a change in behaviour (Figure 14). Quota allocations for these newly limiting species will be exhausted by a higher level of effort than the cod allocation if no change in behaviour is made, so the fleet will still see an increase in landings of non-limiting species other than cod (Table S3). However, the change in the limiting species prevents the cod allocation from being fully utilised. This results in a reduction in cod landings compared to those if no change in behaviour were made (Table S3). The scale of the foregone cod catches will be dependent upon whether cod is a target species and the CPUE of sole (or other limiting species) relative to cod (Table S3). If the CPUE of the new limiting species is relatively high compared to that of cod, foregone cod catches are likely to be larger. Dependent upon the scale of additional landings of non-limiting species, a large reduction in cod catches can result in a fall in revenue, compared to that if no change in behaviour occurred (Figure 14, Table S3).

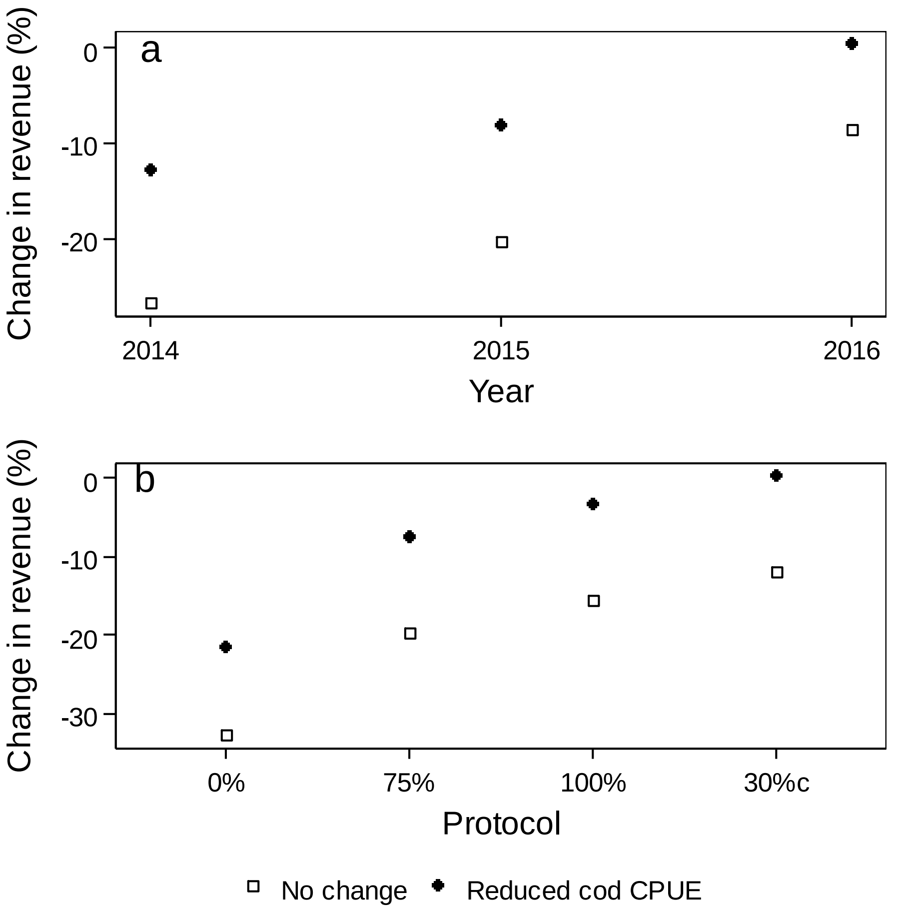

Figure 15 Percentage change in the revenue compared to 2012 of modelled North Sea demersal finfish fleets (a) in 2014 to 2016 and (b) under 4 different catch quota setting protocols where a cod overage has not been allowed, if no change in behaviour is made (open squares) or if the CPUE of cod is reduced by 30% (closed diamonds). The pooled standard error is ±0.1% for year and ±0.2% for protocol when a change in behaviour is made.

In summary, transitioning to catch quotas results in a substantial increase in revenue for some fleets and a reduction in revenue for others. The impact is dependent upon the year, catch quota protocol used and individual characteristics of fleets. Under existing management plans, a larger uplift in 2014 results in higher revenues for all fleets. Revenue of all fleets increases over time due to the improvement in the SSB of the 6 stocks, resulting from catch quotas limiting the F of stocks to below levels defined in the management plans. Whether the revenue of a fleet increases compared to before catch quotas were introduced is dependent upon the catch characteristics of the fleet; whether the limiting species is a target species and the CPUE of the limiting species relative to other target species. Reducing catch rates of the limiting species, through avoiding

<MLS catch or reducing catch rates of all sizes, can result in a dramatic increase in revenue. Reducing catch rates of the limiting species allows a higher level of effort to be exerted before the limiting quota allocation is exhausted. A higher level of effort allows a fleet to catch more non-limiting species, increasing revenue. A large reduction in the CPUE of the limiting species, such as the 30% reduction in the cod CPUE discussed above, results in the greatest increases in revenue. The incentive for this behaviour change will be greatest for fleets that are limited by a non-target species, particularly if a high proportion of their catch of this species is <MLS. However, reducing the catch rate of the limiting species will offer little benefit if the fleet then becomes limited by another species, due to foregone catches. This change in limiting species will be influenced by the level of recruitment in each stock.

4. Discussion

In the introduction, we posed four questions:

1. What is the potential economic impact of transitioning to catch quotas if no change in fishing behaviour occurs?
2. Which catch quota protocol results in the highest revenue for fleets?
3. Are there relative economic winners and losers if no change in behaviour is made?
4. Will the modelled fleets be incentivised to change their behaviour and avoid catching “unwanted” fish, those that are undersized or with limited quotas?

The answers to these questions are not straight forward and will vary between fleets. The model suggests that the mean revenue of fleets will be reduced when catch quotas are implemented. However, this reduction may not be solely due to the introduction of catch quotas. The cod management plan requires a reduction in F, reducing the amount of cod that can be caught in 2014 compared to 2012. However, the impact of catch quotas will vary between years and will be dependent upon how catch quotas are implemented and the individual fleet. Revenue will be lowest in the first year of implementation. This reflects evidence from Norwegian fisheries, where the introduction of a discard ban and supporting measures alongside catch quotas resulted in a short-term decline in the revenue of fleets due to a reduction in fishing opportunities (Diamond and Beukers-Stewart, 2011). Revenue will increase in subsequent years due to an improvement in the condition of stocks. Catch quotas result in a year-on-year reduction in F; by 2016 the exploitation of all modelled stocks is below their F_{MSY}. This reduction in F allows the SSBs to increase, as was seen in Northeast Artic stocks after the change in Norwegian fisheries management mentioned above. Diamond and Beukers-Stewart estimate that SSBs increased by approximately 18% per year (Diamond and Beukers-Stewart, 2011). The increase in SSB allows larger catch quotas to be set for limiting species in each year of the projection. This allows fleets to land more catch resulting in an increase in revenue between 2014 and 2016. In fact by 2016 the revenue of many fleets exceeds that achieved in 2012 under landings quotas. This suggests that a decline in revenue as a result of catch quota implementation may be only temporary, at least for some fleets. The annual increase in revenue is heavily influenced by the quota constraints within each management plan. The increase in SSB could allow much larger catch quotas to be set, however, the between year change in quota size is restricted to a maximum of 15% increase (20% for cod). Consequently, the modelled fleets are operating under much more restrictive catch quotas than is necessary in 2015 and 2016, and revenue could be much higher than estimated if the quota constraints were relaxed. If managers wish to see the fleets achieving higher revenues during the transition to catch quotas existing management plans may need to be revised.

The level of initial uplift applied under each protocol will also influence the impact of catch quotas on revenue. The larger the initial uplift applied to landings quotas, the larger the revenue of fleets in the first year of transition. A larger uplift results in larger catch quotas and quota allocations. Larger quota allocations allow fleets to land more of their limiting species and will be exhausted by a higher level of effort. With more time to fish, fleets can land more non-limiting species. The catch quota protocol that results in the largest catch quota will vary between species dependent upon what proportion of catch is currently discarded. A 30% increase in a landings quota may exceed estimated discards of a stock, or vice versa. So, the catch quota protocol that results in the highest revenue for fleets will vary dependent upon the limiting species of each fleet. Using different catch quota protocols for different species would allow the revenue of all fleets to be maximised in the first year of transition. For example, using the 30%c protocol to set the cod catch quota and the 100% protocol to set the whiting catch quota would maximised the 2014 revenue of all modelled fleets.

The longer term impact of the initial quota uplift level is heavily influenced by the quota constraints within each management plan. A smaller initial uplift in 2014 will result in lower Fs as less catch can be landed, allowing a more rapid rebuilding of SSBs than if the uplift was larger. However, the quota constraints within each management plan prevent larger catch quotas being set. Consequently, fleets continue to see higher revenues in subsequent years when a larger initial uplift is applied.

The characteristics of individual fleets are likely to have the strongest influence on revenues. The impact of transitioning to catch quotas and a discard ban varies greatly between the modelled fleets. Some see large increases in revenue whilst others see dramatic declines. This supports evidence from previous studies where the impact of catch quotas was found to vary greatly between different vessel segments (Condie et al., 2013a, Condie et al., 2013b). The change in revenue is not determined by gear type. Fleets using static, otter or beam trawls rank amongst those with the greatest increases or largest declines in revenue. Similarly, fleets from each of the different Member States are found amongst both the economic winners and losers. Instead the relative change in revenue is determined by the catch characteristics of each fleet. Whether the limiting species is a target will influence the change in revenue, as has been seen in previous studies (Condie et al., 2013a). When the quota allocation for the limiting species is exhausted fishing must stop which could result in foregone catches of other species. If the limiting species is the main target, contributing a high proportion of landings, then foregone catches will be relatively small. This small reduction in catches of non-limiting species could be compensated for by an increase in landings of the limiting species. Conversely, if the limiting species is not a main target foregone catches will be much higher, reducing revenue. The level of foregone catches will also be influenced by a fleet's catching efficiency for the limiting species compared to the CPUE of other species. A relatively high CPUE for the limiting species will result in rapid exhaustion of the limiting quota allocation. This can result in a reduction in catches of other species if the rate at which these species are caught is relatively low. The larger the discrepancy between CPUEs of limiting and non-limiting species the greater the reduction in landings and revenue will be. This discrepancy is more likely to be large for fleets that currently discard a high proportion of their catch of the limiting species. However, some relatively high discarding fleets may still see revenue increase under catch quotas.

So, the relative impact of transitioning to catch quotas on each fleet will be dependent upon:

- The limiting species – is it a key target species?
- The relative CPUE of the limiting species – how does the CPUE of the limiting species compare to the target species?

The model shows that an incentive to change fishing behaviour and adopt more selective fishing practices to avoid catching the limiting species, particularly if a high proportion is <MLS, is created under catch quotas. This supports the findings of previous models (Condie et al., 2013a, Condie et al., 2013b) and evidence from fisheries where fishing mortality is fully documented (Diamond and Beukers-Stewart, 2011, Grafton et al., 2005, Graham et al., 2007). If all catch is documented and

compliance is high the only way income can be maximised is through reducing operating costs, improving the value of catch by avoiding undersized or poor quality fish, or by shifting targeting away from limiting species (Branch et al., 2006). For example, fishers in the British Columbia groundfish trawl fishery reduced catches of rougheye (*Sebastes aleutianus*), shortraker (*S. borealis*) and yelloweye rockfish (*S. ruberrimus*) by more than 50% when TACs for these species were reduced, and maximised income through targeting other species with more available quota instead (Branch and Hilborn, 2008). The incentive to adopt more selective fishing practices and reduce the catch rate of limiting species will be strongest for;

- the least size-selective fleets,
- fleets limited by a non-target species.

Improving selectivity to avoid capturing <MLS fish will reduce the CPUE of the limiting species. A lower CPUE will delay the fulfilment of the limiting quota allocation, increasing the opportunity to catch other species and improving revenue. Moreover, more higher value >MLS fish of the limiting species can be landed increasing the value of the limiting quota allocation. The incentive to adopt this change in selectivity will be greatest for the least size-selective vessels as the more <MLS catch that is avoided, the larger the increase in revenue will be. This supports the findings of Condie et al (2013a) where the incentive to avoid <MLS catch was strongest for the least selective vessels of the North Sea English otter trawler fleet. Moreover, fishers in the UK cod catch quota trial were seen to avoid fishing, change fishing grounds or switch target species during periods when <MLS cod were more abundant (Course et al., 2011, Kindt-Larsen et al., 2011). The improvement in revenue will be larger if catches of the limiting species are avoided all together. Larger reductions in the CPUE of the limiting species will allow more effort to be exerted, increasing the amount of time fleets can spend fishing for non-limiting species. This will be particularly important for fleets limited by a non-target species. However, a large increase in revenue will not occur if the fleet then becomes limited by another species, due to foregone landings of the previously limiting species. The benefit of the behaviour changes evaluated may differ from the values shown here. In reality it is unlikely that fishers could avoid all <MLS catch and changes in selectivity to avoid catching the limiting species may also impact on capture rates of non-limiting species. However, the selectivity changes here highlight the maximum potential benefit fishers could see if they were to adopt more selective fishing practices, providing an indication of how strong the incentive for behaviour change could be and in which fleets such changes are more likely to be seen.

The economic impact of transitioning to catch quotas and any resulting incentive to change fishing practices will differ from the changes estimated here. This analysis does not include all stocks that are exploited by the North Sea demersal finfish fishery, and for many fleets the target species may not be included in this assessment. Moreover, the level of <MLS catch is based on an average for each species, metier, area and Member State, rather than on estimates for each fleet. The value of this <MLS catch is uniform between fleets and is based on an estimate from the UK fishmeal industry. In reality the value of <MLS catch may not be uniform within and between fishing nations. A higher value of <MLS catch in a particular country could reduce any loss in revenue during the transition. It could also reduce the incentive to <MLS catch, but only if its value matches that of >MLS catch. The model also assumes that all fish >MLS are marketable and will acquire the same value, i.e. no market grades exist. In addition it is assumed that the change in supply of each of the species to European markets will not impact on prices, and this may not be the case. Consequently, the estimates of revenue generated by fleets may be higher than could be attained in reality. However it is still possible to discern how different levels of <MLS catch and changes in the landings may impact on fleets when operating under catch quotas, allowing us to identify where the greatest impacts are likely to be felt and which fleets are likely to benefit the most through a change in behaviour and additional support or flexibility in the quota system.

For example, in this model catch quotas for all six species are introduced simultaneously, however catch quotas for non-target species could be introduced by as late as 2019, three years after catch quotas for the defining species of a fishery (European Commission, 2013). Staggering the introduction of catch quotas could allow fleets to develop more selective fishing practices before potentially limiting catch quotas for non-target species are implemented. This could benefit fleets such as the modelled Belgian otter trawler and English beam trawler fleets, which are both limited by cod, a non-target species. Another assumption of the model is that the catch quota will be allocated to fleets based on their share of the total landings of each stock in 2012. However, how a quota is distributed is the responsibility of each Member State, and need not be based on historic landings (European Commission, 2013). A State could choose to distribute quota unequally amongst fleets in order to spread the impact of transitioning to catch quotas more evenly. For example, in the model, the Scottish static fleet sees a large increase in revenue whilst the revenues of the four other Scottish fleets are reduced. All five fleets are limited by cod. The amount of quota allocated to each of the five fleets could be altered. The static fleet could be given a smaller allocation for cod and the additional quota could be distributed between the other four fleets. The additional quota would prevent cod quota allocations being so restrictive, spreading the impact of the transition to catch quotas more evenly between the five Scottish fleets. Alternatively, such fleets could benefit through transfer of quota allocations. The model assumes that the level of quota transfer in 2012 is maintained in all years of the projections. However, quota transfer could increase under catch quotas (European Commission, 2013), allowing fleets to better match fishing opportunities to catch compositions. Whether this will occur is uncertain, fishers may choose to hold on to quota if they are concerned about running out at the end of the year or because they think prices might be higher then. Substitutions are another option, allowing non-target species to be deducted from 9% of the catch quota for another species (European Commission, 2013). These mechanisms for quota flexibility will be particularly useful for those fleets where quota allocations for more than one species are limiting. Such flexibility may reduce the incentive for fleets to adopt more selective fishing practices and avoid capturing limiting species, but it is very unlikely that the incentive will be removed all together. Unless <MLS catch can generate a value that can compare to that of >MLS catch, fleets will continue to maximise the revenue from the limiting quota allocation through avoidance of undersized catch. In addition, buying or leasing additional quota to match any overages will incur a cost and the incentive to reduce the catch rate of limiting species through more selective fishing practices should be maintained, dependent on the relative cost of the additional quota. An incentive to avoid catching the most limiting species will also be created for vessels that are least constrained by their quota allocations. If fishers could prevent their limiting quota allocation from being exhausted they could sell the excess, maximising revenue, particularly if the value of surplus quota exceeds the market price of catch (Hutton et al., 2010).

For some fleets the cost of introducing more selective practices to reduce capture of limiting species may be prohibitively expensive, or may be hugely disproportionate to the level of catch (European Commission, 2013). This could particularly benefit fleets that are limited by a species which is very rarely caught and nearly always discarded. For example, in the model, the English 24-40m and 40m and over otter trawler fleets are limited by very small quota allocations for whiting, a species that contributed only 1% of landings in 2012. Measures have been included in the reformed CFP to prevent such a situation occurring (European Commission, 2013). Fleets where landing and documenting unwanted catches will result in a disproportionate cost for fishers will have access to *de minimis* exemptions. This measure will allow up to 7% of the total catch of regulated species to be discarded; catches will be recorded but not deducted from quota (European Commission, 2013). Fleets may also be exempted if scientific evidence of high discard survival rates is available (European Commission, 2013).

A very important point to note is that the incentives that are created by catch quotas are reliant upon catches being fully documented and catch quotas constraining fishing. However the economic impact of limiting quota allocations will generate an incentive to illegally discard the constraining species. High observer coverage, such as that used in the British Columbia groundfish fishery, may prevent discarding but is likely to be very expensive (Branch et al., 2006). Alternatives include on board cameras and sensors which have shown promise in trials (Kindt-Larsen et al., 2011) but have their own associated costs surrounding installation, maintenance and data validation (Mangi et al., 2013). Self-sampling or the use of a reference fleet are other options favoured by fishers but may have issues with bias (Mangi et al., 2013). In reality, to ensure that monitoring and surveillance is cost-effective, representative and logistically possible, tailored systems may have to be implemented in individual fleets and fisheries (Mangi et al., 2013). Finding an appropriate method or combination of methods to ensure a sufficiently high level of monitoring and enforcement in each fleet is one of the many challenges faced by managers as they implement the large scale changes to the CFP.

5. Conclusion

The changes in management regimes that will be introduced under the reformed CFP are likely to have substantial impacts on the economic status of many fleets. The distribution of economic impacts will not be uniform; some fleets may see dramatic reductions in revenues whilst other benefit from an increase in landings. Potentially large reductions in revenue will create strong incentives to improve the selectivity of fishing practices. Reducing catches of the most limiting species should enable fishers to better match catches to available fishing opportunities. The incentive will be strongest for the least selective vessels, and those fleets that do not target the most limiting species. However, the relative benefit of improving selectivity will be dependent upon catch compositions. Improving selectivity for one limiting species will have less benefit if other species within the catch become restrictive. For other fleets adopting more selective practices may not be economically viable, or may not prevent dramatic reductions in revenue. Flexible transferable quotas or access to the *de minimis* exemptions and substitutions may be particularly important in these situations, if fishers are to prevent fishing becoming unprofitable. Moreover, strong incentives to avoid the most limiting species will be generated, but so will incentives to illegally discard catch. High levels of monitoring and enforcement may be required to ensure that fishers improve revenue through adopting more selective fishing practices rather than non-compliance. How fleets should be monitored is just one of the issues that will face managers in European fisheries as these fundamental changes in how fishing is regulated come into force.

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Chapter 6. Conclusion

Discards are widely viewed as morally wrong (Bellido et al., 2011, Paramor et al., 2005). They represent a waste of food and economic resources, and have contributed to unsustainable fishing (European Commission, 2011b). However, current regulations require un-mandated catch to be discarded in European fisheries. These regulatory discards are due to MLS, landings quotas and catch composition regulations (European-Commission, 2002). Fishers are also allowed to legally discard catch due to its low economic value, lack of market, or relatively high landings and processing costs (Catchpole et al., 2005). Discarding these unwanted over-quota and unmarketable catches prevents a reduction in profits, either through having to stop fishing due to exhausted quotas, having to buy additional quota to cover catches (Bellido et al., 2011) or having to pay landing costs that might not be recouped (Arnason, 1994). So, under the current CFP no incentive is created for fishers to improve the selectivity of their fishing practices and align their catch compositions with available fishing opportunities and market demand.

The reform of the CFP intends to address the current poor management of European fisheries, including these perverse incentives created to discard unwanted catch (European Commission, 2011a). The Commission aims to eliminate discarding and reduce unwanted catches through the phased introduction of a discard ban for regulated species from 2016 (European Commission, 2013). The ban will be supported by additional measures including effort controls or catch quotas for key commercial species (European Commission, 2013). However, as highlighted in Chapter 2, little evidence is available to suggest that a discard ban itself creates incentives for more selective fishing. In many non-European fisheries where a discard ban has been introduced, a lack of data collection has made it difficult to assess whether any changes in selectivity have occurred due to the ban itself. However, experience from these fisheries suggests that the nature of any supporting measures will determine if fishers are encouraged to change how they operate. The most effective are those that result in a reduction in fishing opportunities due to the capture of unwanted catch. For example, in response to real-time area closures triggered by exceeding a threshold level of undersized fish, the Barents Sea *Pandulus* shrimp fishery has developed more selective gear (Graham et al., 2007).

This importance of combining the discard ban with additional measures under the CFP reforms is highlighted in Chapter 3. We found that a discard ban in isolation would not have resulted in an incentive to avoid <MLS or unmarketable catch in the English North Sea otter trawler fleet. We showed that having to retain and land <MLS catch is unlikely to result in a reduction in profits for this fleet. Hold capacity will not have been exhausted by the additional landings, and existing

levels of marketable catch could have been maintained. Moreover, undersized and unmarketable catch would have generated a small profit if sold for fishmeal production. Supporting the discard ban with controls that reduce fishing effort is also unlikely to create an incentive for more selective fishing practices. In our model sufficient hold space was available for fishers to increase their catch per trip of the most valuable species limiting reductions in income, despite unwanted catch being retained. Unwanted catches may be reduced dependent on their co-occurrence with the most valuable target species (Kraak et al., 2013, van Oostenbrugge et al., 2008), but generation of an incentive for fishers to change their behaviour and actively avoid this catch is unlikely. Introducing catch quotas in combination with the discard ban has a much greater potential to incentivise more selective fishing practices in our case study fleet. Under this system total catches are capped and exhaustion of the quota requires fishing to stop (Course et al., 2011). Here, catching unwanted catch will reduce the income of fishers, creating an incentive to avoid it. Avoiding <MLS and unmarketable catch of the regulated species will increase the amount of valuable fish that can be landed under the quota. Moreover, in mixed fisheries avoiding undersized and unmarketable catches of the regulated species will delay the fulfilment of the catch quota allowing continued fishing for other species. If the catch quota is particularly restrictive an incentive to avoid marketable catch of the regulated species will also be created. This incentive is a result of the catch quotas and not the discard ban, however a discard ban may facilitate the full documentation of catches (European Commission, 2002).

In Chapters 3 and 4 we show that the incentive created by catch quotas will vary between different vessels segments within our case study fleet. The incentive will also vary between different fleets within a fishery, as shown in Chapter 5. The incentive is likely to be strongest for those vessels that incur the greatest reduction in income. The reduction in income will be determined by a number of key factors;

- the species regulated under catch quotas;
- the uplift in catch quota compared to existing landings quotas;
- the distribution of quotas between fleets and fleet segments;
- the size and species composition of catches;
- the catching efficiency for the limiting species relative to other species in the catch.

The incentive to introduce more selective fishing practices will be strongest for the vessels that are currently least selective, particularly if the most limiting species is not a primary target. If allocated quota of the limiting species is exhausted by a small level of effort and the catching efficiency of target species is relatively low, the quotas for this species may be used up before a large amount of target species can be caught, further reducing the value of landings.

Fishers could adopt a number of different practices that may increase selectivity, allowing catch compositions to better match available quota. These include adoption of more selective fishing gears, a change in target species, or a change in fishing grounds or season (Course et al., 2011). Reducing fishing in certain months when catches of regulated species were high allowed English North Sea otter trawlers to maximise fleet operating profit in the model in Chapter 4. However, the adoption of a number of more selective gears that are currently available did not benefit fishers due to a reduction in both limiting and valuable un-regulated catches. However, given sufficient time and economic support the fishing industry could potentially improve the performance of these gears, as was seen in the 50% project detailed in Chapter 2 (Armstrong and Revill, 2010). Giving fishers sufficient time to adapt to the changes in selectivity required under catch quotas will be a very important duty of fisheries managers. It will take time to develop new fishing techniques to suit the management system, and these are likely to vary between different fisheries, fleets and vessels, dependent upon the regulated species and the existing selectivity of vessels. If catch quotas are introduced too rapidly fishing may become economically unsustainable for some fleets, before they can adjust their catch compositions. Under the reforms of the CFP catch quotas for species that define a fishery should be introduced by 2016, however, catch quotas for other species can be introduced as late as 2019 (European Commission, 2013). This staggered introduction of catch quotas may give fishers adequate time to develop methods of reducing catches of non-target species, the quotas for which may be limiting. If vessels or fleets are limited by a target species, the economic impact of catch quotas may be reduced by buying or leasing additional quota. If reductions in revenue are less severe due to this additional quota the strength of the incentive to adopt more selective fishing practices may be reduced. However, the cost of acquiring extra quota should still provide an incentive for fishers to adjust their catch composition to better match their quota allocations.

Even with sufficient time it may not be possible for fishers to change their practices sufficiently to match available quota. A number of measures are included under the CFP reforms that may reduce the likelihood that operating under catch quotas becomes unprofitable for these fleets (European Commission, 2013). If the cost of altering the selectivity of fishing is prohibitively expensive or unwanted catches represent only a minimal defined percentage of total annual catches, fleets may be granted access to a *de minimis* exemption. This will allow these fleets to continue to discard up to 7% of the total annual catches of the regulated species in the first few years of the reforms (European Commission, 2013). Fleets may also be allowed to continue to discard catch if evidence of high discard survival rates can be provided (European Commission, 2013). The impact of limiting non-target quota species on fleets excluded from these exemptions may be reduced by allowing the non-target species to be counted against up to 9% of the quota for the target species (European Commission, 2013). Alternatively managers could allocate a larger proportion of the limiting catch quota to these fleets, reducing the prospect that fishing will be constrained by a species that is rarely caught. These provisions should not allow fleets to continue to discard large amounts of unwanted catch, or exceed non-target quotas by a large degree. Consequently an incentive should still be created for fishers to adopt more selective fishing practices and adjust catch compositions as far as is possible, whilst reducing the likelihood that fishing will become unprofitable.

The incentive for more selective fishing is reliant upon the full documentation of catches. However, the same qualities of catch quotas that create the incentives for more selective fishing will also create incentives for non-compliance. Illegal discarding may prevent the total catch being counted against quota, delaying the fulfilment of quota and allowing fishing to continue for longer. High levels of surveillance and enforcement may be needed to prevent such behaviour. Observer programmes with 100% coverage have been used to document total catches in the British Columbia fisheries to great success (Grafton et al., 2005). However, implementing a similar programme in EU fisheries may be prohibitively expensive (Graham et al., 2007, Vestergaard, 1996). Recent catch quota pilot schemes have utilised on-board cameras and sensors to document catches (Kindt-Larsen et al., 2011, Course et al., 2011), but these have their own cost implications. Self-sampling or the use of a reference fleet are other options favoured by fishers but may have issues with bias (Mangi et al., 2013). Consequently, ensuring a high level of monitoring and compliance may be a significant challenge for fisheries managers under the reforms of the CFP.

In this body of work we have shown how catch quotas and a discard ban may create an incentive for more selective fishing practices, how this incentive will be distributed within and between fleets, and the factors that will affect its strength. The findings of the models are based on a multitude of assumptions; however, such assumptions have allowed us to pinpoint which vessels, segments and fleets are likely to see the greatest changes in revenue when the reforms of the CFP come into force. We have identified the nature of the fleets most likely to benefit or lose out under catch quotas, and highlighted which fleets or segments are likely to need support during the transition from landings quotas. This represents new and important information about how fishing activity and behaviour may change in the UK, and in the wider context of European fisheries under the reformed CFP. The take home message is that the reforms of the CFP have the potential to fundamentally change how fisheries are managed and how fishers operate. As the CFP reforms come into force the face of European fishing is likely to see a substantial change.

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Appendices

Supplementary materials from Chapters 3, 4, and 5

Appendix 1 – Supplementary material for Chapter 3.

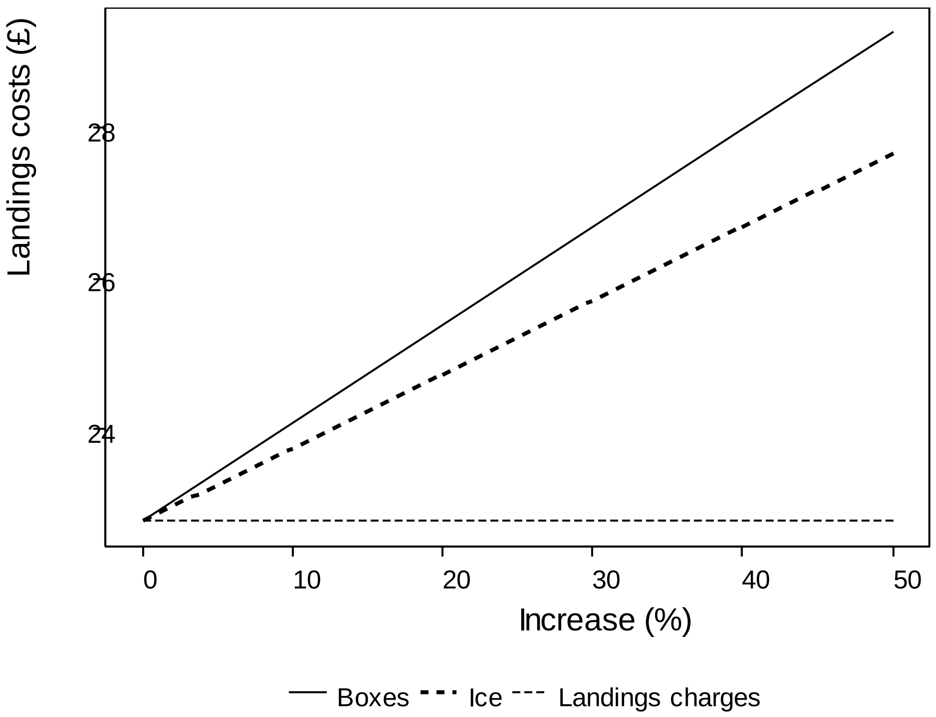

Figure S1 The influence of the increases in cost of boxes (solid line), ice (thick dashed line) and landings charges (thin dashed line) on overall landings costs of 1 t of unmarketable catch.

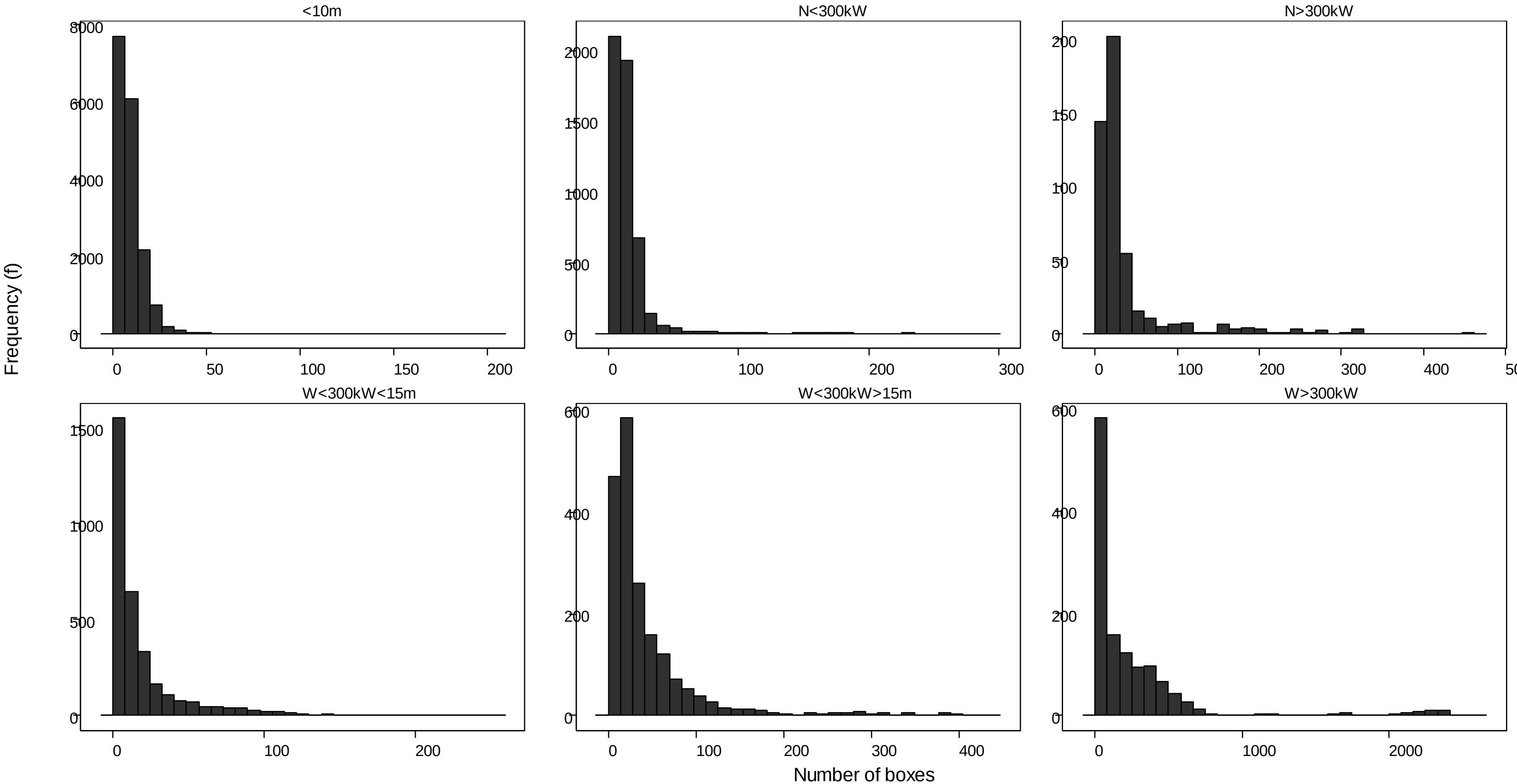

Figure S2 The distribution of the volume of landings (number of fish boxes) achieved on trips documented in the FAD between 2008 and 2010 for <10m, Nephrops and whitefish otter trawlers.

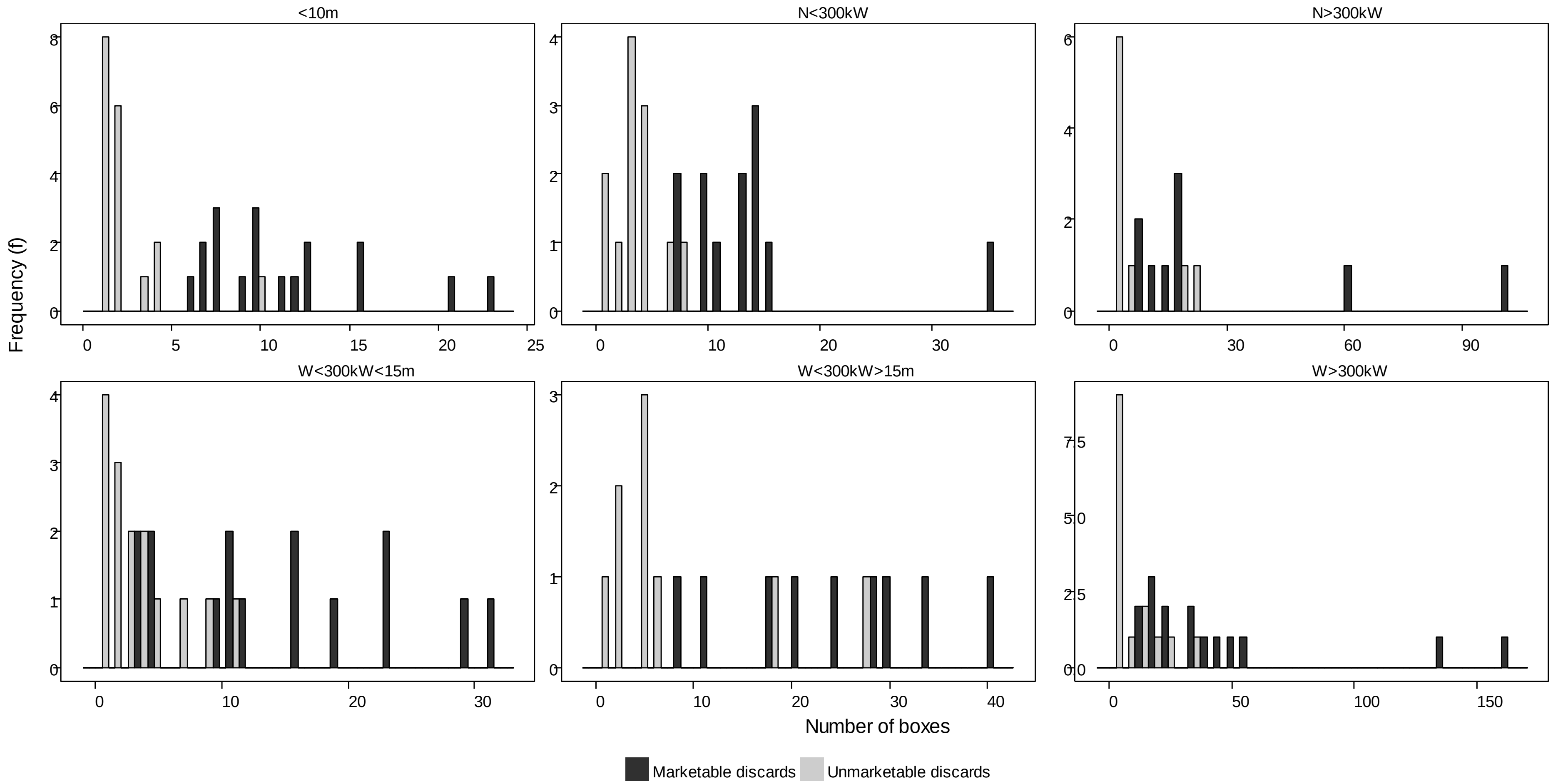

Figure S3 The distribution of the volume of discards (number of fish boxes) achieved on trips sampled in the COP between 2008 and 2010 for <10m, Nephrops and whitefish otter trawlers. The volume of marketable (>MLS and >MMS) discards is shown in dark grey, the volume of unmarketable discards (<MLS and <MMS) is shown in light grey.

Table S1. Change in number of trips, marketable catches and income of English North Sea otter trawlers under a discard ban and a catch quota for cod, haddock, plaice, sole, or whiting compared to 2008-2010, based on retention of all catch ($C\&U$), or avoidance of unmarketable fish of the quota species (No U_q). Parentheses show range due to uncertainty in catch estimates and value of unmarketable catch.

Vessel segment	Catch quota species	Change in annual trips (%)		Change in marketable catch (%)		Change in income (%)	
		$C\&U$	No U_q	$C\&U$	No U_q	$C\&U$	No U_q
<10m trawlers	Cod	-33 (-50, 3)	32 (20, 45)	13 (1, 38)	121 (95, 143)	-18 (-34, 14)	60 (51, 71)
	Haddock	-3 (-11, 7)	15 (12, 20)	63 (44, 79)	94 (59, 127)	18 (14, 22)	40 (31, 50)
	Plaice	-49 (-65, -3)	58 (26, 113)	-13 (-29, 30)	166 (134, 212)	-37 (-54, 7)	92 (65, 137)
	Sole	30 (21, 40)	47 (44, 51)	119 (89, 144)	147 (102, 191)	58 (53, 63)	79 (65, 92)
	Whiting	-25 (-33, -16)	0 (-6, 7)	25 (13, 35)	68 (44, 89)	-9 (-12, -7)	21 (19, 25)
Nephrops trawlers <300kW	Cod	-11 (-22, 2)	25 (18, 32)	36 (30, 43)	92 (68, 114)	11 (6, 16)	56 (46, 66)
	Haddock	-21 (-31, -6)	8 (1, 16)	22 (16, 28)	66 (51, 80)	-1 (-7, 7)	35 (29, 41)
	Plaice	-27 (-37, -13)	46 (33, 60)	13 (7, 18)	124 (101, 145)	-8 (-14, -1)	82 (68, 98)
	Sole	30 (21, 41)	43 (36, 51)	100 (83, 114)	120 (89, 150)	62 (53, 72)	79 (64, 94)
	Whiting	-54 (-64, -33)	-22 (-37, 1)	-29 (-37, -13)	19 (12, 31)	-42 (-52, -24)	-3 (-14, 14)
Nephrops trawlers >300kW	Cod	-52 (-71, 34)	-22 (-48, 62)	-25 (-43, 58)	23 (2, 90)	-38 (-56, 46)	2 (-21, 76)
	Haddock	-39 (-59, 18)	-18 (-40, 28)	-5 (-20, 39)	29 (16, 51)	-21 (-38, 29)	7 (-8, 39)
	Plaice	29 (1, 80)	34 (4, 89)	103 (52, 199)	110 (56, 214)	68 (27, 144)	74 (31, 156)

Table S1 continued.

Vessel segment	Catch quota species	Change in annual trips (%)		Change in marketable catch (%)		Change in income (%)	
		$C\&U$	No U_q	$C\&U$	No U_q	$C\&U$	No U_q
	Sole	30 (8, 64)	36 (12, 74)	104 (60, 173)	114 (60, 189)	69 (36, 122)	77 (41, 136)
	Whiting	-35 (-46, -16)	-21 (-33, -4)	3 (-5, 13)	24 (13, 37)	-15 (-20, -8)	3 (-4, 12)
Whitefish trawlers <300kW <15m	Cod	-22 (-35, -2)	15 (6, 26)	14 (8, 21)	67 (55, 80)	-6 (-16, 9)	38 (29, 48)
	Haddock	8 (3, 14)	15 (9, 21)	57 (40, 74)	67 (45, 88)	30 (22, 39)	38 (29, 47)
	Plaice	-28 (-44, 1)	26 (9, 49)	4 (-7, 25)	83 (72, 95)	-14 (-28, 13)	51 (40, 66)
	Sole	30 (24, 36)	32 (26, 38)	89 (62, 115)	92 (63, 120)	56 (45, 67)	58 (46, 71)
	Whiting	-19 (-29, -5)	-1 (-10, 9)	18 (13, 24)	44 (35, 52)	-2 (-8, 6)	19 (13, 25)
Whitefish trawlers <300kW >15m	Cod	4 (-4, 13)	23 (18, 29)	46 (37, 55)	73 (55, 90)	25 (19, 33)	49 (40, 59)
	Haddock	11 (4, 18)	15 (8, 22)	55 (41, 69)	61 (44, 78)	34 (24, 44)	39 (29, 50)
	Plaice	5 (-12, 30)	31 (20, 45)	47 (34, 62)	84 (65, 108)	26 (13, 45)	58 (43, 78)
	Sole	30 (22, 39)	31 (23, 40)	82 (60, 104)	84 (61, 106)	57 (46, 70)	58 (46, 72)
	Whiting	-35 (-45, -21)	-29 (-39, -15)	-9 (-13, -3)	-1 (-5, 4)	-22 (-29, -12)	-15 (-21, -5)
Whitefish trawlers >300kW	Cod	14 (8, 20)	20 (13, 27)	28 (20, 36)	35 (26, 44)	23 (16, 31)	29 (22, 38)
	Haddock	5 (-1, 11)	9 (3, 15)	18 (11, 26)	22 (15, 31)	13 (7, 21)	17 (10, 25)
	Plaice	26 (20, 34)	33 (27, 39)	42 (35, 50)	50 (41, 58)	36 (30, 43)	44 (37, 51)
	Sole	30 (11, 56)	30 (11, 56)	46 (24, 77)	46 (24, 77)	40 (20, 70)	40 (20, 70)
	Whiting	-19 (-29, -5)	-11 (-20, 2)	-8 (-14, -1)	0 (-5, 6)	-12 (-19, -2)	-4 (-10, 4)

Appendix 2 – Supplementary material for Chapter 4.

Table S1 Percentage change in fishing effort (no. of trips), marketable(>MLS) landings in tonnes and operating profits of English North Sea otter trawler segments under a cod, haddock, plaice, or whiting catch quota, or a combination of cod, haddock and plaice (CHP), cod, haddock and whiting (CHW), cod, plaice and whiting (CPW) or cod, haddock, plaice and whiting catch quotas (CHPW), compared to under the existing landings quotas of 2010, assuming no change in fishing behaviour. Numbers in parentheses show estimates derived using the upper and lower 95% confidence intervals of the mean discard and <MLS catch proportions.

Segment	Catch Quota(s)	Change in fishing effort (%)	Change in marketable landings (%)	Change in operating profits (%)
Mixed trawlers <10m length overall (LOA) and <300kW engine power	Cod	-14 (-48,0)	-6 (-32,2)	-7 (-34,2)
	Haddock	0 (-2,0)	0 (-1,1)	0 (-2,0)
	Plaice	-10 (-29,0)	-9 (-28,1)	-9 (-28,0)
	Whiting	-14 (-28,-4)	-11 (-24,-2)	-13 (-25,-3)
	CHP	-14 (-48,-10)	-4 (-31,-1)	-6 (-33,-3)
	CHW	-15 (-48,-14)	-3 (-29,0)	-6 (-33,-3)
	CPW	-15 (-48,-14)	-2 (-28,1)	-5 (-32,-2)
	CHPW	-15 (-48,-14)	-3 (-29,1)	-5 (-32,-3)
Nephrops trawlers <300kW engine power	Cod	-14 (-48,0)	-11 (-44,1)	-11 (-43,1)
	Haddock	0 (-2,0)	0 (-1,1)	0 (-1,0)
	Plaice	-10 (-29,0)	-9 (-27,1)	-7 (-24,2)
	Whiting	-14 (-28,-5)	-11 (-22,-2)	-11 (-23,-3)
	CHP	-14 (-48,-10)	-9 (-42,-7)	-7 (-41,-6)
	CHW	-15 (-48,-14)	-8 (-41,-6)	-8 (-40,-8)
	CPW	-15 (-48,-14)	-7 (-40,-6)	-5 (-39,-5)
	CHPW	-15 (-48,-14)	-7 (-40,-6)	-5 (-38,-5)
Nephrops trawlers >300kW engine power	Cod	-14 (-48,0)	-11 (-44,1)	-10 (-43,2)
	Haddock	0 (-2,0)	1 (-1,1)	0 (-1,0)
	Plaice	-10 (-29,0)	-9 (-29,1)	-8 (-27,1)
	Whiting	-14 (-28,-4)	-9 (-20,0)	-10 (-22,-1)
	CHP	-15 (-48,-11)	-11 (-43,-9)	-9 (-41,-8)
	CHW	-15 (-48,-15)	-5 (-37,-4)	-6 (-37,-5)
	CPW	-14 (-47,-14)	-5 (-39,-3)	-4 (-38,-3)
	CHPW	-16 (-49,-14)	-7 (-41,-5)	-6 (-40,-5)
Whitefish trawlers <15m LOA and <300kW engine power	Cod	-14 (-48,0)	-9 (-41,3)	-6 (-38,4)
	Haddock	0 (-2,0)	2 (1,2)	2 (1,2)
	Plaice	-11 (-30,0)	-10 (-28,1)	-8 (-26,2)
	Whiting	-14 (-28,-4)	-10 (-22,-1)	-10 (-23,-1)
	CHP	-14 (-48,-11)	-6 (-39,-4)	-1 (-34,0)
	CHW	-15 (-48,-14)	-3 (-37,-1)	0 (-34,1)
	CPW	-15 (-48,-14)	-3 (-38,-2)	0 (-34,1)
	CHPW	-15 (-48,-14)	-2 (-36,-1)	2 (-32,3)

Table S1 continued.

Segment	Catch Quota(s)	Change in fishing effort (%)	Change in marketable landings (%)	Change in operating profits (%)
Whitefish trawlers >15m LOA and <300kW engine power	Cod	-14 (-48,0)	-12 (-46,1)	-10 (-43,2)
	Haddock	0 (-2,0)	1 (-1,1)	1 (0,1)
	Plaice	-10 (-29,0)	-4 (-22,5)	14 (-2,19)
	Whiting	-14 (-28,-4)	-10 (-22,-1)	-10 (-23,-1)
	CHP	-14 (-48,-11)	-4 (-41,-2)	15 (-28,17)
	CHW	-15 (-48,-14)	-8 (-44,-7)	-6 (-41,-5)
	CPW	-15 (-48,-14)	-2 (-39,-1)	16 (-27,17)
	CHPW	-15 (-48,-14)	-2 (-38,-1)	17 (-24,18)
Whitefish trawlers >300kW engine power	Cod	-14 (-49,0)	-13 (-47,0)	-13 (-47,0)
	Haddock	0 (-2,0)	0 (-2,0)	0 (-2,0)
	Plaice	-10 (-29,0)	-3 (-21,6)	8 (-6,14)
	Whiting	-14 (-28,-5)	-14 (-27,-4)	-14 (-27,-4)
	CHP	-14 (-48,-10)	-6 (-43,-3)	5 (-36,9)
	CHW	-15 (-48,-14)	-15 (-47,-14)	-14 (-47,-13)
	CPW	-15 (-48,-14)	-7 (-42,-3)	5 (-35,7)
	CHPW	-15 (-47,-14)	-7 (-42,-3)	4 (-35,7)
Fleet	Cod	-14 (-48,0)	-12 (-44,1)	-10 (-41,1)
	Haddock	0 (-2,0)	0 (-1,1)	0 (-1,0)
	Plaice	-10 (-29,0)	-5 (-23,4)	-1 (-17,7)
	Whiting	-14 (-28,-4)	-12 (-25,-3)	-13 (-26,-3)
	CHP	-14 (-48,-10)	-6 (-41,-4)	0 (-35,1)
	CHW	-15 (-48,-14)	-11 (-43,-10)	-9 (-39,-8)
	CPW	-15 (-48,-14)	-5 (-39,-3)	1 (-33,2)
	CHPW	-15 (-48,-14)	-5 (-39,-3)	0 (-33,2)

Table S2 Percentage change in fishing effort (no. of trips), marketable(>MLS) landings in tonnes and operating profits of English North Sea otter trawler segments under a cod, haddock, plaice, or whiting catch quota, or a combination of cod, haddock and plaice (CHP), cod, haddock and whiting (CHW), cod, plaice and whiting (CPW) or cod, haddock, plaice and whiting catch quotas (CHPW), compared to under the existing landings quotas of 2010 based on 5 different changes in gear selectivity (described in Table 2 of main text). Numbers in parentheses show estimates derived using the upper and lower 95% confidence intervals of the mean discard and <MLS catch proportions.

Selectivity change	Segment	Catch Quota(s)	Change in fishing effort (%)	Change in marketable landings (%)	Change in operating profits (%)
1: Adoption of more selective gear by Nephrops trawlers					
	Mixed trawlers <10m length overall (LOA) and <300kW engine power	Cod	-13 (-47,0)	-11 (-34,-5)	-10 (-35,-3)
		Haddock	0 (0,0)	-7 (-7,-7)	-5 (-5,-4)
		Plaice	-10 (-29,0)	-16 (-33,-7)	-13 (-31,-4)
		Whiting	-3 (-19,0)	-7 (-21,-5)	-6 (-21,-4)
		CHP	-13 (-46,-10)	-10 (-33,-6)	-9 (-34,-6)
		CHW	-13 (-47,-3)	-8 (-33,-4)	-8 (-34,-4)
		CPW	-13 (-47,-10)	-8 (-32,-4)	-8 (-33,-5)
		CHPW	-13 (-47,-10)	-7 (-32,-4)	-7 (-34,-5)
	Nephrops trawlers <300kW engine power	Cod	-12 (-47,0)	-21 (-49,-12)	-19 (-48,-10)
		Haddock	0 (0,0)	-12 (-12,-12)	-11 (-11,-10)
		Plaice	-10 (-30,0)	-20 (-36,-11)	-17 (-33,-9)
		Whiting	-3 (-19,0)	-12 (-25,-11)	-11 (-24,-9)
		CHP	-13 (-46,-10)	-19 (-48,-18)	-17 (-46,-16)
		CHW	-12 (-47,-3)	-18 (-48,-11)	-16 (-46,-10)
		CPW	-13 (-47,-10)	-18 (-48,-17)	-15 (-45,-14)
		CHPW	-13 (-47,-10)	-17 (-47,-16)	-14 (-45,-14)
	Nephrops trawlers >300kW engine power	Cod	-12 (-46,0)	-22 (-51,-14)	-19 (-48,-11)
		Haddock	0 (0,0)	-15 (-15,-14)	-12 (-12,-12)
		Plaice	-10 (-29,0)	-24 (-40,-15)	-21 (-37,-11)
		Whiting	-3 (-20,0)	-14 (-26,-12)	-11 (-24,-10)
		CHP	-13 (-47,-11)	-22 (-49,-21)	-18 (-47,-18)
		CHW	-13 (-48,-3)	-21 (-50,-12)	-18 (-48,-10)
		CPW	-13 (-47,-10)	-20 (-49,-19)	-16 (-46,-15)
		CHPW	-13 (-47,-10)	-18 (-48,-17)	-15 (-45,-14)
	Whitefish trawlers <15m LOA and <300kW engine power	Cod	-12 (-47,0)	-6 (-39,3)	-4 (-35,4)
		Haddock	0 (0,0)	2 (1,3)	2 (1,4)
		Plaice	-10 (-29,0)	-9 (-28,1)	-7 (-25,2)
		Whiting	-3 (-19,0)	3 (-11,5)	2 (-12,3)
		CHP	-13 (-46,-10)	-5 (-37,-3)	0 (-33,2)
		CHW	-12 (-47,-3)	0 (-35,7)	2 (-31,8)
		CPW	-13 (-47,-10)	-1 (-36,1)	3 (-32,4)
		CHPW	-13 (-47,-10)	1 (-35,2)	5 (-30,6)

Table S2 continued.

Selectivity change	Segment	Catch Quota(s)	Change in fishing effort (%)	Change in marketable landings (%)	Change in operating profits (%)
	Whitefish trawlers >15m LOA and <300kW engine power	Cod	-13 (-47,0)	-10 (-44,1)	-8 (-42,2)
		Haddock	0 (0,0)	1 (0,1)	1 (1,2)
		Plaice	-10 (-29,0)	-3 (-22,5)	15 (-2,19)
		Whiting	-3 (-19,0)	2 (-13,4)	2 (-13,3)
		CHP	-13 (-47,-10)	-4 (-40,-2)	15 (-27,17)
		CHW	-13 (-47,-3)	-5 (-41,3)	-3 (-39,5)
		CPW	-13 (-47,-10)	1 (-36,3)	20 (-23,22)
		CHPW	-13 (-47,-10)	1 (-38,3)	21 (-24,22)
	Whitefish trawlers >300kW engine power	Cod	-12 (-47,0)	-12 (-46,0)	-12 (-47,0)
		Haddock	0 (0,0)	0 (0,0)	0 (0,0)
		Plaice	-10 (-29,0)	-3 (-19,6)	9 (-5,14)
		Whiting	-3 (-19,0)	-2 (-18,1)	-2 (-18,1)
		CHP	-13 (-46,-11)	-5 (-41,-2)	6 (-34,9)
		CHW	-12 (-47,-3)	-11 (-47,-2)	-11 (-46,-2)
		CPW	-13 (-47,-10)	-4 (-41,0)	7 (-35,10)
		CHPW	-13 (-46,-10)	-4 (-40,-1)	7 (-33,10)
2: Adoption of more selective gear by Nephrops trawlers					
	Mixed trawlers <10m length overall (LOA) and <300kW engine power	Cod	0 (-36,0)	-10 (-33,-7)	-2 (-29,0)
		Haddock	0 (0,0)	-16 (-16,-16)	-8 (-8,-8)
		Plaice	-9 (-28,0)	-23 (-38,-16)	-16 (-32,-8)
		Whiting	0 (-4,0)	-14 (-17,-13)	-7 (-10,-7)
		CHP	-10 (-37,0)	-17 (-33,-9)	-10 (-29,-2)
		CHW	0 (-36,0)	-7 (-31,-4)	-1 (-27,2)
		CPW	-10 (-37,0)	-15 (-33,-7)	-9 (-28,0)
		CHPW	-10 (-36,0)	-15 (-33,-7)	-9 (-28,0)
	Nephrops trawlers <300kW engine power	Cod	0 (-36,0)	-24 (-51,-24)	-15 (-45,-15)
		Haddock	0 (0,0)	-25 (-25,-25)	-16 (-16,-16)
		Plaice	-9 (-28,0)	-31 (-45,-25)	-21 (-36,-14)
		Whiting	0 (-4,0)	-24 (-27,-24)	-15 (-18,-15)
		CHP	-10 (-37,0)	-31 (-51,-24)	-21 (-43,-13)
		CHW	0 (-36,0)	-23 (-50,-23)	-14 (-44,-14)
		CPW	-9 (-37,0)	-30 (-50,-23)	-20 (-43,-12)
		CHPW	-10 (-36,0)	-30 (-50,-23)	-19 (-42,-12)
	Nephrops trawlers >300kW engine power	Cod	0 (-37,0)	-28 (-52,-27)	-18 (-46,-18)
		Haddock	0 (0,0)	-28 (-29,-28)	-20 (-20,-19)
		Plaice	-9 (-28,0)	-35 (-46,-28)	-25 (-38,-19)
		Whiting	0 (-4,0)	-27 (-29,-27)	-18 (-20,-18)
		CHP	-10 (-37,0)	-34 (-53,-27)	-25 (-46,-17)
		CHW	0 (-36,0)	-26 (-50,-26)	-16 (-44,-16)
		CPW	-10 (-37,0)	-32 (-52,-26)	-23 (-45,-16)
		CHPW	-10 (-37,0)	-33 (-51,-26)	-24 (-44,-16)

Table S2 continued.

Selectivity change	Segment	Catch Quota(s)	Change in fishing effort (%)	Change in marketable landings (%)	Change in operating profits (%)
	Whitefish trawlers <15m LOA and <300kW engine power	Cod	0 (-36,0)	6 (-28,8)	9 (-23,11)
		Haddock	0 (0,0)	2 (1,3)	2 (1,4)
		Plaice	-9 (-28,0)	-9 (-27,1)	-7 (-24,2)
		Whiting	0 (-4,0)	6 (4,8)	5 (3,5)
		CHP	-9 (-37,0)	-1 (-25,9)	4 (-19,14)
		CHW	0 (-36,0)	14 (-22,16)	17 (-18,19)
		CPW	-9 (-37,0)	3 (-23,13)	7 (-18,17)
		CHPW	-10 (-37,0)	4 (-22,15)	8 (-17,19)
	Whitefish trawlers >15m LOA and <300kW engine power	Cod	0 (-36,0)	3 (-32,3)	5 (-29,6)
		Haddock	0 (0,0)	1 (0,1)	1 (1,2)
		Plaice	-9 (-28,0)	-3 (-20,5)	15 (1,19)
		Whiting	0 (-4,0)	5 (2,6)	5 (2,5)
		CHP	-10 (-37,0)	0 (-28,9)	20 (-13,25)
		CHW	0 (-36,0)	8 (-29,9)	11 (-26,12)
		CPW	-9 (-37,0)	5 (-24,13)	25 (-9,29)
		CHPW	-10 (-37,0)	5 (-25,14)	26 (-10,30)
	Whitefish trawlers >300kW engine power	Cod	0 (-36,0)	0 (-36,1)	1 (-36,1)
		Haddock	0 (0,0)	0 (0,0)	0 (0,0)
		Plaice	-10 (-28,0)	-2 (-19,6)	10 (-4,14)
		Whiting	0 (-4,0)	1 (-3,1)	1 (-3,1)
		CHP	-10 (-37,0)	-2 (-32,6)	10 (-24,15)
		CHW	0 (-36,0)	1 (-34,2)	2 (-34,2)
		CPW	-10 (-37,0)	-1 (-31,7)	11 (-22,16)
		CHPW	-10 (-37,0)	-1 (-30,7)	11 (-21,16)
3: Adoption of more selective gear by whitefish trawlers					
	Mixed trawlers <10m length overall (LOA) and <300kW engine power	Cod	0 (-9,0)	-10 (-16,-6)	-22 (-25,-18)
		Haddock	-8 (-16,-4)	-23 (-29,-20)	-33 (-38,-29)
		Plaice	-10 (-30,0)	-24 (-39,-16)	-33 (-47,-26)
		Whiting	-10 (-25,0)	-21 (-33,-14)	-32 (-42,-25)
		CHP	-11 (-29,-8)	-19 (-34,-6)	-29 (-42,-19)
		CHW	-10 (-24,-8)	-16 (-27,-3)	-27 (-38,-17)
		CPW	-11 (-29,-10)	-16 (-32,-4)	-27 (-41,-17)
		CHPW	-11 (-30,-10)	-16 (-33,-3)	-27 (-42,-17)
	Nephrops trawlers <300kW engine power	Cod	0 (-9,0)	3 (-2,4)	3 (-1,4)
		Haddock	-8 (-16,-4)	-8 (-15,-4)	-8 (-15,-4)
		Plaice	-10 (-29,0)	-9 (-27,1)	-7 (-24,2)
		Whiting	-10 (-25,0)	-6 (-18,3)	-7 (-20,2)
		CHP	-11 (-29,-8)	-7 (-24,-3)	-4 (-22,0)
		CHW	-10 (-24,-8)	-3 (-16,1)	-3 (-17,2)
		CPW	-11 (-29,-10)	-3 (-22,1)	-1 (-19,4)
		CHPW	-11 (-29,-10)	-3 (-22,2)	-1 (-19,4)

Table S2 continued.

Selectivity change	Segment	Catch Quota(s)	Change in fishing effort (%)	Change in marketable landings (%)	Change in operating profits (%)
	Nephrops trawlers >300kW engine power	Cod	0 (-9,0)	4 (-2,5)	5 (0,5)
		Haddock	-8 (-15,-4)	-8 (-15,-3)	-8 (-15,-3)
		Plaice	-10 (-30,0)	-9 (-28,1)	-8 (-27,1)
		Whiting	-10 (-25,0)	-4 (-16,4)	-5 (-17,4)
		CHP	-11 (-29,-8)	-7 (-26,-3)	-5 (-24,0)
		CHW	-10 (-24,-8)	1 (-13,4)	0 (-13,5)
		CPW	-11 (-30,-10)	-1 (-21,3)	0 (-19,5)
		CHPW	-11 (-29,-10)	0 (-21,3)	1 (-19,6)
	Whitefish trawlers <15m LOA and <300kW engine power	Cod	0 (-9,0)	-17 (-22,-17)	-29 (-31,-28)
		Haddock	-8 (-16,-4)	-25 (-30,-22)	-36 (-39,-34)
		Plaice	-11 (-30,0)	-28 (-43,-19)	-37 (-49,-30)
		Whiting	-10 (-24,0)	-23 (-33,-16)	-34 (-42,-29)
		CHP	-11 (-29,-8)	-24 (-39,-21)	-31 (-44,-27)
		CHW	-10 (-24,-8)	-19 (-30,-16)	-29 (-38,-25)
		CPW	-11 (-29,-10)	-21 (-36,-18)	-29 (-42,-25)
		CHPW	-11 (-30,-10)	-19 (-35,-16)	-27 (-41,-23)
	Whitefish trawlers >15m LOA and <300kW engine power	Cod	0 (-9,0)	-18 (-24,-18)	-25 (-30,-24)
		Haddock	-9 (-16,-4)	-25 (-31,-22)	-32 (-36,-29)
		Plaice	-10 (-30,0)	-21 (-36,-14)	-11 (-21,-8)
		Whiting	-10 (-25,0)	-23 (-34,-16)	-30 (-40,-24)
		CHP	-11 (-28,-8)	-19 (-33,-17)	-7 (-17,-5)
		CHW	-10 (-25,-9)	-21 (-32,-20)	-27 (-37,-25)
		CPW	-11 (-29,-10)	-16 (-31,-15)	-5 (-18,-4)
		CHPW	-11 (-30,-10)	-16 (-31,-14)	-4 (-17,-2)
	Whitefish trawlers >300kW engine power	Cod	0 (-9,0)	-23 (-30,-23)	-27 (-33,-27)
		Haddock	-8 (-15,-4)	-30 (-35,-27)	-32 (-37,-30)
		Plaice	-10 (-30,0)	-24 (-37,-18)	-16 (-25,-13)
		Whiting	-10 (-24,0)	-31 (-41,-23)	-33 (-43,-27)
		CHP	-11 (-30,-8)	-24 (-36,-21)	-16 (-24,-13)
		CHW	-10 (-25,-8)	-30 (-42,-29)	-33 (-44,-32)
		CPW	-11 (-30,-10)	-24 (-36,-20)	-15 (-29,-13)
		CHPW	-11 (-30,-10)	-24 (-36,-20)	-16 (-28,-13)
4: Adoption of more selective gear by *Nephrops* and whitefish trawlers					
	Mixed trawlers <10m length overall (LOA) and <300kW engine power	Cod	0 (-6,0)	-18 (-23,-10)	-26 (-30,-20)
		Haddock	-6 (-14,-2)	-28 (-34,-25)	-35 (-40,-33)
		Plaice	-10 (-30,0)	-31 (-45,-23)	-37 (-50,-31)
		Whiting	0 (-14,0)	-21 (-30,-20)	-30 (-38,-29)
		CHP	-11 (-29,-7)	-26 (-40,-13)	-33 (-46,-23)
		CHW	-7 (-14,-2)	-21 (-27,-8)	-30 (-35,-19)
		CPW	-11 (-30,0)	-23 (-39,-11)	-32 (-46,-22)
		CHPW	-10 (-29,-7)	-23 (-38,-10)	-31 (-45,-21)

Table S2 continued.

Selectivity change	Segment	Catch Quota(s)	Change in fishing effort (%)	Change in marketable landings (%)	Change in operating profits (%)
	Nephrops trawlers <300kW engine power	Cod	0 (-6,0)	-10 (-12,-9)	-8 (-10,-7)
		Haddock	-6 (-14,-2)	-18 (-24,-14)	-16 (-22,-13)
		Plaice	-10 (-30,0)	-20 (-36,-11)	-17 (-33,-9)
		Whiting	0 (-14,0)	-10 (-20,-9)	-8 (-20,-8)
		CHP	-11 (-29,-7)	-18 (-34,-14)	-14 (-31,-10)
		CHW	-7 (-14,-2)	-13 (-19,-9)	-11 (-18,-6)
		CPW	-11 (-30,0)	-15 (-33,-6)	-13 (-30,-3)
		CHPW	-10 (-30,-7)	-15 (-32,-11)	-12 (-29,-7)
	Nephrops trawlers >300kW engine power	Cod	0 (-6,0)	-12 (-14,-11)	-8 (-11,-8)
		Haddock	-6 (-13,-2)	-21 (-27,-17)	-18 (-24,-14)
		Plaice	-10 (-30,0)	-24 (-38,-15)	-21 (-35,-11)
		Whiting	0 (-14,0)	-11 (-22,-10)	-9 (-20,-8)
		CHP	-11 (-29,-7)	-21 (-36,-17)	-17 (-32,-12)
		CHW	-7 (-14,-2)	-14 (-20,-10)	-11 (-17,-6)
		CPW	-11 (-31,0)	-17 (-35,-7)	-13 (-32,-3)
		CHPW	-10 (-30,-7)	-17 (-33,-13)	-13 (-29,-8)
	Whitefish trawlers <15m LOA and <300kW engine power	Cod	0 (-6,0)	-17 (-19,-17)	-29 (-31,-28)
		Haddock	-6 (-14,-2)	-23 (-28,-21)	-34 (-38,-33)
		Plaice	-10 (-30,0)	-27 (-43,-19)	-36 (-49,-30)
		Whiting	0 (-14,0)	-15 (-24,-13)	-27 (-35,-27)
		CHP	-11 (-29,-6)	-23 (-39,-20)	-31 (-44,-27)
		CHW	-7 (-14,-2)	-16 (-21,-13)	-26 (-31,-22)
		CPW	-10 (-30,0)	-20 (-37,-11)	-28 (-43,-22)
		CHPW	-10 (-30,-7)	-18 (-35,-15)	-26 (-41,-22)
	Whitefish trawlers >15m LOA and <300kW engine power	Cod	0 (-5,0)	-18 (-21,-18)	-25 (-27,-24)
		Haddock	-7 (-14,-2)	-24 (-29,-20)	-31 (-36,-28)
		Plaice	-10 (-30,0)	-21 (-35,-14)	-10 (-20,-8)
		Whiting	0 (-14,0)	-14 (-24,-13)	-22 (-31,-22)
		CHP	-11 (-30,-7)	-19 (-34,-18)	-7 (-18,-6)
		CHW	-7 (-15,-2)	-18 (-24,-15)	-24 (-30,-21)
		CPW	-11 (-30,0)	-16 (-31,-8)	-4 (-15,-1)
		CHPW	-11 (-30,-7)	-14 (-30,-13)	-2 (-14,-1)
	Whitefish trawlers >300kW engine power	Cod	0 (-6,0)	-23 (-28,-23)	-27 (-31,-27)
		Haddock	-6 (-13,-2)	-29 (-34,-25)	-32 (-37,-28)
		Plaice	-10 (-30,0)	-24 (-36,-18)	-16 (-24,-13)
		Whiting	0 (-14,0)	-23 (-34,-23)	-26 (-37,-26)
		CHP	-11 (-29,-7)	-24 (-36,-20)	-15 (-24,-13)
		CHW	-6 (-14,-2)	-28 (-33,-24)	-31 (-36,-27)
		CPW	-11 (-30,0)	-23 (-37,-17)	-15 (-24,-12)
		CHPW	-10 (-29,-7)	-23 (-36,-20)	-15 (-24,-12)

Table S2 continued.

Selectivity change	Segment	Catch Quota(s)	Change in fishing effort (%)	Change in marketable landings (%)	Change in operating profits (%)
5: Adoption of more selective gear by *Nephrops* and whitefish trawlers					
	Mixed trawlers <10m length overall (LOA) and <300kW engine power	Cod	0 (0,0)	-30 (-33,-22)	-32 (-34,-25)
		Haddock	0 (-5,0)	-33 (-36,-33)	-35 (-38,-35)
		Plaice	-9 (-29,0)	-38 (-51,-32)	-40 (-52,-34)
		Whiting	0 (0,0)	-31 (-32,-29)	-33 (-34,-33)
		CHP	-9 (-28,0)	-35 (-48,-28)	-37 (-49,-31)
		CHW	0 (-5,0)	-27 (-30,-19)	-30 (-34,-23)
		CPW	-10 (-28,0)	-34 (-47,-26)	-36 (-49,-30)
		CHPW	-11 (-29,0)	-34 (-47,-27)	-37 (-49,-30)
	Nephrops trawlers <300kW engine power	Cod	0 (0,0)	-24 (-25,-23)	-15 (-16,-13)
		Haddock	0 (-5,0)	-25 (-29,-25)	-16 (-20,-16)
		Plaice	-9 (-29,0)	-31 (-46,-25)	-22 (-37,-14)
		Whiting	0 (0,0)	-24 (-25,-23)	-15 (-15,-14)
		CHP	-9 (-29,0)	-30 (-45,-24)	-20 (-36,-13)
		CHW	0 (-5,0)	-23 (-27,-22)	-14 (-18,-12)
		CPW	-10 (-28,0)	-30 (-44,-23)	-20 (-34,-12)
		CHPW	-11 (-29,0)	-31 (-44,-23)	-21 (-35,-12)
	Nephrops trawlers >300kW engine power	Cod	0 (0,0)	-28 (-28,-26)	-18 (-19,-17)
		Haddock	0 (-5,0)	-28 (-32,-28)	-20 (-24,-20)
		Plaice	-9 (-29,0)	-34 (-48,-28)	-25 (-41,-19)
		Whiting	0 (0,0)	-27 (-28,-26)	-18 (-19,-17)
		CHP	-9 (-29,0)	-34 (-47,-27)	-24 (-39,-17)
		CHW	0 (-5,0)	-26 (-29,-25)	-16 (-20,-15)
		CPW	-9 (-27,0)	-33 (-45,-26)	-23 (-37,-16)
		CHPW	-11 (-30,0)	-33 (-47,-26)	-24 (-40,-16)
	Whitefish trawlers <15m LOA and <300kW engine power	Cod	0 (0,0)	-17 (-19,-14)	-29 (-31,-24)
		Haddock	0 (-5,0)	-18 (-21,-17)	-30 (-31,-30)
		Plaice	-9 (-29,0)	-27 (-42,-19)	-36 (-48,-30)
		Whiting	0 (0,0)	-15 (-16,-12)	-27 (-29,-25)
		CHP	-9 (-28,0)	-22 (-38,-15)	-30 (-43,-24)
		CHW	0 (-5,0)	-10 (-13,-7)	-21 (-23,-16)
		CPW	-10 (-29,0)	-20 (-36,-11)	-28 (-42,-22)
		CHPW	-11 (-29,0)	-18 (-34,-9)	-26 (-39,-19)
	Whitefish trawlers >15m LOA and <300kW engine power	Cod	0 (0,0)	-18 (-18,-17)	-25 (-26,-23)
		Haddock	0 (-5,0)	-18 (-22,-18)	-26 (-28,-25)
		Plaice	-9 (-29,0)	-20 (-34,-14)	-9 (-18,-8)
		Whiting	0 (0,0)	-14 (-16,-12)	-22 (-24,-20)
		CHP	-9 (-28,0)	-18 (-33,-12)	-5 (-17,-4)
		CHW	0 (-5,0)	-12 (-16,-10)	-19 (-22,-17)
		CPW	-10 (-28,0)	-15 (-30,-8)	-4 (-14,-1)
		CHPW	-11 (-29,0)	-14 (-30,-7)	-2 (-14,0)

Table S2 continued

Selectivity change	Segment	Catch Quota(s)	Change in fishing effort (%)	Change in marketable landings (%)	Change in operating profits (%)
	Whitefish trawlers >300kW engine power	Cod	0 (0,0)	-23 (-24,-23)	-27 (-27,-26)
		Haddock	0 (-5,0)	-24 (-27,-23)	-27 (-30,-27)
		Plaice	-9 (-29,0)	-23 (-36,-18)	-15 (-23,-12)
		Whiting	0 (0,0)	-23 (-23,-23)	-26 (-27,-26)
		CHP	-9 (-28,0)	-23 (-36,-18)	-15 (-23,-12)
		CHW	0 (-5,0)	-23 (-27,-22)	-26 (-29,-25)
		CPW	-10 (-29,0)	-23 (-35,-17)	-14 (-23,-11)
		CHPW	-10 (-29,0)	-23 (-35,-17)	-14 (-23,-11)

Table S3 Percentage change in fishing effort (no. of trips), marketable(>MLS) landings in tonnes and operating profits of English North Sea otter trawler segments under a cod, haddock, plaice, or whiting catch quota, or a combination of cod, haddock and plaice (CHP), cod, haddock and whiting (CHW), cod, plaice and whiting (CPW) or cod, haddock, plaice and whiting catch quotas (CHPW), compared to under the existing landings quotas of 2010, based on the assumption that fishers will select trips that will *maximise* fleet operating profit (see Table 3 in main text). Numbers in parentheses show estimates derived using the upper and lower 95% confidence intervals of the mean discard and <MLS catch proportions.

Segment	Catch Quota(s)	Change in fishing effort (%)	Change in marketable landings (%)	Change in operating profits (%)
Mixed trawlers <10m length overall (LOA) and <300kW engine power	Cod	0 (-14,0)	9 (1,14)	8 (2,11)
	Haddock	0 (0,0)	0 (0,1)	0 (0,0)
	Plaice	0 (0,0)	1 (1,2)	1 (0,2)
	Whiting	-2 (-7,0)	1 (-3,2)	1 (0,2)
	CHP	0 (-14,0)	11 (-4,15)	9 (1,12)
	CHW	-1 (-14,-1)	11 (1,17)	9 (3,13)
	CPW	-7 (-18,-1)	-1 (-12,12)	2 (-5,10)
	CHPW	-1 (-14,-1)	12 (-6,13)	10 (-1,10)
Nephrops trawlers <300kW engine power	Cod	0 (-19,0)	3 (-16,4)	3 (-13,4)
	Haddock	0 (0,0)	0 (0,1)	0 (0,1)
	Plaice	0 (0,0)	2 (1,3)	4 (2,7)
	Whiting	-10 (-24,-1)	-3 (-14,2)	-2 (-10,2)
	CHP	0 (-11,0)	2 (-10,6)	5 (-6,9)
	CHW	-7 (-18,-7)	-3 (-12,-2)	-1 (-9,0)
	CPW	-8 (-32,-5)	-3 (-24,-2)	0 (-21,1)
	CHPW	-4 (-31,-4)	-13 (-23,1)	-8 (-20,4)
Nephrops trawlers >300kW engine power	Cod	0 (-16,0)	4 (-3,5)	5 (0,5)
	Haddock	0 (0,0)	1 (0,1)	0 (0,1)
	Plaice	0 (0,0)	1 (1,2)	2 (1,4)
	Whiting	-4 (-12,0)	5 (3,7)	5 (3,5)
	CHP	0 (-6,0)	5 (1,6)	7 (4,9)
	CHW	-6 (-16,-2)	5 (3,7)	6 (5,7)
	CPW	-7 (-10,-3)	1 (-1,7)	3 (1,8)
	CHPW	-10 (-12,-3)	-11 (-12,7)	-8 (-9,9)
Whitefish trawlers <15m LOA and <300kW engine power	Cod	-1 (-24,0)	-5 (-36,3)	-2 (-30,4)
	Haddock	0 (0,0)	2 (1,3)	2 (1,4)
	Plaice	0 (0,0)	1 (1,2)	3 (2,5)
	Whiting	-7 (-19,-1)	0 (-5,3)	1 (-2,3)
	CHP	-2 (-14,0)	-4 (-19,6)	0 (-12,9)
	CHW	-11 (-22,-5)	-8 (-26,4)	-1 (-22,7)
	CPW	-7 (-25,-6)	4 (-16,5)	10 (-9,11)
	CHPW	-6 (-25,-6)	-16 (-28,0)	-4 (-17,5)

Table S3 continued.

Segment	Catch Quota(s)	Change in fishing effort (%)	Change in marketable landings (%)	Change in operating profits (%)
Whitefish trawlers >15m LOA and <300kW engine power	Cod	-1 (-24,0)	1 (-14,1)	2 (-13,3)
	Haddock	0 (0,0)	1 (0,1)	1 (1,1)
	Plaice	-2 (-3,0)	-10 (-16,5)	2 (-7,19)
	Whiting	-23 (-31,-13)	-3 (-5,-1)	-1 (-2,1)
	CHP	-3 (-30,-1)	0 (-8,7)	19 (5,33)
	CHW	-11 (-27,-8)	1 (-7,2)	4 (-6,5)
	CPW	-17 (-47,-8)	6 (-47,8)	29 (-37,30)
	CHPW	-12 (-46,-11)	-9 (-41,7)	14 (-28,25)
Whitefish trawlers >300kW engine power	Cod	-1 (-2,0)	-2 (-2,1)	-2 (-2,2)
	Haddock	0 (0,0)	0 (0,0)	0 (0,0)
	Plaice	-1 (-6,0)	5 (-4,10)	17 (12,21)
	Whiting	-4 (-10,0)	1 (0,1)	1 (0,1)
	CHP	-7 (-16,-1)	-1 (-14,5)	10 (-1,17)
	CHW	-3 (-13,-1)	0 (-2,2)	1 (-1,2)
	CPW	-13 (-18,-3)	3 (0,6)	15 (12,23)
	CHPW	-18 (-20,-3)	-2 (-5,6)	9 (7,19)
Fleet	Cod	0 (-16,0)	0 (-4,1)	3 (0,4)
	Haddock	0 (0,0)	0 (0,1)	0 (0,1)
	Plaice	0 (0,0)	2 (-3,4)	8 (6,9)
	Whiting	-5 (-12,-1)	0 (-2,1)	1 (-1,1)
	CHP	-1 (-12,0)	1 (-5,5)	10 (5,11)
	CHW	-4 (-15,-4)	1 (-1,2)	4 (1,6)
	CPW	-8 (-20,-4)	2 (-5,5)	9 (6,11)
	CHPW	-3 (-19,-3)	-3 (-6,5)	8 (5,12)

Table S4 Percentage change in fishing effort (no. of trips), marketable(>MLS) landings in tonnes and operating profits of English North Sea otter trawler segments under a cod, haddock, plaice, or whiting catch quota, or a combination of cod, haddock and plaice (CHP), cod, haddock and whiting (CHW), cod, plaice and whiting (CPW) or cod, haddock, plaice and whiting catch quotas (CHPW), compared to under the existing landings quotas of 2010, based on the worst case scenario in which fishers select trips that will *minimise* fleet operating profit (see Table 3 in main text). Numbers in parentheses show estimates derived using the upper and lower 95% confidence intervals of the mean discard and <MLS catch proportions.

Segment	Catch Quota(s)	Change in fishing effort (%)	Change in marketable landings (%)	Change in operating profits (%)
Mixed trawlers <10m length overall (LOA) and <300kW engine power	Cod	-44 (-95,0)	-41 (-75,2)	-56 (-78,2)
	Haddock	0 (-69,0)	0 (-55,1)	0 (-72,0)
	Plaice	-100 (-100,0)	-100 (-100,1)	-100 (-100,0)
	Whiting	-77 (-79,-73)	-58 (-61,-53)	-77 (-79,-73)
	CHP	-45 (-100,-45)	-100 (-100,-38)	-100 (-100,-56)
	CHW	-70 (-95,-50)	-51 (-74,-47)	-64 (-78,-62)
	CPW	-100 (-100,-50)	-100 (-100,-51)	-100 (-100,-64)
	CHPW	-100 (-100,-50)	-100 (-100,-50)	-100 (-100,-64)
Nephrops trawlers <300kW engine power	Cod	-63 (-98,0)	-66 (-88,1)	-71 (-90,1)
	Haddock	0 (-65,0)	0 (-50,1)	0 (-56,0)
	Plaice	-100 (-100,0)	-97 (-98,1)	-98 (-99,2)
	Whiting	-75 (-80,-65)	-70 (-78,-53)	-77 (-84,-62)
	CHP	-65 (-100,-61)	-96 (-96,-68)	-97 (-97,-68)
	CHW	-83 (-98,-33)	-41 (-88,-39)	-45 (-89,-44)
	CPW	-100 (-100,-33)	-97 (-98,-40)	-98 (-99,-44)
	CHPW	-100 (-100,-33)	-97 (-98,-31)	-98 (-99,-36)
Nephrops trawlers >300kW engine power	Cod	-66 (-98,0)	-75 (-96,1)	-76 (-95,2)
	Haddock	0 (-62,0)	1 (-61,1)	0 (-65,0)
	Plaice	-100 (-100,0)	-100 (-100,1)	-100 (-100,1)
	Whiting	-63 (-70,-52)	-57 (-64,-51)	-63 (-71,-57)
	CHP	-67 (-100,-67)	-100 (-100,-76)	-100 (-100,-76)
	CHW	-72 (-98,-57)	-68 (-95,-59)	-69 (-95,-64)
	CPW	-100 (-100,-58)	-100 (-100,-69)	-100 (-100,-70)
	CHPW	-100 (-100,-100)	-100 (-100,-100)	-100 (-100,-100)
Whitefish trawlers <15m LOA and <300kW engine power	Cod	-45 (-95,0)	-47 (-66,3)	-50 (-62,4)
	Haddock	0 (-75,0)	2 (-29,2)	2 (-45,2)
	Plaice	-100 (-100,0)	-100 (-100,1)	-100 (-100,2)
	Whiting	-77 (-82,-68)	-62 (-70,-43)	-73 (-79,-58)
	CHP	-44 (-100,-44)	-100 (-100,-31)	-100 (-100,-38)
	CHW	-74 (-94,-20)	-27 (-65,-25)	-30 (-61,-29)
	CPW	-100 (-100,-20)	-100 (-100,-27)	-100 (-100,-30)
	CHPW	-100 (-100,-100)	-100 (-100,-100)	-100 (-100,-100)

Table S4 continued.

Segment	Catch Quota(s)	Change in fishing effort (%)	Change in marketable landings (%)	Change in operating profits (%)
Whitefish trawlers >15m LOA and <300kW engine power	Cod	-51 (-91,0)	-68 (-82,1)	-66 (-78,2)
	Haddock	0 (-50,0)	1 (-58,1)	1 (-63,1)
	Plaice	-94 (-94,0)	-54 (-56,5)	-36 (-36,19)
	Whiting	-60 (-69,-50)	-72 (-80,-61)	-77 (-84,-66)
	CHP	-46 (-94,-42)	-52 (-84,-37)	-33 (-82,-24)
	CHW	-58 (-91,-28)	-51 (-82,-51)	-52 (-77,-51)
	CPW	-94 (-94,-30)	-54 (-55,-41)	-36 (-51,-20)
	CHPW	-94 (-94,-30)	-54 (-55,-28)	-35 (-50,-23)
Whitefish trawlers >300kW engine power	Cod	-67 (-91,0)	-74 (-82,0)	-76 (-82,0)
	Haddock	0 (-61,0)	0 (-55,0)	0 (-62,0)
	Plaice	-64 (-69,0)	-40 (-56,6)	-21 (-44,14)
	Whiting	-74 (-86,-59)	-90 (-98,-78)	-92 (-98,-82)
	CHP	-61 (-90,-50)	-40 (-84,-36)	-21 (-85,-18)
	CHW	-67 (-91,-54)	-78 (-81,-53)	-78 (-82,-59)
	CPW	-64 (-70,-54)	-40 (-77,-36)	-21 (-77,-18)
	CHPW	-64 (-64,-31)	-40 (-77,-36)	-20 (-77,-17)
Fleet	Cod	-49 (-95,0)	-66 (-80,1)	-66 (-80,1)
	Haddock	0 (-68,0)	0 (-53,1)	0 (-65,0)
	Plaice	-98 (-98,0)	-59 (-63,4)	-64 (-65,7)
	Whiting	-75 (-79,-69)	-79 (-87,-68)	-82 (-87,-74)
	CHP	-49 (-98,-48)	-59 (-80,-50)	-64 (-79,-49)
	CHW	-72 (-95,-44)	-65 (-80,-53)	-66 (-80,-62)
	CPW	-98 (-98,-44)	-59 (-64,-57)	-64 (-66,-63)
	CHPW	-98 (-98,-44)	-59 (-64,-39)	-64 (-65,-48)

Appendix 3 – Supplementary material from Chapter 5

Table S1 The target F, actual resulting F and SSB of 6 North Sea demersal stocks between 2014 and 2016, based on the 4 different catch quota setting protocols, with (+ ov) or without a 10% cod overage.

		Target F			F			SSB (t)			Catch quota (t)			Landings (t)		
Stock	Protocol	2014	2015	2016	2014	2015	2016	2014	2015	2016	2014	2015	2016	2014	2015	2016
Cod	0%	0.22	0.32	0.40	0.14	0.13	0.13	79,066	118,255	163,291	30,506	36,607	43,928	27,910	33,578	40,139
	75%	0.22	0.31	0.40	0.17	0.16	0.16	79,066	114,842	154,636	35,572	42,687	51,224	32,753	39,335	46,978
	100%	0.22	0.31	0.39	0.18	0.17	0.17	79,066	113,722	151,833	37,261	44,713	53,656	34,367	41,247	49,093
	30%c	0.22	0.31	0.38	0.19	0.18	0.18	79,066	112,392	148,225	39,658	47,589	57,107	36,349	43,588	51,944
	0% + ov	0.22	0.32	0.40	0.16	0.14	0.13	79,066	116,480	161,059	33,556	36,912	45,033	30,595	33,825	41,111
	75% + ov	0.22	0.31	0.39	0.19	0.17	0.17	79,066	112,910	151,784	39,129	43,042	52,512	35,934	39,632	47,972
	100% + ov	0.22	0.30	0.38	0.20	0.18	0.18	79,066	111,701	148,793	40,987	45,086	55,005	37,690	41,553	50,108
	30%c + ov	0.22	0.30	0.37	0.21	0.19	0.19	79,066	110,227	144,841	43,623	47,986	58,543	39,834	43,905	52,864
Haddock	0%	0.3	0.3	0.3	0.07	0.06	0.06	232,750	232,884	263,785	41,179	47,355	54,459	12,134	12,791	17,473
	75%	0.3	0.3	0.3	0.08	0.08	0.08	232,750	230,964	260,199	49,211	51,750	58,091	14,311	15,340	21,344
	100%	0.3	0.3	0.3	0.09	0.08	0.08	232,750	230,316	258,995	51,889	51,750	57,982	15,047	16,218	22,510
	30%c	0.3	0.3	0.3	0.09	0.09	0.09	232,750	229,443	257,625	53,532	51,750	57,848	16,048	17,115	24,368
	0% + ov	0.3	0.3	0.3	0.08	0.07	0.06	232,750	231,768	262,589	41,179	47,355	54,459	13,407	13,020	18,117
	75% + ov	0.3	0.3	0.3	0.09	0.08	0.08	232,750	229,632	258,757	49,211	51,750	57,870	15,829	15,647	22,105
	100% + ov	0.3	0.3	0.3	0.10	0.08	0.08	232,750	228,911	257,589	51,889	51,750	57,783	16,648	16,554	23,231
	30%c + ov	0.3	0.3	0.3	0.10	0.09	0.09	232,750	227,942	255,957	53,532	51,750	57,667	17,766	17,445	25,033
Plaice	0%	0.3	0.3	0.3	0.05	0.05	0.05	743,214	873,685	1,011,217	111,631	128,375	147,631	47,025	49,349	53,845
	75%	0.3	0.3	0.3	0.06	0.06	0.06	743,214	864,429	989,587	147,927	170,116	195,633	59,777	63,680	69,013
	100%	0.3	0.3	0.3	0.07	0.07	0.07	743,214	861,127	982,819	160,026	184,029	211,634	64,059	67,547	73,091
	30%c	0.3	0.3	0.3	0.07	0.07	0.07	743,214	862,999	986,704	145,120	166,888	191,921	61,817	65,807	71,612
	0% + ov	0.3	0.3	0.3	0.05	0.05	0.05	743,214	871,776	1,008,662	111,631	128,375	147,631	49,383	49,900	54,787
	75% + ov	0.3	0.3	0.3	0.07	0.06	0.07	743,214	862,005	986,789	147,927	170,116	195,633	63,094	64,159	70,224
	100% + ov	0.3	0.3	0.3	0.07	0.07	0.07	743,214	858,553	979,558	160,026	184,029	211,634	67,566	68,340	74,209

Table S1 continued.

Stock	Protocol	Target F 2014	Target F 2015	Target F 2016	F 2014	F 2015	F 2016	SSB (t) 2014	SSB (t) 2015	SSB (t) 2016	Catch quota (t) 2014	Catch quota (t) 2015	Catch quota (t) 2016	Landings (t) 2014	Landings (t) 2015	Landings (t) 2016
	30%c + ov	0.3	0.3	0.3	0.07	0.07	0.07	743,214	860,461	985,127	145,120	166,888	191,921	64,971	66,332	72,951
Saithe	0%	0.24	0.3	0.3	0.12	0.11	0.11	162,360	222,918	318,558	85,581	92,260	106,099	38,739	46,211	56,194
	75%	0.24	0.3	0.3	0.14	0.13	0.13	162,360	217,447	302,748	85,581	92,260	106,099	45,489	54,527	66,190
	100%	0.24	0.3	0.3	0.15	0.14	0.14	162,360	215,622	298,127	85,581	92,260	106,099	47,743	57,315	69,314
	30%c	0.24	0.3	0.3	0.16	0.15	0.15	162,360	213,550	293,408	111,256	94,567	108,753	50,481	60,519	71,971
	0% + ov	0.24	0.3	0.3	0.13	0.11	0.11	162,360	219,843	314,055	85,581	92,260	106,099	42,486	46,644	57,582
	75% + ov	0.24	0.3	0.3	0.15	0.13	0.13	162,360	213,989	297,973	85,581	92,260	106,099	49,869	55,045	67,753
	100% + ov	0.24	0.3	0.3	0.16	0.14	0.14	162,360	212,198	294,336	85,581	92,260	106,099	52,335	57,872	70,129
	30%c + ov	0.24	0.3	0.3	0.17	0.15	0.15	162,360	210,468	290,345	111,256	94,567	108,753	55,381	61,106	73,549
Sole	0%	0.21	0.28	0.2	0.05	0.05	0.05	44,592	52,265	66,308	11,900	11,780	12,905	2,815	3,301	3,827
	75%	0.21	0.28	0.2	0.07	0.07	0.07	44,592	51,266	64,075	11,900	11,780	12,830	3,727	4,364	4,967
	100%	0.21	0.28	0.2	0.08	0.08	0.08	44,592	50,930	63,463	11,900	11,780	12,749	4,025	4,663	5,276
	30%c	0.21	0.28	0.2	0.07	0.07	0.07	44,592	51,321	64,179	15,470	13,150	13,673	3,688	4,320	4,934
	0% + ov	0.21	0.28	0.2	0.06	0.05	0.05	44,592	52,152	66,194	11,900	11,780	12,874	2,923	3,324	3,879
	75% + ov	0.21	0.28	0.2	0.08	0.07	0.07	44,592	51,128	63,893	11,900	11,780	12,830	3,864	4,394	5,011
	100% + ov	0.21	0.28	0.2	0.08	0.08	0.08	44,592	50,784	63,269	11,900	11,780	12,688	4,180	4,701	5,312
	30%c + ov	0.21	0.28	0.2	0.07	0.07	0.07	44,592	51,171	63,975	15,470	13,150	13,624	3,831	4,320	4,992
Whiting	0%	0.23	0.23	0.23	0.06	0.05	0.05	330,809	389,326	441,852	28,681	32,983	37,930	13,109	14,169	15,973
	75%	0.23	0.23	0.23	0.07	0.06	0.06	330,809	387,351	438,342	40,435	46,500	53,475	15,611	17,131	19,400
	100%	0.23	0.23	0.23	0.07	0.07	0.07	330,809	386,699	437,127	44,353	51,006	58,657	16,453	18,168	20,582
	30%c	0.23	0.23	0.23	0.07	0.07	0.07	330,809	386,071	435,945	37,285	42,878	49,309	17,250	19,175	21,873
	0% + ov	0.23	0.23	0.23	0.06	0.05	0.05	330,809	388,340	440,926	28,681	32,983	37,930	14,382	14,402	16,501
	75% + ov	0.23	0.23	0.23	0.07	0.06	0.06	330,809	386,159	437,116	40,435	46,500	53,475	17,119	17,439	20,014
	100% + ov	0.23	0.23	0.23	0.08	0.07	0.07	330,809	385,430	435,827	44,353	51,006	58,657	18,041	18,465	21,312
	30%c + ov	0.23	0.23	0.23	0.08	0.07	0.07	330,809	384,759	434,547	37,285	42,878	49,309	18,950	19,413	22,682

Table S2 Median percentage change in the effort of each fleet, the species landings and the revenue of modelled North Sea demersal finfish fleets compared to 2012 when operating under catch quotas set using the 30%c protocol. The species for which the quota allocation is most limiting. The proportion of 2012 landings from 6 stocks contributed by each species. The catch per unit effort (CPUE) of each species in each projection year, 2014-2016.

Fleet	Limiting species	Stock	2012 discard rate (%)	% of 2012 landings	CPUE 2014	CPUE 2015	CPUE 2016	Change in effort (%) 2014	Change in effort (%) 2015	Change in effort (%) 2016	Change in landings (%) 2014	Change in landings (%) 2015	Change in landings (%) 2016	Change in revenue (%) 2014	Change in revenue (%) 2015	Change in revenue (%) 2016
BE Beam <24m	Plaice	Cod	7	5	0.14	0.18	0.21	-46	-44	-43	3	35	57	-20	-8	8
		Haddock	12	0	0	0	0				-50	-47	-22			
		Plaice	57	56	2.94	3.14	3.33				105	134	159			
		Saithe	0	0	0	0	0				-34	-14	5			
		Sole	0	35	0.5	0.59	0.71				-42	-31	-21			
		Whiting	33	3	0.1	0.11	0.13				18	33	53			
BE Beam >=24m	Cod	Cod	25	16	0.57	0.69	0.83	-47	-49	-49	25	50	80	1	8	23
		Haddock	12	2	0.02	0.02	0.03				-51	-48	-26			
		Plaice	30	76	2.76	2.95	3.12				23	23	35			
		Saithe	0	0	0	0	0				-33	-20	-3			
		Sole	0	6	0.09	0.11	0.13				-44	-38	-27			
		Whiting	33	1	0.03	0.04	0.04				11	24	40			
BE Otter	Cod	Cod	69	7	0.64	0.78	0.93	-78	-78	-78	25	50	81	-62	-58	-52
		Haddock	12	0	0	0	0				-80	-78	-69			
		Plaice	0	86	2.35	2.51	2.66				-64	-63	-60			
		Saithe	0	0	0	0	0				-72	-66	-59			
		Sole	0	6	0.11	0.13	0.15				-77	-74	-69			
		Whiting	33	1	0.04	0.04	0.05				-53	-48	-39			
DK Beam	Cod	Cod	29	6	0.32	0.39	0.47	-50	-53	-52	25	50	80	-15	-12	-1
		Haddock	12	0	0.01	0.01	0.01				-54	-51	-31			
		Plaice	0	94	3.52	3.76	3.99				-19	-19	-10			
		Saithe	0	0	0	0	0				-37	-25	-9			

Table S2 continued.

Fleet	Limiting species	Stock	2012 discard rate (%)	% of 2012 landings	CPUE			Change in effort (%)			Change in landings (%)			Change in revenue (%)		
					2014	2015	2016	2014	2015	2016	2014	2015	2016	2014	2015	2016
		Sole	0	0	0.01	0.01	0.01				-47	-42	-31			
		Whiting	0	0	0	0	0				0	0	0			
DK FDF	Cod	Cod	3	30	2.26	2.77	3.33	-32	-35	-35	25	50	79	4	21	39
		Haddock	9	12	0.41	0.45	0.65				-39	-35	-8			
		Plaice	0	23	1.53	1.64	1.73				11	11	17			
		Saithe	0	34	1.74	2.2	2.69				-13	3	20			
		Sole	0	0	0.01	0.01	0.01				-28	-22	-10			
		Whiting	10	1	0.05	0.06	0.07				6	17	29			
DK Otter <24m	Cod	Cod	43	23	1.24	1.51	1.82	-60	-62	-61	25	50	80	-25	-14	1
		Haddock	27	13	0.24	0.26	0.38				-55	-52	-32			
		Plaice	2	45	1.31	1.4	1.48				-33	-33	-26			
		Saithe	0	19	0.42	0.53	0.65				-49	-39	-26			
		Sole	0	0	0	0	0				-58	-53	-44			
		Whiting	49	0	0	0	0				10	22	41			
DK Otter 24-40m	Cod	Cod	26	14	0.56	0.69	0.83	-48	-50	-50	25	50	80	-7	2	14
		Haddock	27	6	0.11	0.13	0.18				-42	-39	-11			
		Plaice	2	65	1.82	1.95	2.07				-13	-13	-7			
		Saithe	0	14	0.3	0.38	0.46				-34	-21	-8			
		Sole	0	0	0	0	0				-45	-40	-29			
		Whiting	43	1	0.03	0.03	0.03				29	43	61			
DK Seine	Cod	Cod	27	29	3.53	4.32	5.19	-48	-51	-50	25	50	80	-9	3	21
		Haddock	15	29	1.36	1.5	2.19				-50	-48	-25			
		Plaice	0	38	3.15	3.36	3.57				-16	-16	-8			
		Saithe	0	4	0.27	0.34	0.41				-35	-22	-6			

Table S2 continued.

Fleet	Limiting species	Stock	2012 discard rate (%)	% of 2012 landings	CPUE 2014	CPUE 2015	CPUE 2016	Change in effort (%) 2014	Change in effort (%) 2015	Change in effort (%) 2016	Change in landings (%) 2014	Change in landings (%) 2015	Change in landings (%) 2016	Change in revenue (%) 2014	Change in revenue (%) 2015	Change in revenue (%) 2016
		Sole	0	0	0	0	0				-45	-39	-29			
		Whiting	49	0	0.01	0.01	0.02				43	59	80			
DK Static	Whiting	Cod	4	40	2.32	2.85	3.42	-99	-99	-99	-98	-98	-98	-99	-98	-98
		Haddock	8	1	0.01	0.02	0.02				-99	-99	-99			
		Plaice	0	51	2.66	2.84	3.01				-99	-98	-98			
		Saithe	0	1	0.04	0.05	0.06				-99	-99	-98			
		Sole	0	7	0.24	0.28	0.35				-99	-99	-99			
		Whiting	99	0	0	0	0				125	158	197			
EN Beam	Cod	Cod	15	0	0.03	0.04	0.04	-40	-43	-43	25	50	80	-9	-7	3
		Haddock	12	0	0	0	0				-45	-42	-17			
		Plaice	0	97	4.63	4.94	5.24				-3	-3	4			
		Saithe	0	0	0	0	0				-24	-10	5			
		Sole	0	3	0.09	0.1	0.12				-37	-31	-19			
		Whiting	35	0	0	0.01	0.01				29	43	63			
EN FDF	Cod	Cod	0	23	2.34	2.87	3.44	-30	-33	-33	25	50	79	0	16	37
		Haddock	0	19	0.85	0.94	1.36				-43	-40	-14			
		Plaice	0	6	0.55	0.58	0.62				15	14	19			
		Saithe	0	47	3.37	4.25	5.2				-11	6	23			
		Sole	0	0	0	0	0				-26	-19	-6			
		Whiting	0	5	0.42	0.48	0.55				-1	8	22			
EN Otter <24m	Cod	Cod	46	12	0.69	0.85	1.02	-62	-63	-63	25	50	80	-33	-26	-13
		Haddock	5	25	0.37	0.41	0.59				-68	-66	-51			
		Plaice	0	33	0.99	1.06	1.12				-38	-37	-32			
		Saithe	0	5	0.12	0.15	0.18				-52	-42	-29			
		Sole	0	2	0.03	0.04	0.04				-60	-55	-47			

Table S2 continued.

Fleet	Limiting species	Stock	2012 discard rate (%)	% of 2012 landings	CPUE 2014	CPUE 2015	CPUE 2016	Change in effort (%) 2014	Change in effort (%) 2015	Change in effort (%) 2016	Change in landings (%) 2014	Change in landings (%) 2015	Change in landings (%) 2016	Change in revenue (%) 2014	Change in revenue (%) 2015	Change in revenue (%) 2016
		Whiting	51	24	1.24	1.4	1.6				9	20	40			
EN Otter >=40m	Whiting	Cod	16	1	0.04	0.05	0.06	-68	-68	-68	-31	-15	-5	-48	-43	-38
		Haddock	2	0	0	0	0				-74	-69	-59			
		Plaice	0	99	3.69	3.94	4.17				-48	-44	-40			
		Saithe	0	0	0	0	0				-61	-50	-38			
		Sole	0	0	0	0	0				-66	-60	-54			
		Whiting	80	0	0.07	0.08	0.09				125	158	196			
EN Otter 24-40m	Whiting	Cod	34	1	0.12	0.14	0.17	-67	-67	-67	-10	11	24	-41	-34	-27
		Haddock	2	11	0.29	0.32	0.46				-73	-68	-58			
		Plaice	0	81	4.43	4.73	5.01				-47	-42	-39			
		Saithe	0	0	0	0	0				-60	-49	-36			
		Sole	0	0	0	0.01	0.01				-65	-59	-53			
		Whiting	79	6	1.45	1.64	1.88				125	157	196			
EN <10m	Cod	Cod	35	35	0.25	0.3	0.36	-54	-55	-56	25	50	80	-28	-19	-3
		Haddock	6	13	0.03	0.03	0.05				-61	-58	-41			
		Plaice	0	4	0.02	0.02	0.02				-25	-26	-18			
		Saithe	0	0	0	0	0				-42	-31	-16			
		Sole	0	20	0.05	0.06	0.08				-52	-47	-36			
		Whiting	48	27	0.19	0.22	0.25				24	37	59			
FR Nets	Cod	Cod	3	32	0.22	0.26	0.32	-32	-33	-33	25	50	81	-20	-9	9
		Haddock	0	0	0	0	0				0	0	0			
		Plaice	0	14	0.08	0.09	0.1				12	13	24			
		Saithe	0	0	0	0	0				0	0	0			
		Sole	0	52	0.2	0.23	0.28				-28	-20	-3			

Table S2 continued.

Fleet	Limiting species	Stock	2012 discard rate (%)	% of 2012 landings	CPUE			Change in effort (%)			Change in landings (%)			Change in revenue (%)		
					2014	2015	2016	2014	2015	2016	2014	2015	2016	2014	2015	2016
FR OTH	Cod	Cod	14	10	0.02	0.03	0.03	-40	-42	-42	25	50	80	6	21	42
		Haddock	5	1	0	0	0				-48	-44	-21			
		Plaice	0	1	0	0	0				-1	-2	7			
		Saithe	0	21	0.03	0.03	0.04				-23	-9	10			
		Sole	0	1	0	0	0				-36	-30	-17			
		Whiting	14	66	0.11	0.13	0.15				-1	10	25			
FR Otter >=40m	Cod	Cod	27	1	0.06	0.07	0.09	-49	-51	-51	25	50	80	-34	-21	-5
		Haddock	12	1	0.02	0.02	0.04				-53	-50	-28			
		Plaice	0	0	0	0	0				0	0	0			
		Saithe	0	98	3.2	4.05	4.95				-35	-22	-7			
		Whiting	33	0	0.02	0.02	0.02				8	20	38			
FR Otter 10-40m	Cod	Cod	15	14	0.2	0.25	0.3	-41	-43	-43	25	50	80	29	45	69
		Haddock	12	2	0.01	0.01	0.02				-45	-42	-17			
		Plaice	0	1	0.01	0.01	0.01				-3	-4	3			
		Saithe	0	0	0	0	0				-25	-10	5			
		Sole	0	0	0	0	0				-37	-31	-20			
		Whiting	39	84	1.41	1.59	1.82				37	51	72			
FR <10m	Cod	Cod	11	22	0.02	0.03	0.03	-38	-39	-39	25	50	81	-6	6	29
		Plaice	0	20	0.02	0.02	0.02				2	3	15			
		Sole	0	21	0.01	0.01	0.02				-34	-26	-11			
		Whiting	40	36	0.04	0.05	0.05				49	64	93			
GE Beam >=24m	Whiting	Cod	27	2	0.06	0.07	0.09	-87	-87	-87	-68	-61	-54	-79	-76	-74
		Haddock	12	0	0	0	0				-88	-86	-82			
		Plaice	40	83	3.7	3.96	4.2				-65	-62	-58			
		Saithe	0	0	0	0	0				0	0	0			

Table S2 continued.

Fleet	Limiting species	Stock	2012 discard rate (%)	% of 2012 landings	CPUE 2014	CPUE 2015	CPUE 2016	Change in effort (%) 2014	Change in effort (%) 2015	Change in effort (%) 2016	Change in landings (%) 2014	Change in landings (%) 2015	Change in landings (%) 2016	Change in revenue (%) 2014	Change in revenue (%) 2015	Change in revenue (%) 2016
		Sole	0	15	0.26	0.31	0.37				-86	-84	-81			
		Whiting	92	0	0.04	0.04	0.05				125	158	197			
GE Otter <24m	Cod	Cod	43	3	0.76	0.93	1.12	-60	-61	-61	25	50	80	-29	-27	-19
		Haddock	4	1	0.06	0.07	0.1				-66	-64	-49			
		Plaice	6	95	11.81	12.61	13.37				-31	-30	-23			
		Saithe	0	1	0.06	0.07	0.09				-50	-39	-26			
		Sole	0	0	0.02	0.03	0.03				-58	-53	-44			
		Whiting	33	0	0.02	0.02	0.02				-15	-7	8			
GE Otter >=40m	Cod	Cod	1	2	0.34	0.41	0.49	-31	-34	-34	25	50	80	-11	6	24
		Haddock	1	1	0.08	0.09	0.13				-43	-40	-13			
		Plaice	6	0	0	0	0				20	20	27			
		Saithe	0	96	10.19	12.86	15.73				-12	5	22			
		Whiting	24	0	0.01	0.02	0.02				28	41	61			
GE Otter 24-40m	Cod	Cod	10	22	2.47	3.03	3.63	-37	-40	-40	25	50	80	-4	13	33
		Haddock	4	6	0.26	0.29	0.42				-47	-43	-19			
		Plaice	2	11	1	1.07	1.14				5	4	13			
		Saithe	0	61	4.34	5.48	6.7				-20	-5	14			
		Sole	0	0	0	0.01	0.01				-33	-27	-14			
		Whiting	27	0	0.04	0.05	0.05				22	35	54			
GE Static	Cod	Cod	20	58	3.6	4.41	5.29	-43	-46	-46	25	50	80	-31	-22	-7
		Haddock	12	1	0.03	0.04	0.05				-48	-44	-21			
		Plaice	0	4	0.18	0.19	0.2				-8	-8	1			
		Saithe	0	0	0.01	0.01	0.01				-28	-15	2			
		Sole	0	37	1.09	1.27	1.55				-40	-34	-23			

Table S2 continued.

Fleet	Limiting species	Stock	2012 discard rate (%)	% of 2012 landings	CPUE 2014	CPUE 2015	CPUE 2016	Change in effort (%) 2014	Change in effort (%) 2015	Change in effort (%) 2016	Change in landings (%) 2014	Change in landings (%) 2015	Change in landings (%) 2016	Change in revenue (%) 2014	Change in revenue (%) 2015	Change in revenue (%) 2016
		Whiting	33	0	0	0	0				19	32	50			
NL Beam <24m	Whiting	Cod	9	2	0.01	0.02	0.02	-77	-76	-76	-53	-42	-32	-71	-66	-61
		Haddock	0	0	0	0	0				0	0	0			
		Plaice	56	40	0.48	0.51	0.54				-13	-4	5			
		Sole	0	56	0.19	0.22	0.27				-75	-71	-66			
		Whiting	85	2	0.06	0.06	0.07				125	158	197			
NL Beam >=40m	Whiting	Cod	12	2	0.08	0.09	0.11	-78	-78	-77	-54	-43	-34	-66	-61	-56
		Haddock	0	0	0	0	0				-82	-79	-72			
		Plaice	43	75	3.38	3.61	3.83				-37	-30	-24			
		Saithe	0	0	0	0	0				0	0	0			
		Sole	0	21	0.35	0.41	0.5				-76	-72	-67			
		Whiting	86	1	0.1	0.11	0.13				125	158	197			
NL Beam 24-40m	Whiting	Cod	12	2	0.05	0.06	0.07	-75	-74	-74	-48	-36	-25	-64	-58	-52
		Haddock	0	0	0	0	0				0	0	0			
		Plaice	48	68	2.86	3.05	3.24				-20	-12	-3			
		Saithe	0	0	0	0	0				-69	-59	-49			
		Sole	0	30	0.41	0.48	0.59				-73	-68	-63			
		Whiting	84	1	0.09	0.1	0.11				125	158	197			
NL Otter	Cod	Cod	26	18	1.27	1.56	1.87	-49	-52	-52	24	49	79	17	29	43
		Haddock	12	3	0.07	0.08	0.12				-55	-50	-30			
		Plaice	38	75	5.67	6.05	6.42				30	33	46			
		Saithe	0	0	0.01	0.02	0.02				-37	-27	-9			
		Sole	0	0	0.01	0.01	0.01				-47	-42	-32			
		Whiting	64	4	0.42	0.47	0.54				102	125	155			

Table S2 continued.

Fleet	Limiting species	Stock	2012 discard rate (%)	% of 2012 landings	CPUE			Change in effort (%)			Change in landings (%)			Change in revenue (%)		
					2014	2015	2016	2014	2015	2016	2014	2015	2016	2014	2015	2016
NO Static	Cod	Cod	0	33	3.76	4.61	5.53	-30	-33	-33	25	50	80	4	25	49
		Haddock	0	6	0.31	0.34	0.49				-43	-39	-13			
		Plaice	0	0	0.01	0.02	0.02				15	14	21			
		Saithe	0	61	4.85	6.12	7.48				-11	6	24			
		Whiting	0	0	0	0	0				-1	9	25			
SC FDF	Cod	Cod	0	26	2.89	3.55	4.26	-30	-33	-33	25	50	80	-11	1	21
		Haddock	5	49	2.48	2.74	3.98				-40	-36	-9			
		Plaice	0	1	0.09	0.09	0.1				15	14	21			
		Saithe	0	13	1.04	1.31	1.6				-11	6	24			
		Whiting	7	11	1.03	1.16	1.33				6	18	31			
SC Otter <24m	Cod	Cod	43	17	1.01	1.23	1.48	-60	-62	-62	25	50	80	-34	-25	-9
		Haddock	25	49	0.96	1.06	1.54				-57	-54	-35			
		Plaice	0	3	0.09	0.1	0.1				-35	-35	-28			
		Saithe	0	7	0.17	0.22	0.26				-50	-40	-26			
		Sole	0	0	0	0	0				-58	-53	-44			
		Whiting	31	24	0.96	1.08	1.24				-18	-10	4			
SC Otter >=24m	Cod	Cod	28	17	1.87	2.3	2.76	-49	-52	-51	25	50	80	-26	-17	0
		Haddock	6	47	1.72	1.9	2.77				-56	-53	-33			
		Plaice	0	10	0.71	0.76	0.81				-17	-18	-9			
		Saithe	0	10	0.57	0.72	0.89				-36	-23	-7			
		Sole	0	0	0	0	0				-46	-40	-29			
		Whiting	9	16	1.13	1.28	1.46				-21	-13	0			
SC Static	Cod	Cod	0	80	0.03	0.04	0.05	-30	-33	-34	25	50	78	21	44	70
		Haddock	9	7	0	0	0				-37	-34	-6			
		Plaice	0	1	0	0	0				14	14	18			

Table S2 continued.

Fleet	Limiting species	Stock	2012 discard rate (%)	% of 2012 landings	CPUE			Change in effort (%)			Change in landings (%)			Change in revenue (%)		
					2014	2015	2016	2014	2015	2016	2014	2015	2016	2014	2015	2016
		Saithe	0	12	0	0	0.01				-11	5	23			
		Sole	0	0	0	0	0				-26	-19	-7			
		Whiting	0	0	0	0	0				-1	8	18			
SC <10m OTB	Cod	Cod	41	22	0.06	0.08	0.09	-59	-60	-60	25	50	80	-31	-22	-5
		Haddock	22	56	0.05	0.06	0.09				-57	-54	-35			
		Plaice	0	9	0.01	0.01	0.02				-33	-33	-26			
		Saithe	0	2	0	0	0				-48	-37	-24			
		Sole	0	0	0	0	0				-56	-51	-42			
		Whiting	45	12	0.03	0.03	0.04				6	16	35			

Table S3 The limiting species if no change in behaviour is made, compared to if the CPUE of cod is reduced by 30%. The percentage of the cod catch <MLS if no change in behaviour is made. The percentage of landings in 2012 contributed by cod or the limiting species. The CPUE of cod and the limiting species. The resulting change in cod landings, total landings and revenue under the 30%c protocol.

Fleet	Year	Limiting species - no change	Limiting species	% of cod catch <MLS – no change	% of 2012 landings from cod	% of 2012 landings from limiting species	cod CPUE	CPUE of limiting species	Change in cod landings (%)	Change in total landings (%)	Change in revenue (%)
BE Beam <24m	2014	Plaice	Plaice	1	5	56	0.1	2.93	-30	-2	-2
	2015	Plaice	Plaice	1	5	56	0.12	3.1	-28	-1	-2
	2016	Plaice	Plaice	1	5	56	0.15	3.27	-26	-1	-1
BE Beam >=24m	2014	Cod	Cod	0	16	16	0.4	0.4	0	35	31
	2015	Cod	Cod	0	16	16	0.49	0.49	0	32	28
	2016	Cod	Cod	0	16	16	0.6	0.6	-1	27	24
BE Otter	2014	Cod	Cod	25	7	7	0.45	0.45	0	34	40
	2015	Cod	Cod	25	7	7	0.55	0.55	0	31	38
	2016	Cod	Cod	25	7	7	0.67	0.67	1	28	36
DK Beam	2014	Cod	Cod	0	6	6	0.23	0.23	0	38	35
	2015	Cod	Cod	0	6	6	0.28	0.28	0	36	32
	2016	Cod	Cod	0	6	6	0.34	0.34	0	33	29
DK FDF	2014	Cod	Cod	5	30	30	1.59	1.59	0	25	21
	2015	Cod	Cod	5	30	30	1.96	1.96	-4	17	14
	2016	Cod	Sole	5	30	0	2.39	0.01	-22	-7	-9
DK Otter <24m	2014	Cod	Cod	21	23	23	0.87	0.87	0	25	32
	2015	Cod	Cod	21	23	23	1.07	1.07	0	22	30
	2016	Cod	Cod	21	23	23	1.31	1.31	0	19	29
DK Otter 24-40m	2014	Cod	Cod	2	14	14	0.4	0.4	0	33	26
	2015	Cod	Cod	2	14	14	0.49	0.49	0	29	23
	2016	Cod	Cod	2	14	14	0.6	0.6	-6	20	15

Table S3 continued.

Fleet	Year	Limiting species - no change	Limiting species	% of cod catch <MLS – no change	% of 2012 landings from cod	% of 2012 landings from limiting species	cod CPUE	CPUE of limiting species	Change in cod landings (%)	Change in total landings (%)	Change in revenue (%)
DK Seine	2014	Cod	Cod	9	29	29	2.47	2.47	0	23	21
	2015	Cod	Cod	9	29	29	3.06	3.06	0	19	18
	2016	Cod	Cod	9	29	29	3.73	3.73	-6	12	12
DK Static	2014	Whiting	Whiting	1	40	0	1.63	0	-30	-13	-17
	2015	Whiting	Whiting	1	40	0	2.02	0	-28	-14	-16
	2016	Whiting	Whiting	1	40	0	2.46	0	-27	-13	-16
EN <10m	2014	Cod	Cod	8	35	35	0.17	0.17	0	22	27
	2015	Cod	Cod	8	35	35	0.22	0.22	0	20	25
	2016	Cod	Cod	8	35	35	0.26	0.26	0	18	23
EN Beam	2014	Cod	Cod	0	0	0	0.02	0.02	0	42	42
	2015	Cod	Cod	0	0	0	0.02	0.02	0	39	38
	2016	Cod	Sole	0	0	3	0.03	0.12	-12	18	18
EN FDF	2014	Cod	Cod	0	23	23	1.64	1.64	0	27	20
	2015	Cod	Cod	0	23	23	2.03	2.03	-7	15	10
	2016	Cod	Sole	0	23	0	2.47	0	-23	-6	-10
EN Otter <24m	2014	Cod	Cod	12	12	12	0.49	0.49	0	33	33
	2015	Cod	Cod	12	12	12	0.6	0.6	0	30	31
	2016	Cod	Cod	12	12	12	0.73	0.73	0	28	29
EN Otter >=40m	2014	Whiting	Whiting	1	1	0	0.03	0.07	-30	-1	-1
	2015	Whiting	Whiting	1	1	0	0.04	0.08	-28	0	-1
	2016	Whiting	Whiting	1	1	0	0.04	0.09	-27	0	-1
EN Otter 24-40m	2014	Whiting	Whiting	0	1	6	0.08	1.43	-30	-1	-2
	2015	Whiting	Whiting	0	1	6	0.1	1.6	-28	-1	-1
	2016	Whiting	Whiting	0	1	6	0.12	1.82	-27	-1	-1

Table S3 continued.

Fleet	Year	Limiting species - no change	Limiting species	% of cod catch <MLS – no change	% of 2012 landings from cod	% of 2012 landings from limiting species	cod CPUE	CPUE of limiting species	Change in cod landings (%)	Change in total landings (%)	Change in revenue (%)
FR <10m	2014	Cod	Cod	0	22	22	0.02	0.02	0	31	30
	2015	Cod	Cod	0	22	22	0.02	0.02	0	28	27
	2016	Cod	Sole	0	22	21	0.02	0.02	-5	20	20
FR Nets	2014	Cod	Cod	0	32	32	0.15	0.15	0	24	33
	2015	Cod	Cod	0	32	32	0.19	0.19	0	20	29
	2016	Cod	Sole	0	32	52	0.23	0.28	-12	6	14
FR OTH	2014	Cod	Cod	0	10	10	0.01	0.01	0	36	27
	2015	Cod	Cod	0	10	10	0.02	0.02	0	31	22
	2016	Cod	Sole	0	10	1	0.02	0	-12	14	7
FR Otter >=40m	2014	Cod	Cod	5	1	1	0.04	0.04	0	38	37
	2015	Cod	Cod	5	1	1	0.05	0.05	0	31	31
	2016	Cod	Cod	5	1	1	0.06	0.06	0	25	25
FR Otter 10-40m	2014	Cod	Cod	8	14	14	0.14	0.14	0	36	31
	2015	Cod	Cod	8	14	14	0.18	0.18	-1	31	26
	2016	Cod	Sole	8	14	0	0.22	0	-13	11	9
GE Beam >=24m	2014	Whiting	Whiting	0	2	0	0.04	0.04	-30	-1	-1
	2015	Whiting	Whiting	0	2	0	0.05	0.04	-28	-1	-1
	2016	Whiting	Whiting	0	2	0	0.06	0.04	-27	0	-1
GE Otter <24m	2014	Cod	Cod	16	3	3	0.53	0.53	0	39	40
	2015	Cod	Cod	16	3	3	0.66	0.66	0	37	37
	2016	Cod	Cod	16	3	3	0.8	0.8	1	35	35
GE Otter >=40m	2014	Cod	Cod	2	2	2	0.24	0.24	0	37	35
	2015	Cod	Cod	2	2	2	0.29	0.29	-1	29	28
	2016	Cod	Cod	2	2	2	0.35	0.35	-7	18	17

Table S3 continued.

Fleet	Year	Limiting species - no change	Limiting species	% of cod catch <MLS – no change	% of 2012 landings from cod	% of 2012 landings from limiting species	cod CPUE	CPUE of limiting species	Change in cod landings (%)	Change in total landings (%)	Change in revenue (%)
GE Otter 24-40m	2014	Cod	Cod	5	22	22	1.73	1.73	0	27	22
	2015	Cod	Cod	5	22	22	2.14	2.14	0	21	18
	2016	Cod	Sole	5	22	0	2.61	0.01	-16	1	-1
GE Static	2014	Cod	Cod	0	58	58	2.52	2.52	0	11	28
	2015	Cod	Cod	0	58	58	3.12	3.12	0	10	26
	2016	Cod	Cod	0	58	58	3.8	3.8	-7	3	16
NL Beam <24m	2014	Whiting	Whiting	0	2	2	0.01	0.06	-30	-1	-1
	2015	Whiting	Whiting	0	2	2	0.01	0.06	-28	-1	-1
	2016	Whiting	Whiting	0	2	2	0.02	0.07	-27	-1	-1
NL Beam >=40m	2014	Whiting	Whiting	0	2	1	0.05	0.1	-30	-1	-2
	2015	Whiting	Whiting	0	2	1	0.07	0.11	-28	-1	-1
	2016	Whiting	Whiting	0	2	1	0.08	0.13	-27	-1	-1
NL Beam 24-40m	2014	Whiting	Whiting	0	2	1	0.04	0.09	-30	-1	-1
	2015	Whiting	Whiting	0	2	1	0.04	0.1	-28	-1	-1
	2016	Whiting	Whiting	0	2	1	0.05	0.11	-27	0	-1
NL Otter	2014	Cod	Whiting	6	18	4	0.89	0.41	-24	2	-3
	2015	Cod	Whiting	6	18	4	1.1	0.46	-22	3	-1
	2016	Cod	Whiting	6	18	4	1.34	0.52	-24	-3	-6
NO Static	2014	Cod	Cod	0	33	33	2.64	2.64	0	22	16
	2015	Cod	Cod	0	33	33	3.26	3.26	0	17	12
	2016	Cod	Cod	0	33	33	3.97	3.97	-4	12	8
SC <10m OTB	2014	Cod	Cod	12	22	22	0.04	0.04	0	26	24
	2015	Cod	Cod	12	22	22	0.05	0.05	0	22	22
	2016	Cod	Cod	12	22	22	0.07	0.07	0	20	21

Table S3 continued.

Fleet	Year	Limiting species - no change	Limiting species	% of cod catch <MLS – no change	% of 2012 landings from cod	% of 2012 landings from limiting species	cod CPUE	CPUE of limiting species	Change in cod landings (%)	Change in total landings (%)	Change in revenue (%)
SC FDF	2014	Cod	Cod	5	26	26	2.03	2.03	0	24	22
	2015	Cod	Cod	5	26	26	2.51	2.51	0	20	19
	2016	Cod	Cod	5	26	26	3.06	3.86	-5	14	13
	2016	Cod	Haddock	5	26	49	3.06	3.06	-5	14	13
SC Otter <24m	2014	Cod	Cod	13	17	17	0.71	0.71	0	28	28
	2015	Cod	Cod	13	17	17	0.87	0.87	0	25	25
	2016	Cod	Cod	13	17	17	1.06	1.06	0	23	23
SC Otter >=24m	2014	Cod	Cod	6	17	17	1.31	1.31	0	29	26
	2015	Cod	Cod	6	17	17	1.63	1.63	0	25	22
	2016	Cod	Cod	6	17	17	1.98	1.98	0	22	20
SC Static	2014	Cod	Cod	0	80	80	0.02	0.02	0	5	3
	2015	Cod	Cod	0	80	80	0.03	0.03	-7	-2	-5
	2016	Cod	Sole	0	80	0	0.03	0	-23	-19	-21

Table S4 The number of replicate runs with variable recruitment that each fleet is limited by a quota allocation for each species under the 30%c protoc0l when fishers change behaviour to reduce the CPUE of cod by 30%.

		Count of no. of runs limited by each species					
Fleet	Year	Cod	Haddock	Whiting	Plaice	Saithe	Sole
BE Beam <24m	2014	0	3	0	97	0	0
	2015	1	13	1	83	0	2
	2016	2	23	0	66	0	9
BE Beam >=24m	2014	72	7	7	13	0	1
	2015	66	22	1	6	1	4
	2016	46	32	1	2	3	16
BE Otter	2014	100	0	0	0	0	0
	2015	98	2	0	0	0	0
	2016	95	5	0	0	0	0
DK Beam	2014	95	5	0	0	0	0
	2015	78	18	0	0	0	4
	2016	57	30	0	0	2	11
DK FDF	2014	69	16	6	5	2	2
	2015	44	26	0	0	6	24
	2016	13	35	0	0	4	48
DK Otter <24m	2014	88	4	8	0	0	0
	2015	81	17	1	0	0	1
	2016	66	31	2	0	0	1
DK Otter 24-40m	2014	70	13	16	0	0	1
	2015	57	26	13	0	1	3
	2016	36	42	9	0	3	10
DK Seine	2014	59	6	35	0	0	0
	2015	54	22	20	0	0	4
	2016	37	32	18	0	3	10
DK Static	2014	0	0	100	0	0	0
	2015	0	0	100	0	0	0
	2016	0	0	100	0	0	0
EN <10m	2014	83	4	13	0	0	0
	2015	80	11	7	0	0	2
	2016	62	23	11	0	0	4
EN Beam	2014	71	11	16	1	0	1
	2015	51	25	11	0	2	11
	2016	31	34	3	0	4	28
EN FDF	2014	70	14	2	7	3	4
	2015	40	24	0	2	7	27
	2016	10	32	0	0	4	54
EN Otter <24m	2014	90	2	8	0	0	0
	2015	89	8	2	0	0	1
	2016	80	16	2	0	0	2
EN Otter >=40m	2014	0	0	100	0	0	0
	2015	0	2	98	0	0	0
	2016	0	9	90	0	0	1
EN Otter 24-40m	2014	0	0	100	0	0	0
	2015	1	3	96	0	0	0
	2016	2	9	88	0	0	1

Table S4 continued.

Fleet	Year	Count of no. of runs limited by each species					
		Cod	Haddock	Whiting	Plaice	Saithe	Sole
FR <10m	2014	57	0	41	1	0	1
	2015	61	0	29	0	0	10
	2016	41	0	18	1	0	40
FR Nets	2014	60	0	35	3	0	2
	2015	53	0	18	1	0	28
	2016	26	0	6	1	0	67
FR OTH	2014	84	11	2	2	0	1
	2015	60	25	1	0	3	11
	2016	27	33	0	0	4	36
FR Otter >=40m	2014	86	6	8	0	0	0
	2015	77	22	1	0	0	0
	2016	65	31	1	0	3	0
FR Otter 10-40m	2014	67	10	21	1	0	1
	2015	49	25	16	0	2	8
	2016	29	34	8	0	4	25
GE Beam >=24m	2014	0	0	100	0	0	0
	2015	0	0	100	0	0	0
	2016	0	2	98	0	0	0
GE Otter <24m	2014	97	3	0	0	0	0
	2015	91	8	0	0	0	1
	2016	81	17	0	0	0	2
GE Otter >=40m	2014	59	13	14	11	3	0
	2015	45	27	11	5	12	0
	2016	38	39	7	1	15	0
GE Otter 24-40m	2014	75	10	13	1	0	1
	2015	52	25	4	0	3	16
	2016	23	33	0	0	4	40
GE Static	2014	79	10	10	0	0	1
	2015	63	25	3	0	1	8
	2016	35	34	3	0	4	24
NL Beam <24m	2014	0	0	100	0	0	0
	2015	0	0	100	0	0	0
	2016	0	0	100	0	0	0
NL Beam >=40m	2014	0	0	100	0	0	0
	2015	0	1	99	0	0	0
	2016	0	3	97	0	0	0
NL Beam 24-40m	2014	0	0	100	0	0	0
	2015	0	0	100	0	0	0
	2016	0	0	100	0	0	0
NL Otter	2014	5	4	87	4	0	0
	2015	12	14	71	1	0	2
	2016	10	20	66	0	1	3
NO Static	2014	74	14	2	7	3	0
	2015	57	27	1	3	12	0
	2016	41	39	0	1	19	0

Table S4 continued.

		Count of no. of runs limited by each species					
Fleet	Year	Cod	Haddock	Whiting	Plaice	Saithe	Sole
SC <10m OTB	2014	90	4	6	0	0	0
	2015	85	13	1	0	0	1
	2016	71	27	0	0	0	2
SC FDF	2014	68	16	6	7	3	0
	2015	56	28	1	3	12	0
	2016	39	42	1	1	17	0
SC Otter <24m	2014	96	4	0	0	0	0
	2015	86	13	0	0	0	1
	2016	71	27	0	0	0	2
SC Otter >=24m	2014	96	4	0	0	0	0
	2015	81	15	0	0	0	4
	2016	55	29	0	0	3	13
SC Static	2014	69	16	2	7	3	3
	2015	39	26	0	2	7	26
	2016	9	35	0	0	4	52