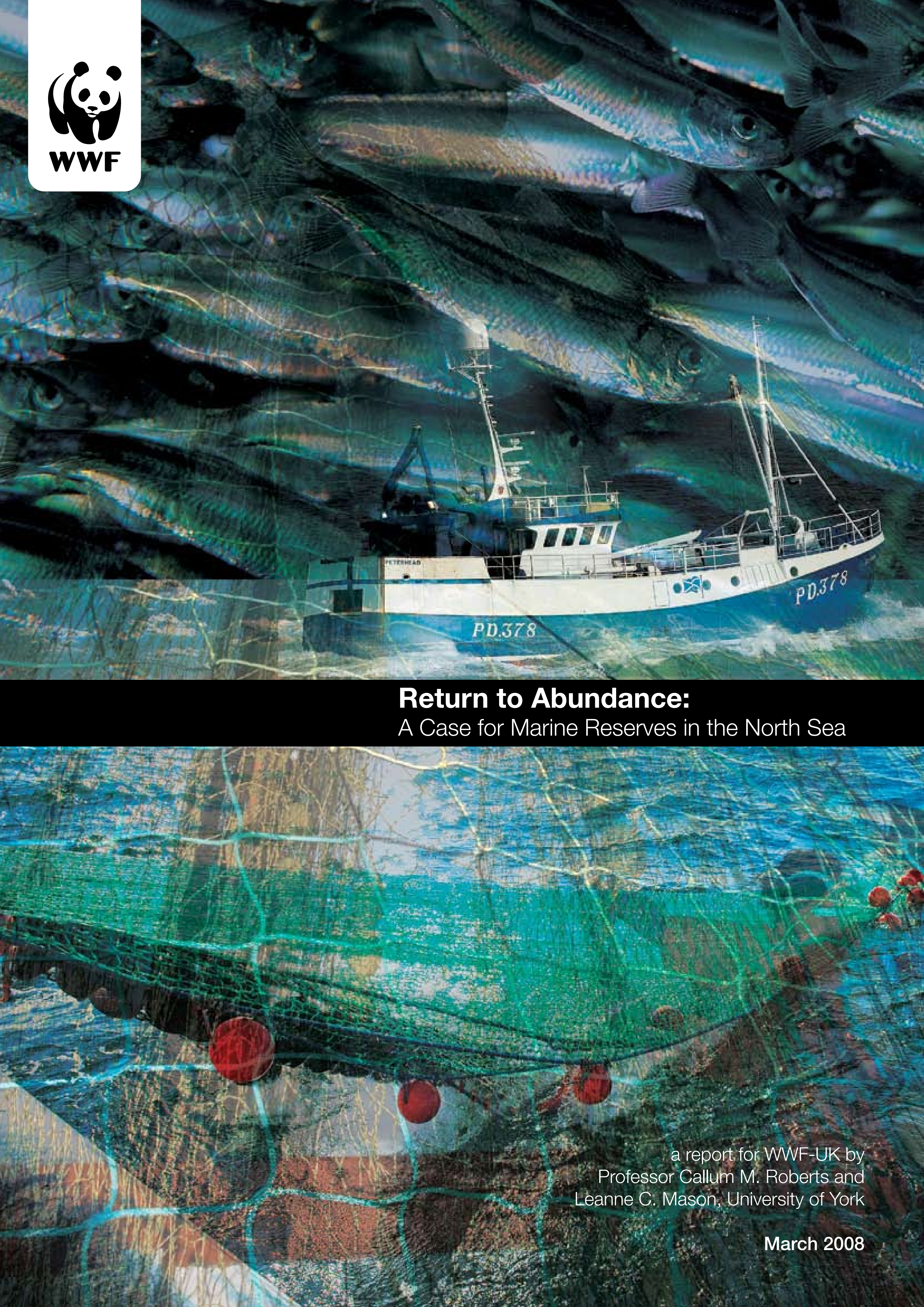

Return to Abundance:
A Case for Marine Reserves in the North Sea

a report for WWF-UK by
Professor Callum M. Roberts and
Leanne C. Mason, University of York

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About the authors

Callum Roberts is professor of marine conservation at the University of York. His research focuses on threats to marine ecosystems and species, and on finding the means to protect them. His latest book, The Unnatural History of the Sea, charts the effects of 1000 years of exploitation on ocean life and was chosen by The Washington Post as one of their Best 10 Books of 2007. Callum is a Pew Fellow in Marine Conservation.

www.york.ac.uk/res/unnatural-history-of-the-sea

Leanne Mason is a doctoral researcher whose main focus has been to explore methods to identify sites for marine protected areas. She uses computer tools including geographic information systems and decision support software to help design networks of marine reserves that best meet conservation and societal needs, while minimising costs.

Disclaimer

The views expressed in this report are those of the authors and do not necessarily reflect the views of policies of WWF-UK.

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Foreword

The world's oceans are under more pressure than ever before. At least 75% of global fish stocks are over-fished at or beyond sustainable limits, and important habitats are being lost or degraded at an unprecedented rate. Against this backdrop, scientists and policy makers believe that by establishing Marine Protected Areas (MPAs) – including Marine Reserves, we can help to restore the balance in our use of the oceans.

Marine Protected Areas have been successfully trialled around the world, in both temperate and tropical seas, resulting in clear increases in fish abundance, and fisheries productivity. Yet the UK's only statutory no-take marine reserve, Lundy Island in the Bristol Channel, represents only 0.001% of UK sea area and is a mere 3.3 km2 area. As a consequence of its scale it is unlikely that this reserve will have any significant effect on the wider ecosystem, or help threatened fish stocks recover.

This report examines the benefits of establishing a network of marine reserves in the North Sea, and considers how and where pilot sites could be realised. Only by adopting an ecosystem approach can marine systems be managed to reverse the decline in the seas around the UK and beyond, achieve long-term sustainability and in turn higher levels of productivity.

In 2007 DEFRA published its Delivering Fisheries 2027 – towards an implementation plan, stating that within the next five years it would "set up and run a controlled trial for a Marine Protected Area to test its effectiveness for increasing fish stocks." WWF-UK believes that it's time to start delivering on this pledge and fulfil our International commitments to establish a network of MPAs under the OSPAR convention. In order to demonstrate the merits or otherwise of this management practice it is vital that a trial of sites with the potential to have ecosystem scale effects is put into action as soon as possible.

Glyn Davies.

Glyn Davies
Director of Programmes

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Summary

Hundreds of years of intensive fishing have transformed the marine environment of the North Sea. The total biomass of populations of major fishery species has declined over the past century by between 50% and 98%, and some species have become locally extinct. Much of the seabed has been repeatedly trawled, leading to vast expanses now being dominated by mobile sediment, rather than by communities of biologically rich and structurally complex surface-living invertebrates. Many commercially important species are now seriously overfished and some, such as cod, appear to be in long term decline.

Existing fisheries management regimes have failed to prevent overfishing of most target species, and to adequately protect the habitats upon which these and other species depend. There is an urgent need for protected areas – these would provide refuges for commercially important species so that their populations can begin to rebuild, and would promote the recovery of habitats that have suffered from disturbance and damage by fishing gears.

This report presents the case for a network of protected areas in the North Sea. It draws on experience gathered from fishery closures in the North Atlantic and evidence from marine reserves (areas protected from all fishing) in temperate seas. Temperate fishery closures and reserves have been shown to be highly successful in enabling rebuilding populations of many important fishery species to increase, and in facilitating habitat recovery, although these changes do not necessarily occur immediately, and recovery can continue for decades. While some species respond quickly, recovery can continue for decades. Theoretical evidence and limited practical experience indicate that if reserve networks are to contribute successfully to fisheries management goals, protect the full spectrum of marine life and recover and sustain essential ecosystem processes and services, they must be extensive, covering 20-40% of the area of the sea. Some habitats that are highly vulnerable to damage will require higher levels of protection.

We present designs for networks of marine reserves that cover at least 30% of the area of all marine habitats in the UK Exclusive Economic Zone of the North Sea, and 50% of the area of the most vulnerable ones. We also target places important to vulnerable life stages of commercially valuable species, including nursery and spawning areas. We have produced network designs that consist of 12-18 individual reserves all of which achieve all of the targets set. The design process shows that a large amount of flexibility is possible when selecting the locations of individual reserves without sacrificing management targets.

To reduce problems of displacement of fishing effort from reserves, we also present designs that exclude areas that receive the top 20% highest fishing intensities. These networks consist of 11-15 individual reserves and achieve most of the goals set, but fail to meet targets for 10 habitats. However, eight of these habitats achieve some degree of representation within the networks. Of the two largest fishery sectors, these networks would displace 26.9-29.3% of demersal trawling with nets >70mm, and 26.2-39.1% of beam trawling. The figures depend on where reserves are placed.

We also present a design for a network of five experimental marine reserves and five paired reference areas. Defra stated in 2006 that it plans to conduct a trial of marine protected areas in

British waters. Collectively, the paired reserves and reference areas cover 10.16% of the North Sea area of the UK EEZ, although only 5.08% of that would be closed to fishing. This should have little impact on opportunities for fishing. Ideally, all five experimental marine reserves would be implemented, to allow for scientifically rigorous analysis of the effects. The amount of fishing effort they would displace would depend on which members of each pair were chosen for reserves. For the two largest fishing sectors, in total the reserves would displace 0.8%-2.8% of UK demersal trawling with nets >70mm mesh, and 7.9-10.9% of UK beam trawling effort (most of it in one reserve).

1 Historical changes in the North Sea environment

The North Sea environment today is very different from that of 200 years ago, before the advent of large-scale industrial fishing (Roberts 2007). The changes are due to the effects of fish removals by fishing (both capture and killing *in situ*); the impacts of fishing gears on habitats, oil and gas exploitation; pollution; and, latterly changes in environmental conditions accompanying global warming.

The onset of commercial sea fishing in the North Sea can be traced to within a few decades around AD1050. At the time, fishers used hook and line to catch cod and allied species, and nets to catch the abundant herring that seasonally entered British coastal waters (Barrett et al., 2004). Bottom trawling was invented in the 14th century and spread slowly. At the beginning of the 19th century it was still largely confined to the English Channel and south-east England, as well as several ports in continental Europe. By the middle of the 19th century the English fleet consisted of around 800 sail-powered trawlers working mainly in nearshore coastal areas, and trawling had spread further into the North Sea. But the great expansion of trawling came with the adoption of steam power in the late 19th century. By 1890, virtually the whole of the North Sea was trawled, in many places more than once a year.

The expansion of trawling brought heavy, destructive fishing gear into contact with vast areas of undisturbed seabed. Bottom trawling has been controversial ever since it was invented. In the second half of the 19th century, several Royal Commissions of Enquiry were instigated to investigate complaints made by fishers about the destructive nature of trawling. Roberts (2007) sifted through the testimony of hundreds of fishers, scientists and others given to these Royal Commissions, together with other contemporary sources of evidence such as books and scientific reports. This evidence sheds new light on the transformation of the seabed caused by trawling.

In the 19th century, undisturbed areas of seabed in the North Sea supported a far greater biomass of invertebrates, especially of filter-feeders such as corals, molluscs, seafans, hydroids, sponges and ascidians. They existed in a dynamic interplay between physical disturbance, colonisation and growth. In shallow storm-swept areas only limited communities could develop before being damaged or destroyed. However, over enormous expanses of the North Sea, disturbance levels were lower and these animals built complex physical structures on the seabed. These biological structures consolidated sediments and provided three-dimensional habitat that was important to many commercial species, as well as to others. Those habitats developed over long timescales – of decades, centuries and, in some cases, millennia.

Recent experiments with bottom trawling show that the first few passes do the greatest harm, removing accumulated biomass of invertebrates and plants (Kaiser et al., 2006). Very soon after trawlers first opened up new fishing grounds in the North Sea, the complex seabed habitat was converted to mobile sand, mud and gravel. Today’s experiments on recovery rates following bottom trawling suggest full recovery on timescales of one to 10 years, or longer, depending on the type of habitat examined (e.g. Dinmore et al., 2003; Kaiser et al., 2006). But these results reflect the fact that the experiments usually examine places that were affected by trawling long ago and often remain subject to intermittent trawling disturbance. If a site chosen for a trawling experiment was last trawled two years previously, then it can be expected that it will fully recover to a similar state within two years after experimental trawling. But this result does not indicate that the site has recovered to an undisturbed state within two years. That would take far longer, except in a few areas with very high levels of natural disturbance.

Sites that have never been impacted by trawling are extremely rare today. This means that it is almost impossible to undertake experiments that look at the impacts of trawling on pristine habitats. Nor can we estimate timescales of recovery to undisturbed states. In fact, the lack of untrawled habitats makes it very difficult to determine what pristine habitats looked like. What is certain is that there are no pristine habitats left in the North Sea.

As well as impacts on habitats, fishing has reduced the size of fish populations in the North Sea and has had profound effects on the structure of food webs. Populations of large predatory fish such as cod, haddock, plaice, turbot and halibut are estimated to have been reduced by 90% since 1900 (Christensen et al., 2003). The largest species may have been reduced in density to 2% or less of their abundance before fishing (Jennings and Blanchard, 2004), and some species have all but disappeared from the North Sea, such as angel sharks and common skate (www.iucn.org/themes/marine/pdf/casestudies-xoxo150506.pdf). The biomass of once abundant forage fish species, such as herring, blue whiting and Norway pout have been reduced by 50% or more (Jennings and Blanchard, 2004). These once supported large populations of predatory species, including marine mammals, sharks and tuna (Roberts, 2007).

The collapse of populations of bottom-living species in the North Sea has reduced direct predation on prey species such as herring. Bundy (2005) estimated that fish which feed in the water column made up 30% of the total biomass of fish prior to the overfishing seen there in recent decades. While this has increased supplies of these species to fisheries, largely for conversion to fishmeal, it has also shifted foodwebs from dominance by bottom fish to pelagic fish. Similar shifts have been seen in many intensively exploited marine ecosystems such as the Scotian Shelf in eastern Canada. They now make up three-quarters of the biomass (Bundy, 2005). There have also been ecosystem shifts in the North Sea and throughout the north Atlantic from dominance by fish to invertebrates like *Nephrops* and *Pandalus* shrimps (Worm and Myers, 2003). Taken together, fishing-induced changes in the North Sea environment have reduced biodiversity and simplified ecosystem structure, altering ecosystem processes (Bradshaw et al., 2002; Tillin et al., 2006; Worm et al., 2006). In turn, these structural shifts impact on ecosystem services important to people, such as the provision of seafood.

One of the consequences of the long history of fishing impacts in the North Sea is that fishers, managers, scientists and the general public today have come to consider the depleted and degraded state as normal. Over time, diminished resources have led to diminished expectations of what the North Sea could support with reductions in fishing pressure. This phenomenon over the past state of ecosystems has been called the ‘shifting baseline syndrome, where younger generations come to accept higher levels of ecosystem degradation than older generations because they have no direct experience of the more productive states that prevailed in the past (www.shiftingbaselines.org).

Brodziak et al. (2004) describe the shifting baseline phenomenon for the Georges Bank scallop fishery. In the early 1990s, fishing mortality rates were very high, but few fishers or managers at the time believed that reducing scallop mortalities was either necessary or desirable because the fishery seemed viable. They argue that people accepted the low abundance of scallops as normal and found it hard to conceive of levels of biomass several times higher than any seen in recent decades. It came as a great surprise to many people when scallop populations rebounded and scallop sizes increased dramatically after closed areas were implemented (discussed in detail in Section 2.1).

The EU’s own data on fish stocks shows that the North Sea has been locked into a cycle of population decline among many of the major commercial species since the 1970s (Prime Minister’s Strategy Unit, 2004). Data from earlier periods indicates that by this time, stocks of many species had already declined a long way from historical abundances (Roberts, 2007). Continuation of present management policies will result in continued declines and cannot succeed in rebuilding the productivity of UK waters (RCEP, 2004; Horwood et al., 2006; Kelly et al., 2006).

There is an urgent need to shift course in management by implementing real protection for fish and habitats in marine reserves. This change in policy is required not only because fishing has caused such severe impacts to the North Sea. Climate change impacts overlay the effects of fishing and pollution and will affect the North Sea biota to an increasing degree over coming decades. The reality of climate change provides a compelling argument for management approaches that rebuild resilience in North Sea ecosystems, so that they can continue to function and deliver the goods and services upon which maritime industries and surrounding nations depend. In this report, we describe how marine reserves can be used to strengthen fisheries management in the North Sea and deliver lasting protection to species and their habitats (Roberts et al., 2005).

2 Experience from marine reserves and fishery closures in temperate seas

It has often been asserted that marine reserves will not work in temperate waters, and that evidence for their effects is predominantly from tropical habitats such as coral reefs. While it is true that there are a disproportionately large number of studies from coral reefs compared to other habitats, it is not the case that all the evidence for reserve effects comes from the tropics.

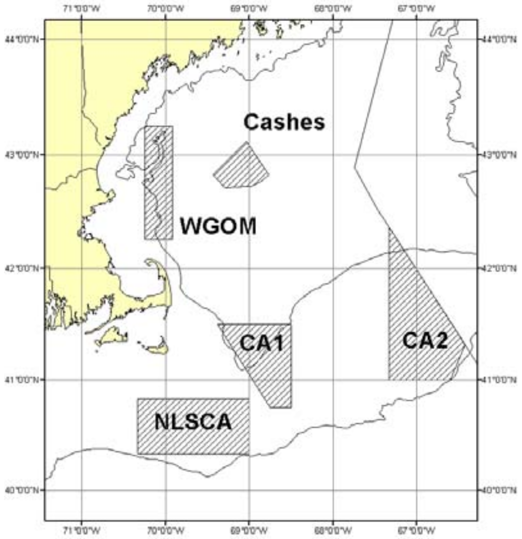
A recent study undertook a comprehensive meta-analysis of the effects of marine reserves from across the world (Lester and Halpern in review; PISCO, 2007). It included the findings of studies from 124 marine reserves spread throughout tropical and temperate zones. The number of studies reporting data from tropical reserves only narrowly exceeded the number of studies from temperate waters. There is substantial experience with temperate marine reserves (Gell and Roberts, 2003).

Comparing the effects of reserves on fish, invertebrates and algae, Lester and Halpern found that temperate reserves outperformed tropical ones on two key measures: biomass and density of protected organisms. Biomass was greater in reserves than matched reference areas by 554% in temperate reserves compared to 368% in tropical reserves. Density of organisms was 230% greater in temperate reserves than reference areas compared to 117% in tropical reserves. Marine reserves are clearly highly effective in temperate waters, just as they are in the tropics.

There are no existing marine reserves in the North Atlantic on the large scale necessary to accommodate the mobility of some key commercially exploited species in this region, such as cod or haddock. However, in several places fishery closures offer valuable insights into some of the likely effects of marine reserves.

2.1 GEORGES BANK, GULF OF MAINE

Georges Bank extends offshore for 280km and forms the southern border of the Gulf of Maine in the North-west Atlantic. Georges Bank fisheries for cod, haddock and flounder were severely overexploited in the 1970s and ’80s, leading to steep declines in landings. In 1994, the New England Fisheries Management Council adopted a fisheries recovery plan that included closing three areas to fishing gears that target groundfish or damage their habitats. The three areas totalled 17,000 sq km of the bank. Together, the closed areas included 31% of the trawl fishing effort expended on Georges Bank before protection between 1991-93 (Murawski et al., 2005). Closed areas were supplemented by regulations stipulating larger mesh sizes and reduced fishing effort that together reduced fishing mortality in the groundfishery by approximately 50%.



Map 1: **Closed areas off the northeast USA. (CA-I = closed area I, CA-II = closed area II, NLSCA = Nantucket Lightship Closed Area, WGOM = Western Gulf of Maine, Cashes = Cashes Led**ge

The package of measures has led to a dramatic recovery of populations of several exploited species. The increase in biomass has been significant inside protected areas for scallops, haddock, and yellowtail and winter flounder. Biomass of yellowtail flounder, for example, increased from around 6,000 tonnes in 1994 to an estimated 60,000 tonnes in 2002, and recruitment has risen six-fold (Stone et al., 2004). Haddock spawning stock biomass on Georges Bank increased over ten-fold from 14,600 tonnes in 1994 to 117,000 tonnes in 2004 (Brodziak and Traver, 2006; www.nefsc.noaa.gov/sos/spsyn/pg/haddock).

There are gradients in the population density of haddock, winter and yellowtail flounder from the closed areas into adjoining fishing grounds consistent with spillover from the closures (Murawski et al., 2005). Highest densities occur within the closed areas, reducing with increasing distance from boundaries. Evidence from satellite monitoring of the fishing fleet indicates that fishers take advantage of higher densities close to closed area boundaries by 'fishing-the-line'. In 2001-03, an estimated 10% of fishing effort was concentrated within 1km of closed area boundaries, and 25% within 5km. Over this period, 42% of the total United States catch of haddock was taken within 1km of the boundary of a closed area, and 73% within 5km of a boundary. Half the yellowtail flounder catch and 43% of winter flounder catches were made within 5km of closed area boundaries.

Average revenues per trawl tow in areas within 4km of closed area boundaries were double those in areas further away (US$470 per hour fishing versus US$273 per hour for fishing at distances of 10-50km from boundaries) (Murawski et al., 2005). However, the variance in catch rates was greater close to boundaries, explaining in part why fishers continued to target places more distant from closed areas.

The scallop fishery has experienced a similar recovery. By 2003, nine years after closed areas were established, scallop biomass was 25 times greater inside closed areas than it was prior to protection, due to increased densities and body size. In 2003, biomass was four to five times greater inside compared to outside protected areas. Biomass in fishing grounds was also up compared to pre-protection. Satellite tracking data showing the distribution of scallop fishing effort outside closed areas, together with data on oceanographic circulation, suggests that fishers target areas that benefit from exported scallop larvae, although this remains to be proven conclusively (Lewis et al., 2001; Rago and McSherry, 2002; Hart and Rago, 2006). Fishers exploiting areas close to closed area boundaries may also benefit from spillover of scallops moving from closed areas (R Steneck, pers. comm.). Scallop landings have also profited from a series of limited re-openings of sections of the closed areas initiated in 1999.

In contrast to the above experiences, densities of cod on Georges Bank have shown little evidence of recovery, despite fishing mortality today being at a historical low compared to the last 43 years (Mayo and O'Brien, 2006; www.nefsc.noaa.gov/sos/spsyn/pg/cod). As of 2006, spawning stock biomass of cod was estimated to be only 10% of that required to achieve maximum sustainable yield.

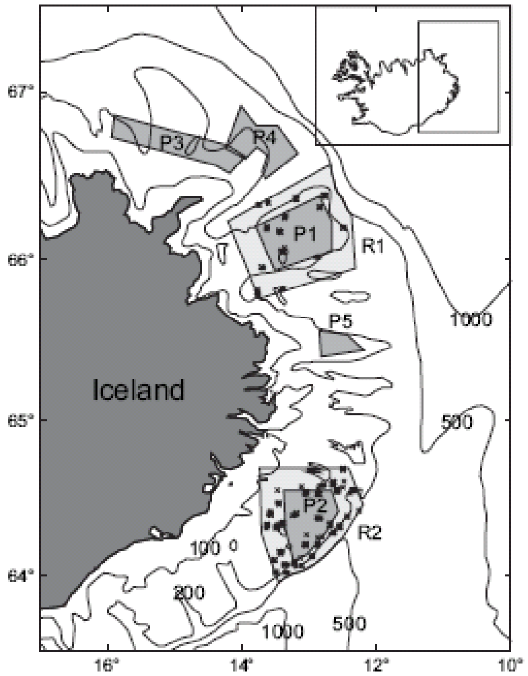
In addition to direct benefits to fisheries, closed areas on Georges Bank have had beneficial effects on bottom habitats. The overall production of benthic biomass has increased in an area of hard-bottom gravel pavement habitat by greater than ten-fold following six years of protection (Hermsen et al., 2003). Scallops and green sea urchins, together with a suite of other surface living macrofauna, dominated production in the protected area. Furthermore, the structural complexity and biomass of bottom habitats has been increased through recolonisation of surface-living invertebrate species. A study of Closed Area II showed a four-fold increase in abundance, eighteen-fold increase in biomass, and four-fold increase in production of macrofauna in gravel habitats (Collie et al., 2005).

Protected habitats showed increases in species of crab, mollusc, echinoderm and polychaete, among others. Protected habitats also showed increases in species of sponge, bryozoan and anemone that stabilise and consolidate bottom substrates. Even highly mobile sand wave habitats showed a greater abundance of surface-living sponges (Lindholm et al., 2004). These changes may in turn have indirect benefits for fisheries, increasing survival and feeding opportunities for juvenile fish (Lindholm et al., 1999) and transferring production to organisms from higher trophic levels that are targeted by fisheries (Hermsen et al., 2003).

It has often been affirmed that implementation of fishing gear and effort restrictions on Georges Bank coincident with the establishment of closed areas makes it impossible to separate the role of spatial protection from these other measures in rebuilding populations (e.g. CEFAS, 2005; Sweeting and Polunin, 2005). However, recent data on the spatial distribution of population biomass of haddock, yellowtail flounder and scallops, showing greatly elevated populations inside closed areas together with spillover into surrounding fisheries, now renders the benefits of these closed areas unambiguous (Murawski et al., 2005).

2.2 ICELAND

Several areas have been closed to a number of fisheries at various times in Icelandic waters. Two fishery closures were introduced in the waters east of Iceland in 1993 and that excluded longlines and bottom and pelagic trawls in order to protect bottom living fish (Jaworski et al., 2006). The two areas were Digranesflak (1,621 sq km) and Breiddalsgrunn (1,397 sq km). Jaworksi et al. (2006) used regular bottom trawl surveys, conducted inside the protected areas and in two reference areas between 1985 and 2004, to reveal how groundfish populations responded to protection. The reference areas surrounded the closed areas.



Map 2: **Closed areas off the coast of Iceland.**
P= Protected Areas R= reference areas

Both closed areas had positive impacts on commercially exploited fish species. The effects of protection differed between the two closures, perhaps in part due to the ten-fold greater fishing intensity in Breiddalsgrunn prior to protection. In Digranesflak, the abundance of haddock and small long rough dab (*Hippoglossoides platessoides*) increased, while in Breiddalsgrunn the size of haddock and cod increased significantly. In Digranesflak, abundance of haddock remained relatively unchanged for 5-9 years after protection, but then increased rapidly. Larger size classes responded later than small, showing the effect on growth of protected fish. The average size of haddock in the Digranesflak area increased by 20cm over the period of the closure compared to 4cm outside the closed area. Several other species showed higher abundance inside this closed area, including Atlantic wolffish, redfish and saithe, but the differences were not significant within the timescale of the study. The authors point out that reference areas surrounding Digranesflak experienced low trawl fishing effort in the years following closure, reducing the contrasts between protected and fished areas.

In Breiddalsgrunn, larger size classes of cod and haddock increased markedly in abundance following the closure, and the response to protection occurred more quickly than in Digranesflak. The authors note that there was no apparent tendency of fishers to fish close to the borders of closed areas after protection. However, they did note that the same patterns of changes were often seen in populations inside closed areas and surrounding reference areas, which may have been due to spillover of fish from closed areas. Breiddalsgrunn was reopened to fishing after four years in 1997. Most of the benefits of protection were dissipated within three to seven years following reopening.

Jaworski et al. (2006) conclude that “species with great mobility, such as cod and haddock, may benefit from area closures”.

2.3 CANADA, EMERALD BANK/WESTERN BANK

In 1987, the Canadian Department of Fisheries and Oceans closed two large shallow banks off the coast of Nova Scotia to bottom trawling. The closed area covered 13,700 sq km and encompassed a key spawning and nursery ground for haddock, the intention being to protect juvenile haddock from bycatch and discarding.

Fisher and Frank (2002) used government survey data to look at changes in fish populations and community structure over a 31-year period, comparing the closed area to a nearby reference area, Brown’s Bank, which was similar environmentally. After 10 years of protection, Frank et al. (2000) found that haddock populations had not recovered in the way that had been anticipated, although a later analysis showed a 44% increase in abundance of the species from an average of 81.5 fish per trawl tow to 117.6 fish per tow (Fisher and Frank, 2002).

However, there were greater increases in a variety of other species, including silver hake (up 96%), winter flounder (up 3,200%), American plaice (up 54%), Pollock (up 151%), herring (up 1,792%), redfish (up 3,825%), and mackerel (up 233%), among others. However, several other commercially important species failed to respond to the protection of this site, including halibut (no change in abundance), cusk (down 77%), thorny skate (down 89%) and cod (down 18%) (Fisher and Frank, 2002).

Lack of recovery by previously dominant, large bodied species such as cod, halibut and skate, together with a rise in dominance by smaller bodied species like herring and mackerel, suggest that there may have been a shift in the ecosystem to some alternative state (Baskett et al., 2007).

Population changes in exploited species led to significant alterations in fish community structure in the closed area following protection. Fisher and Frank (2002) found that similar shifts occurred in the reference area, Brown's Bank, despite this site receiving no protection from trawling. Examination of population trends on Brown's Bank reveal that changes there are time-lagged by one to three years following changes in the closed area, suggesting to the authors that there was spillover of fish from the closure (Fisher and Frank, 2002).

The authors conclude that: "…establishment of fishery closures or MPAs is likely to have positive benefits to the component species at both a local and regional level. The timescale of such changes in our study was relatively long and the recovery of the target species (haddock) is only now beginning to take place… This will require commitment to long-term monitoring and patience by managers and stakeholders to realise the benefits of such conservation measures."

2.4 EXPERIENCE FROM COD CLOSURES IN THE NORTH SEA AND IRISH SEA

North Sea: North Sea cod stocks have declined steeply from a level of approximately 250,000 tonnes of spawning stock biomass in 1970, to approximately 40,000 tonnes today (Horwood et al., 2006). In response to this severe decline, since 2000 the EU has implemented restrictive catch quotas, although it has rejected fishing moratoria recommended to it by the International Council for the Exploration of the Sea (ICES). For 75 days in 2001, as an emergency measure, the EU introduced two closed areas covering more than 103,000 sq km of the southern and eastern North Sea (Dinmore et al., 2003; CEFAS, 2005). The closures covered approximately one fifth of the area of the North Sea and were intended to protect adult cod during the spawning season.

Closed areas included important fishing grounds for the EU beam trawl fleet, and while they were in place some beam trawling effort was redirected to other parts of the North Sea. Dinmore et al. (2003) analysed the effect of the north-east closure on fishing patterns by larger beam trawlers using satellite data from onboard Vessel Monitoring Systems. Fishing patterns were non-random both outside and during the closure period, being more clumped than would be expected by chance. Some areas received significantly more fishing effort and some less than expected given a random distribution of fishing. Examining the distribution of fishing at a scale of 1 square nautical mile, if fishing effort were distributed randomly, nearly 70% of squares would be hit per year. In reality, only around 30% were trawled.

Fishing effort shifted west of the north-east closed area while the closed area was in place and then shifted east again on reopening (Dinmore et al., 2003). The fishing effort was slightly more spread out with the closed area in place, leading to more places being fished at low trawling frequency than during periods outside the time of closure. Rijnsdorp et al. (2001) found similar results for the southern closed area. In the first week after the closure, the number of trips by beam trawlers to adjacent areas doubled, much of the effort shifting to the north. Dinmore et al. (2003) estimated that redirected fishing effort would slightly reduce overall production by bottom-living invertebrates. Trawling in areas that have not been impacted for some time will cause a greater reduction in production of invertebrates than trawling in frequently impacted areas. This is because lightly trawled areas support a higher biomass of larger bodied species than frequently impacted sites.

Viewed from the perspective of cod protection, the closed area was a complete failure. Prior to closure fishers targeted the area more intensively, and the fishing fleet redeployed into the closed area as soon as it was reopened (STECF, 2003). Furthermore, without targeting greater protection at juvenile cod, which suffer high levels of bycatch in other North Sea fisheries such as for *Nephrops*, protecting spawning adults may have little benefit. In some cases, it is conceivable that protection of one age class (e.g. spawning cod) may increase mortality of age-classes in other areas due to redirection of fishing effort. As Horwood et al. (2006) point out, the lack of high density concentrations of cod at which to target protection limits the effectiveness of temporary closed areas as a means for achieving stock recovery of this species. The conclusions reached regarding the 2001 closed areas were that they were not large enough and not sustained for long enough to benefit cod (STECF, 2003).

Irish Sea: In 2000, similar measures were initiated in the Irish Sea to protect and recover cod spawning stock biomass. From the 1970s to the late 1980s, cod spawning stocks in the Irish Sea fluctuated between approximately 10,000 and 20,000 tonnes (Kelly et al., 2006). Thereafter, the population declined, falling to only 4,000 to 5,000 tonnes by 2000. Closed areas were first introduced in 2000. As in the North Sea, they were intended to protect spawning concentrations of cod. Two areas, one in the east and another in the western Irish Sea, were closed for 45 days to cod fishing. However, *Nephrops* trawls and beam trawls were permitted to fish within approximately 35-40% of the area of the closures.

The following year, the closed areas were revised and the eastern closure abandoned as part of a cod recovery plan (Kelly et al., 2006). The stated aim was that “The closure to protect cod should, therefore, be established in such a way that fisheries for Norway lobster, shrimps and flatfish should not be significantly diminished while minimising the risk to cod.” European Commissioners allowed fishing for other species in nearly all the closed area, including *Nephrops* trawling and beam trawling, and semi-pelagic haddock trawls despite high levels of bycatch of cod, either as adults, juveniles or both.

As observed in the North Sea example, temporary closed areas have failed to achieve any recovery in the Irish Sea cod population. As of 2005, the spawning stock was still below 6,000 tonnes. Kelly et al. (2006) show that the cod recovery plan has failed to achieve a sufficient reduction in fishing mortality. In their view, only a drastic cut in fishing mortality can recover the stock, which implies also cutting fishing effort or greatly improving selectivity of fleets with significant cod bycatch, including *Nephrops* trawls and beam trawls.

Fishing is not the only factor impacting populations of cod in the North and Irish Seas. Both have been affected by increases in ambient water temperature associated with climate change, probably through population shifts to the north and reduced larval survival (Beaugrand et al., 2003; Horwood et al., 2006). Horwood et al. (2006) asked whether rebuilding targets for North Sea cod were attainable under the new reduced productivity regime. They estimated that by 2004, cod recovery measures put in place in the North Sea had reduced fishing mortality by 37% compared to 2000. They concluded that it was possible to rebuild the cod spawning stock to a target level of 150,000 tonnes, but deeper cuts in fishing mortality would be necessary, to just 40% of fishing intensities prevailing in 2000. Given the mixed species nature of North Sea fisheries, to achieve this implies significant cuts in fishing effort for other species.

As Horwood et al. (2006) note, as cod populations have declined around Britain, the level of uncertainty associated with stock assessments has increased. This provides a clear rationale for a higher level of precaution in management than is currently practised. The establishment of a large-scale and well designed marine reserve network would materially enhance the level of precaution, giving cod a greater chance to recover than present piecemeal efforts.

3 Designing a marine reserve network for the North Sea

3.1 THE CASE FOR MARINE RESERVES IN THE NORTH SEA

A recurring feature in the failure of fisheries managers to achieve sustainability of catches for the fishing industry is that the focus of management is too narrow. Management measures target individual species or small groups of species, and committees charged with managing different species or groups communicate little with one another, even when the species they manage are as closely linked as predators and prey. Attempts to manage species stripped of their ecosystem context are certain to fail in the long term. Such efforts will also fail to reverse habitat degradation and decline of non-target species. These issues are compounded by the tendency for assessments of populations of commercially valued species to be dropped when the abundance of these species falls to low levels. Just when more effort needs to be invested in management to effect recovery, the species cease to be monitored closely or protected adequately because the economic rationale for doing so has diminished (Roberts, 2007).

Piecemeal management also characterises the European experience with spatial protection of fish stocks. Many of the fishery closures implemented in northern European waters have failed or had limited success, largely because they afford little protection even to the target species. Closures have been for too little time (e.g. the 2001 cod closure in the North Sea, STECF, 2003), or exclude too little of the fishing effort (e.g. the Plaice Box, Pastoors et al., 2000), or allow continued access by fleets using methods that catch the species subject to closure or damage their habitats (e.g. Irish Sea cod closures, Kelly et al., 2006).

There is an urgent need to expand the remit of fisheries management away from single species towards the ecosystem level (Pikitch et al., 2004). One reason for the success of fishery closures reviewed in this report from America, Canada and Iceland is that they have been protected from a much broader range of fishing gears than European fishery closures. Managers in these nations have recognised that fisheries that have bycatch problems or damage habitats must also be excluded from closed areas. For example, ICES reported in 2007 that 95% of cod caught in the North Sea are taken before they reach maturity, largely as bycatch by vessels fishing for haddock, whiting, *Nephrops*, plaice and sole. ICES has recommended either lowest possible or zero catches for North Sea cod since 2001, until 2007 when a small increase in the amount of cod in the North Sea was recorded and ICES moved from their zero quota recommendation. They were unable to agree a TAC but instead recommended that total removals (including landings and discards) not exceed 22,000 tonnes. But cod recovery cannot be achieved while bycatch by other fishery sectors remains high. Allowing continued access to fishery closures for some fishery sectors may buy industry support, but it undermines benefits for target species.

Closures that eliminate the most damaging gears can be very effective, as the examples in this report show, but usually only if they are closed year-round. Seasonal closed areas like those in the Irish and North Seas and parts of the Gulf of Maine result in derby fisheries that can dissipate and negate the benefits of protection (CEFAS, 2005; Murawski et al., 2005; Kelly et al., 2006). Derby fisheries are those where closed area status results in a concentration of fishing effort inside the closure either before or after the period of protection.

Marine reserves that exclude all fishing year-round avoid problems of derby fisheries and bycatch, since no fishing vessels are permitted access. While they displace fishing effort, they do so only when established (unless displaced fishing effort is removed at the point of implementation, see below). Dinmore et al. (2003) argue that this is preferable to repeated implementation of temporary closed areas, from the point of view of impacts on bottom habitats, because it would reduce the cumulative impacts of redirected fishing.

To be of any real value in protecting wider aspects of marine ecosystems beyond single species, closed areas must be protected from a wide range of fishing methods. The evidence shows that real benefits begin to accrue once mobile fishing gears are excluded. More protection provides higher conservation benefits in terms of facilitating recovery of exploited species and their habitats. Hence, marine reserves that exclude all fishing are the most effective tool for delivering stock and habitat protection (Lubchenco et al., 2003). Furthermore, they can be expected to achieve greater success in reversing many of the effects of more than 150 years of intensive fishing in the North Sea. Marine reserves are a fundamental part of the reform necessary to turn around the success of fisheries management and build a productive future for the fishing industry (Roberts, 2007).

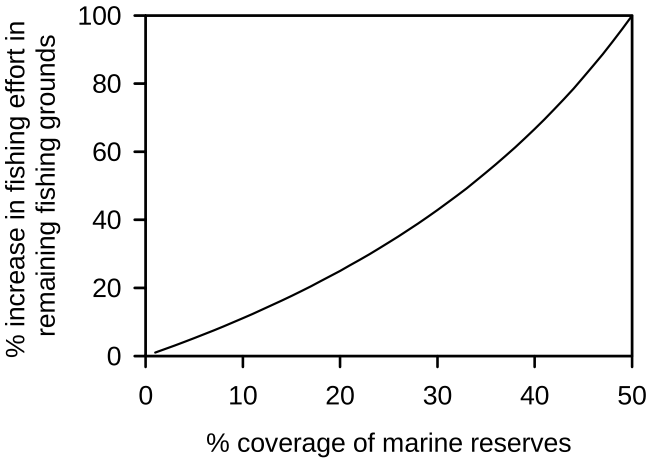
Ultimately, the options for establishing protected areas, whether marine reserves or fishery closures, are constrained by the space available. Perhaps the most compelling argument for establishing a network of marine reserves is that there simply isn’t the space or the management capital available to set up the multitude of other types of closed areas needed to manage single species or groups of a few species. The protected areas we establish need to be targeted as broadly as possible to provide the maximum benefit to the full spectrum of marine life present. They also need to be well designed and not simply result from some emergency response to the latest crisis for one particular species or other. Only that way will it be possible to recover some degree of the lost productivity of the North Sea, producing sustainability and long-term security for the fishing industry.

3.2 THE PROBLEM OF DISPLACED FISHING EFFORT

Many marine reserves and fisheries closures have been implemented without any simultaneous reduction in fishing pressure. Fishing effort expended prior to protection in the reserve or reserves is simply redeployed in other areas. This has been the case in the majority of reserves established to date in developing countries. If there are no restrictions, displaced fishing effort will increase fishing intensity in areas that remain open in proportion to the amount of effort that is displaced and the magnitude of the reduction in fishing grounds.

For example, if reserves are created covering 30% of fishing grounds and including 30% of the total fishing effort (i.e. fishing is evenly spread), then fishing intensities in unprotected areas will rise by an average of 43% ((30/(100-30)) x 100) (Figure 1). For an area trawled once a year, this is equivalent to adding an extra trawl pass once every 28 months. If fishing effort is patchy, then the calculations alter. For example, a reserve covering 30% of fishing grounds but including only 10% of effort would increase fishing intensities in unprotected areas by only 14% ((10/(100-30)) x 100). For an area trawled once a year this is the equivalent of adding an extra trawl pass once every seven years and two months. Hence, creating reserves in areas that are lightly fished to begin with will reduce the impact of redirected fishing effort. Whilst this may be an important consideration in protected area design, protecting lightly fished areas is not always desirable, since places targeted by fishers are often areas of high biological value and conservation interest.

Figure 1: The effects of increasing coverage of reserves on the intensity of fishing in remaining fishing grounds if fishing effort is displaced from reserves



The fact that fishing effort may be redirected towards other areas is not an argument against the creation of marine reserves. It does not undermine the benefits of protection within reserves. But it does require care in the selection of reserves and their design. It is clearly not desirable to protect one area only to redirect fishing to more vulnerable habitats, or concentrations of vulnerable life stages of a species (such as spawning aggregations or nursery grounds). Given the expectation that successful reserves will lead to ‘fishing-the-line’, it is also not desirable to locate boundaries adjacent to unprotected areas of high biological importance or conservation value.

One near universal prediction of studies that examine the effects of marine reserves is that the benefits of protection will be greater if displaced fishing effort is retired rather than redirected elsewhere (e.g. Dinmore et al., 2003; CEFAS, 2005). In places like the North Sea, current fishing effort is typically greater than necessary to achieve sustainable catches. In 1994, it was estimated that fishing effort in the North Sea was 40% higher than required, leading to serious overfishing (RCEP, 2004). Since then, decommissioning programmes have reduced fishing effort but not by nearly enough (Horwood et al., 2006). Under these circumstances, creating marine reserves can be viewed as an opportunity to reduce fishing effort to more sustainable levels. Retiring fishing effort pro-rata with the proportion included in the reserve network would avoid most of the problems of redirected fishing effort. In the example networks of marine reserves presented in this report, we show how much fishing effort would need to be retired for each fishing gear type to avoid redirecting any extra effort to unprotected areas.

Areas closed to bottom fishing on Georges Bank were implemented together with a package of measures to reduce fishing effort over a period of five years (see Section 2.1). These measures resulted in an approximate halving of fishing effort that reduced problems of redirected fishing and contributed to the rebuilding of populations of several groundfish species.

3.3 OBJECTIVES FOR THE NETWORK

We explored design options for a possible marine reserve network for the North Sea that would meet multiple objectives. They include but are not limited to:

- improving the sustainability of fisheries;
- protecting biodiversity; and
- securing essential ecosystem services that depend on healthy, intact ecosystems.

3.4 SIZE OF THE NETWORK

Gell and Roberts (2003) reviewed evidence from 40 studies that asked the question: how much of the sea should marine reserve networks cover to achieve various objectives? The evidence suggested that goals of maximising fisheries catches and sustainability could best be achieved with reserve networks that cover 20-40% of the sea. Conservation goals also require extensive networks. To represent the full spectrum of marine habitats in reserves and replicate them in different reserves of sufficient size to support viable populations would require coverage of 10-20% of the sea. Adding connectivity considerations to ensure that reserves are sufficiently close together to exchange eggs and larvae of protected species would entail upping reserve coverage to the order of 30% or more (Roberts et al., 2006).

The delivery of essential ecosystem processes and services scales positively with biomass of marine organisms in the system, which increases with coverage of reserves. To have a significant impact on ecosystem services, reserves will need to be extensive, again covering of the order of 20-40% of the sea. Finally, some habitats and areas that support vulnerable concentrations of marine wildlife are so open to damage and depletion that they require higher levels of protection.

Taking the above factors into account, in designing the reserve networks we set a target of protecting 30% of the area of every marine habitat type in the North Sea EEZ of the United Kingdom, and 50% of the area of the most vulnerable habitats. We limited analysis to this region as this is the part of the North Sea for which we have the most complete data on the distribution of marine habitats and commercially important species, as well as on the distribution of fishing effort by different sectors of the UK fishing fleet. To benefit commercially important species, we also included targets of protecting 30% of the area of identified nursery and spawning grounds of 14 species. In addition, we set a target of protecting

50% of the area of places used as nursery grounds or for spawning by six or more of these species.

To undertake the analysis we divided the North Sea area of the UK EEZ into quarters of ICES statistical rectangles, giving 449 planning units. We took this approach for several reasons. First, we feel, based on evidence from temperate fishery closures and marine reserves, that this represents the minimum size for a viable reserve. The boundaries of ICES rectangles follow lines of latitude and longitude, which means that their area decreases going north, owing to the convergence of lines of latitude. A whole planning unit in the far north of the study area covers 723 sq km, whereas one in the far south covers 960 sq km. Some of the planning units are smaller than a full quarter ICES rectangle because they abut coasts or the edge of the UK EEZ. However, in reserve network designs generated by the analyses, these were almost always picked as part of larger reserves. In addition, most of the reserves in network designs consisted of three or more conjoined planning units, and so cover more than 2,000 sq km of habitat. Such reserves are similar in scale to the successful Icelandic fishery closed areas described in Section 2.2.

Second, to facilitate enforcement and compliance it is essential that marine reserve boundaries are easily identifiable. We feel that his is best achieved by having straight edges that follow lines of latitude and longitude, where possible. Third, the data we have used is coarse in resolution and so this planning unit size is relatively robust against data errors. Fourth, ocean process and species distributions are liable to change over space and time and so large reserve sizes buffer against year-to-year shifts in importance of local areas.

It has often been stated that only extremely large marine reserves can produce benefits for mobile species such as cod. Experience with cod recovery from existing fishery closures has been mixed. Closed areas on Georges Bank have not yet produced any cod recovery, whereas a smaller closed area in Iceland did benefit cod. Reasons for lack of cod recovery are complex and still debated. There are concerns that ecosystem shifts following cod collapse have produced an alternative stable state from which cod recovery is difficult (Frank et al., 2005). Similar problems may hinder recovery of cod around Britain.

However, putting this concern aside for a moment, in the case of Iceland, cod benefited from a closed area of a size that would be very practical to implement in the North Sea. Recent evidence suggests that cod are not as highly mobile as once believed and that in many places the species has a metapopulation structure made up of sub-populations, each of which spawns in distinctive and largely separate areas. Wright et al. (2006) looked at data from tagging studies of cod in the northern North Sea and west of Scotland. They found that 67-97% of adult cod remained within 100km of spawning areas throughout the year, implying that spawning groups were resident in particular regions. If so, then a network of marine reserves of the sizes and overall scale suggested in this report could provide valuable protection to cod.

3.5 DATA ANALYSES

Planning units were scored for their physical, habitat and species attributes using the computer package ArcGIS. Details of data layers and data treatment are given in Appendices 1 and 2. We then used a computer program, *Marxan*, to create reserve network designs. A description of the program is given in Appendix 3. In brief, *Marxan* works by selecting sites for protection to create efficient reserve networks that meet user-defined conservation targets while trying to minimise costs. The costs include parameters that are generally proxies for real financial costs and include measures of the area and the total boundary length of reserves within the network.

We set the cost of each planning unit to the amount of fishing effort it received, using the average annual days of fishing in each ICES rectangle between 2000 and 2006. Planning units that received a high level of fishing effort would have a high cost and so be more expensive to include in a reserve network. The rationale behind this is to reduce the inclusion of heavily fished places in the network, and thus displace as little fishing effort as possible when implementing reserves. Such an approach increases the likelihood of support from the fishing industry.

3.6 RESULTS

3.6.1 Unconstrained network designs

Marxan produced a variety of reserve networks, which can be seen in Figure 2, which met all the targets that we set (Appendix 1). They cover 34.9-38.2% of the study area in order to meet representation targets of 30% coverage for most habitats/critical life stages, and 50% representation for more vulnerable habitats. The spatial characteristics of the reserve networks (Table 1) show that they comprise between 12-18 separate candidate reserves, have between 139-153 planning units, and the total boundary length is 7,159 ± 262 km. The nine reserve networks illustrated show that there is considerable flexibility in choice of individual reserves without sacrificing network targets.

The summed irreplaceability score (Figure 3) shows how many times each planning unit was selected to meet the targets that we set during thousands of runs of *Marxan*. These results are helpful in identifying places that are critical to meeting targets. Figure 2: The most efficient marine reserve network designs from *Marxan*, each chosen from 1,000 runs, using the targets in Appendix 1. All targets set were achieved in these networks

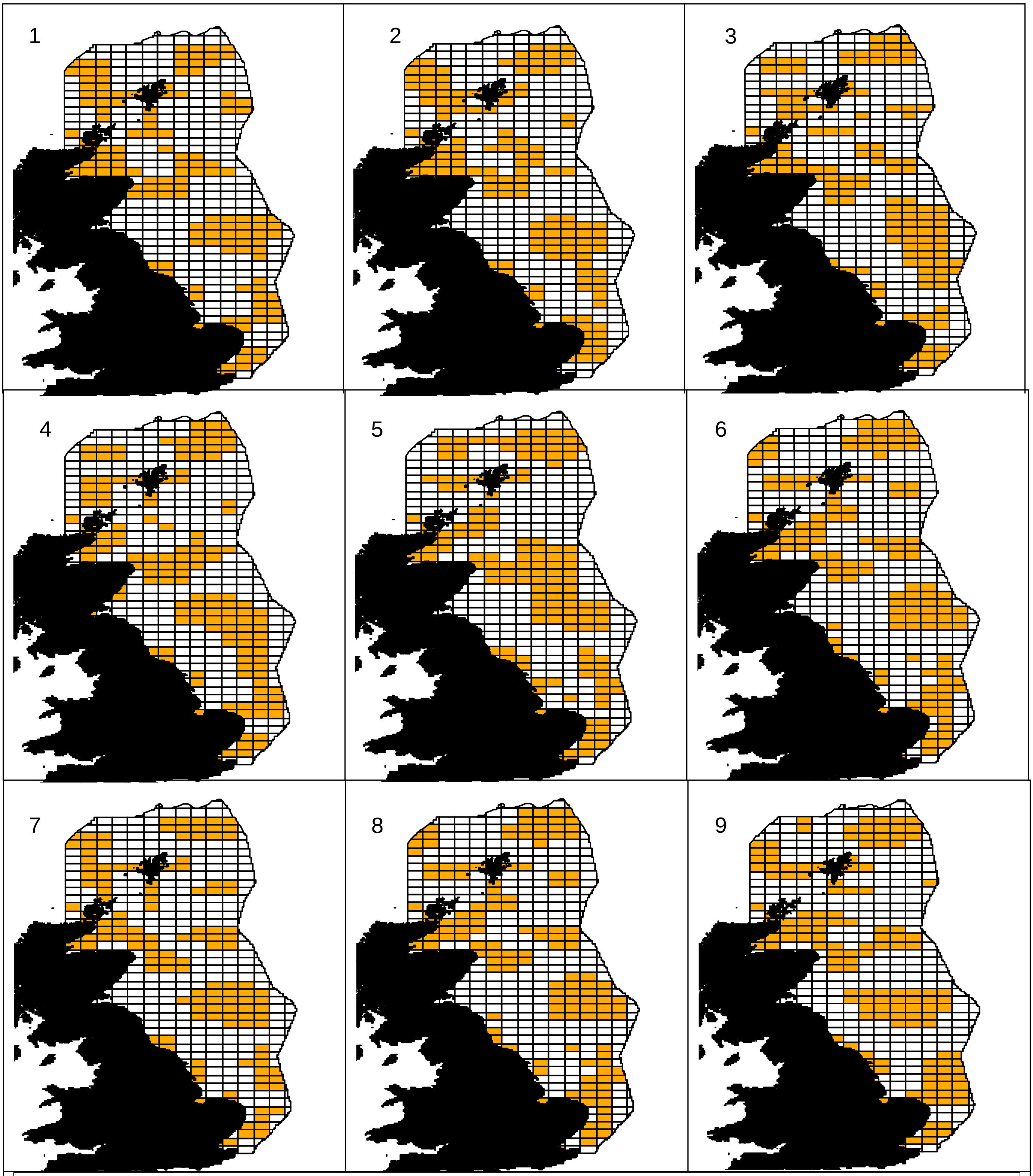


Figure 2: The most efficient marine reserve network designs from ***Marxan, each chosen from 1,000 runs, using the targetsin Appendix 1.All targets set were achieved in these networks.***

Figure 3: Irreplaceability scores: the number of times each planning unit was chosen for inclusion in a reserve network from 9,000 runs of *Marxan*

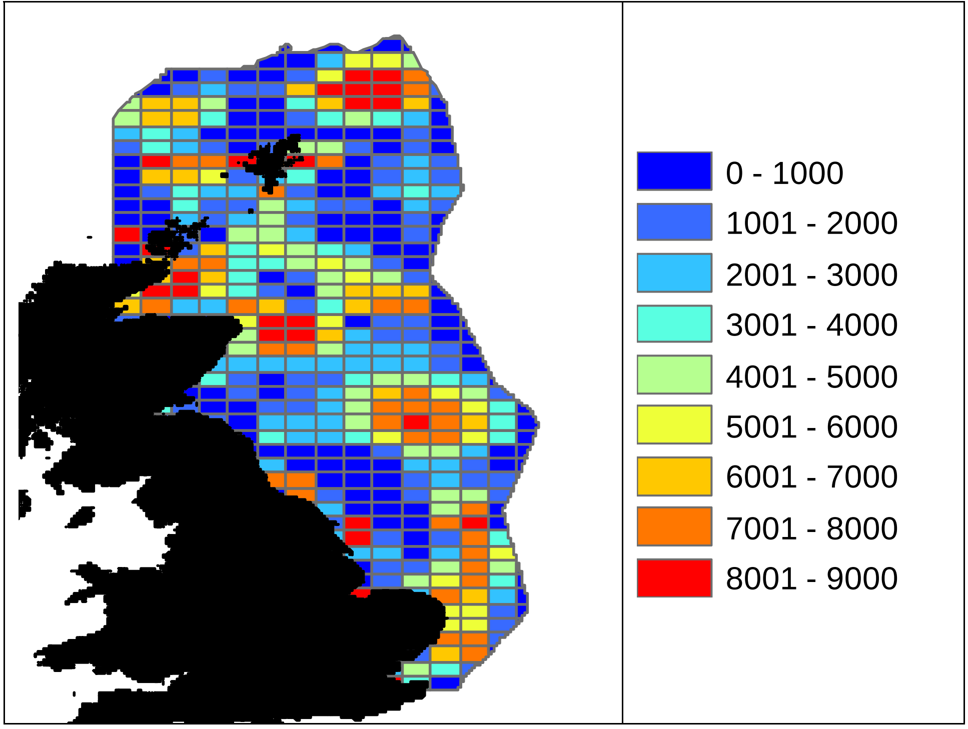


Table 1: Spatial characteristics of the nine marine reserve networks created by *Marxan*

Network number	*Total boundary (km)*	*Number of reserves*	*Number of planning units*
1	7,319	14	142
2	7,026	12	146
3	7,421	17	144
4	7,276	18	149
5	6,896	12	153
6	7,041	13	153
7	7,322	14	139
8	7,364	17	147
9	7,088	13	150

3.6.2 Minimising fishing effort displacement

To minimise fishing effort displacement, we identified the top 20% most intensively fished planning units (90 planning units) and excluded them from being in any marine reserve network (Figure 5). These 90 planning units are subject to 45.3% of the North Sea fishing effort by the UK fleet in the UK EEZ (averaged over 2000-2006). We then set about creating a network that would meet the same targets (Table 1) and with the same planning unit costs based on fishing intensity. The latter means that areas not locked out still have relative costs depending on the amount of fishing effort that they receive. Our intention was to produce network designs that will represent and protect North Sea biodiversity and will displace as little fishing effort as possible.

Figure 4: The most efficient marine reserve network designs from *Marxan* that minimise fishing effort displacement, each chosen from 1,000 runs, using the targets in Appendix 1

Figure 5: The number of times each planning unit was chosen for inclusion in a reserve network from 9,000 runs of *Marxan* where the top 20% of cells for fishing effort were excluded from being in reserve networks

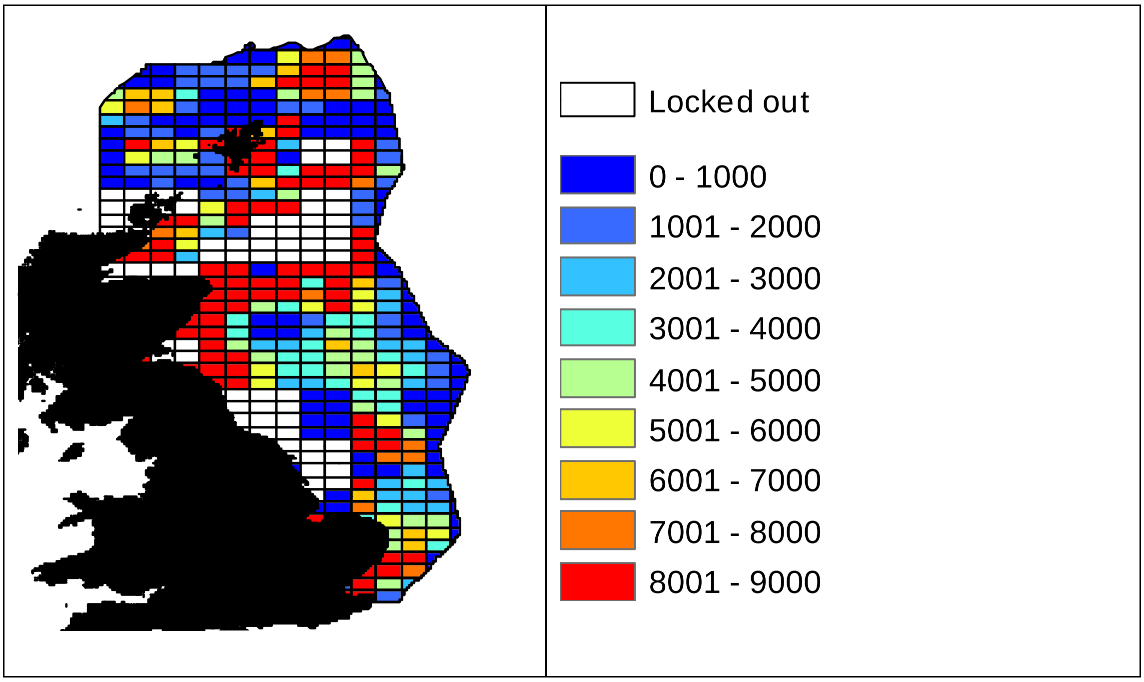


Table 2: Spatial characteristics of the nine marine reserve networks created by *Marxan* with the top 20% of planning units for fishing effort excluded

Network number	*Total boundary (km)*	*Number of reserves*	*Number of planning units*
1	7,823	15	172
2	8,318	14	162
3	8,154	15	166
4	8,445	14	159
5	8,207	12	162
6	8,050	12	164
7	7,773	14	170
8	8,268	11	166
9	8,017	15	166

Tables 3 and 4 below show the percent of fishing effort displaced for each of the different fishing industry sectors from implementing each of the nine marine reserve networks. Table 3 shows the percentage effort displacement by gear and some of the results look quite high. This is because many of the gear classes have low amounts of fishing effort and therefore loss of just a few days fishing accounts for a large percentage of the total fishing days with those gears. However, as table 4 shows, the percentage of total North Sea fishing effort displaced would be low.

Table 3: For reserve networks avoiding the most intensive fishing areas, the percentage of fishing effort (days fished) displaced under each reserve scenario by percentage of that gear

Reserve number	*Beam trawl ≥ 80mm*	*Demersal long lining*	*Demersal trawling (70-90mm and ≥ 100)*	*Demersal trawling (16-30mm)*	*Static demersal nets*	*Unregulated gear*
1	33.0	43.1	27.5	48.8	30.8	29.0
2	26.2	50.3	28.3	50.3	25.0	32.3
3	27.5	44.4	26.9	50.0	27.4	30.7
4	31.5	46.5	27.5	50.0	26.5	30.4
5	32.2	40.1	26.9	48.6	30.1	27.8
6	39.1	43.8	27.5	51.0	31.3	28.6
7	28.9	32.8	27.8	49.7	28.8	31.0
8	30.7	43.5	29.3	50.7	29.2	29.5
9	33.7	43.6	27.2	51.8	34.2	29.0

Table 4: The percentage of fishing effort (days fished) that will be displaced under each marine reserve network scenario by percentage of the total fishing effort in the North Sea

Reserve number	*Beam trawl ≥ 80mm*	*Demersal long lining*	*Demersal trawling (70-90mm and ≥100)*	*Demersal trawling (16-30mm)*	*Static demersal nets*	*Unregulated gear*
1	0.7	0.3	20.0	0.0	0.4	7.8
2	0.7	0.3	19.0	0.0	0.5	7.4
3	0.9	0.3	19.4	0.0	0.5	7.4
4	0.9	0.3	19.0	0.0	0.5	6.8
5	1.1	0.3	19.5	0.0	0.5	6.9
6	0.8	0.2	19.6	0.0	0.5	7.5
7	0.8	0.3	20.7	0.0	0.5	7.2
8	0.9	0.3	19.2	0.0	0.6	7.1
9	0.8	0.3	19.9	0.0	0.5	7.3

Marxan produced a variety of reserve networks (Figure 4) that excluded the 20% of top scoring planning units for fishing effort. These reserve networks meet all but 10 of the targets we set (see Appendix 1). Of those 10, only two habitats received no representation at all as the feature occurred only within the locked-out planning units. The other eight ranged in representation from 13.2-28.9% of the area. The summed irreplaceability score (Figure 5) shows that certain places are picked more frequently than others and are key to meeting the targets and constraints that we set. Many of the places that were frequently picked are the same as in the first runs of *Marxan* that we carried out where no planning units were excluded. The spatial characteristics of the reserves are similar, with the number of individual reserves per network varying between 12 and 15, and the number of planning units between 159 and 172. There is less variation than for the first run of *Marxan* because with 20% of the planning units excluded there is less choice as to where to protect, and certain areas have become more important to meeting the targets.

3.7 SELECTION OF AREAS FOR IMPLEMENTATION OF EXPERIMENTAL MARINE RESERVES

Defra’s Marine and Fisheries Business Plan for 2006-07 (Defra, 2006) contains the objective of planning a controlled marine protected area trial, including identifying areas in which to conduct the trial. The implementation of the trial was planned for September 2006 to March 2007.[1] The objectives of the trial are not explicitly stated in the business plan, but it is listed under the activity headed “Manage Marine Fish Stocks Sustainably”. Presumably, then, the aim is to test the benefits of marine reserves for fisheries stock protection and management.

Taking this as a starting point, we explored options for siting experimental marine reserves in the North Sea. An experiment must meet certain conditions to produce reliable results. It should compare experimental marine reserves to environmentally similar reference areas. In order to generalise the results, it should include replicate marine reserves and reference areas and it should cover the range of environmental conditions encountered in the management area. Experimental marine reserves must be large enough to provide adequate refuges from fishing to the species of interest. Of course, once established, experimental reserves must be properly enforced and monitored.

Very small marine reserves – of the order of a few square kilometres or less – have had demonstrable effects in both tropical and temperate habitats such as coral reefs and kelp forests (Gell and Roberts, 2003). However, many exploited species in temperate continental shelf ecosystems, although certainly not all, are more mobile than the species that live in habitats with pronounced physical/biological structures such as reefs. Many continental shelf species move distances ranging from kilometres to tens or hundreds of kilometres over the course of a year (Palumbi, 2004). Marine reserves need not encompass the full range of movements of a species to be effective. All species show a range of mobility. While some individuals may travel long distances, others may remain in much smaller areas for most of their adult lives. For example, there are anecdotal reports of huge cod beneath North Sea oil rigs that appear to have escaped capture because they reside within the small protected zones surrounding rigs.

If reserves protect key life stages they can also be beneficial, even for highly mobile species (Roberts and Sargant, 2002). Fishery managers have long protected nursery grounds to safeguard juveniles from premature capture. Spawning aggregations can also be vulnerable to overfishing and fishing disturbance. For example, protection of spawning aggregations of the red hind grouper in the US Virgin Islands produced large increases in body size and an increase in the ratio of males to females in this sequential hermaphrodite, despite the seasonal closure only encompassing 1.5% of grouper fishing grounds (Beets and Friedlander, 1999).

To be effective in supporting fisheries management, experimental marine reserves in the North Sea must be large enough to accommodate the range of movements of a sufficient number of individuals of the species for which protection is desired. Georges Bank closures (Section 2.1) ranged from approximately 4,000 to 7,000 sq km and encompassed about 25% of the fishing grounds on Georges Bank, and 31% of the trawl fishing effort prior to closure (Murawski et al., 2005). This is equivalent to square protected areas with an edge length of approximately 60-80 km. The dimensions of ICES rectangles are familiar to both managers and fishers in the North

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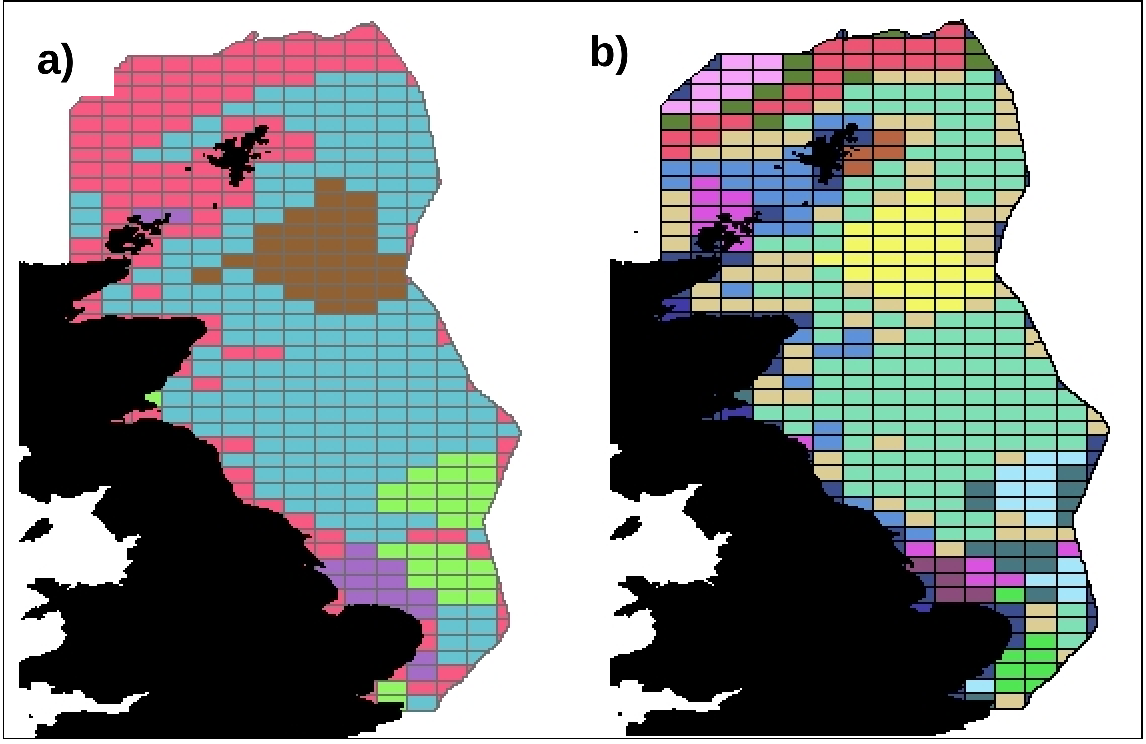
[1] Defra has not replied to my e-mail enquiring as to the status of this work.

Sea. In the southern part of the North Sea, each ICES rectangle covers 3,840 sq km, while in the north each covers 2,890 sq km, slightly smaller than the smallest Georges Bank closed area, and two to three times the size of each of the closed areas described from Iceland (Section 2.2). Marine reserves of this size should be sufficient to protect a broad suite of commercially important species in the North Sea. Hence, we set the size of experimental reserves and paired reference areas to match the size of ICES rectangles. Since the planning units consist of quarter ICES rectangles, some reserve and reference sites identified straddle two ICES rectangles.

In order to measure the effects of marine reserves on marine life and habitats it is necessary to establish reference areas as control sites. Reference areas should match test sites as closely as possible in environmental conditions and external pressures. To achieve this, we used the marine seabed landscapes classification developed by the Joint Nature Conservation Committee (JNCC) to determine the similarity of habitat, and the level of fishing effort (days fished) to which the sites were subjected, to choose sites that receive similar disturbance. To determine the similarity of planning units we carried out a non-hierarchical classification (k-means cluster analysis) on the planning units using the marine seabed landscape types (Appendix 2, Figure 1) and fishing effort (Appendix 2, Figure 2) as the subjects. This classification method forms a user-determined number of clusters (groups) that each planning unit will be assigned to. We tried out a range of cluster sizes to assess the extent to which planning units remained classified in the same clusters as other planning units. The results of the cluster analysis were mapped and two examples are shown in Figure 6 below.

Figure 6: Planning unit classification from a k-means cluster analysis using data on marine seabed landscape type and fishing effort (the number of days fished), with (a) five and (b) 15 clusters



We chose paired reserve and control areas based on the five-cluster version of the analysis (Figure 6a). We identified five matched pairs of suitable experimental reserves and reference areas (Figure 7). To select these five matched pairs we used the results of the clustering classification and the location of nursery and spawning areas of commercially valuable species to pick suitable areas. We reasoned that inclusion of nursery and spawning areas will increase the value of protection of a site for fishery management purposes (Roberts and Sargant, 2002). We avoided areas subject to the highest levels of fishing effort (the most intensively fished quartile of planning units) in order to displace as little fishing effort as possible. The five pairs are distributed across nearly the full range of latitude in the North Sea. They cover 10.16% of the area of the UK North Sea EEZ, although fishing would only be restricted in half that area, or 5.08%.

Ideally, all five experimental marine reserves would be implemented. The amount of fishing effort they displace would depend on which members of each pair were chosen for reserves. For the two largest fishing sectors, they would displace a total of 0.8-2.8% of UK demersal trawling with nets >70mm mesh, and 7.9-10.9 % of UK beam trawling effort (most of it in Pair 4, blue on Figure 7). However, a more limited selection of reserves (two to four) could still yield valuable scientific information if available resources for implementation and monitoring are insufficient for the full experiment.

Figure 7: Matched reserve-reference area pairs

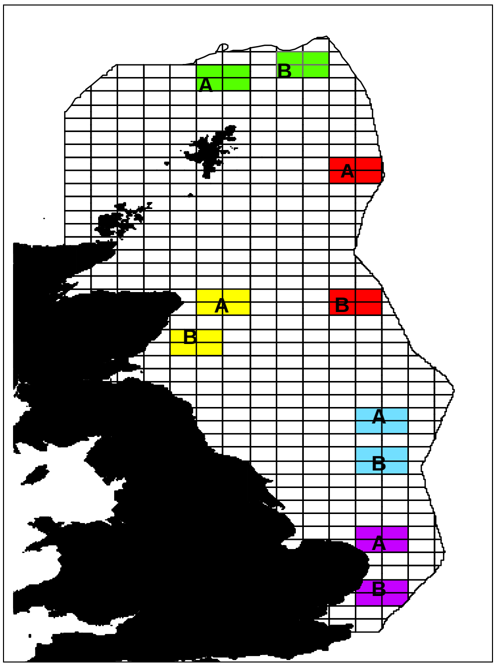


Table 5: Fishing effort that would be displaced by implementation of each of the pairs of experimental marine reserves and reference areas. The two lines for each reserve-reference pair show the fishing effort present in each of the sites making up the pair separately (As and Bs refer to labels in Figure 7)

		Beam trawl ≥ 80mm	*Demersal long lining*	*Demersal trawling (70-90mm and ≥ 100)*	*Demersal trawling (16-30mm)*	*Static demersal nets*	*Unregulated gear*
Total North Sea fishing days per gear		2,778	652	72,333	10	1,743	24,867
Pair 1 (Green)	A	0.2	0.4	94	0	69	5
	B	0.1	0.1	69	0	17	5
Pair 2 (Red)	A	0.1	0.0	760	0.6	0	67
	B	0.1	0.3	254	0	0	8
Pair 3 (Yellow)	A	0.7	0.0	774	0	0	165
	B	1.1	0.0	176	0	0.5	366
Pair 4 (Blue)	A	191	6	76	0	2	4
	B	209	12	249	0	14	57
Pair 5 (Purple)	A	27	59	18	0	11	179
	B	95	30	168	0	54	53

Pair 1 (green): All the planning units were in the same cluster group when they were split into 10 cluster groups or less, showing a high level of similarity. Both sites in this pair include iceberg plough zones (see Appendix 2, Figure 1), which are regions of more complex seabed.

Pair 2 (red): All planning units share the same cluster group up to and including when 25 clusters were defined. This is a very high degree of similarity. Both sites contain the same seabed habitat: shelf sand plain.

Pair 3 (yellow): Each site contains planning units from three different cluster groups (when split into 10-15 clusters or less). The habitats included in each are a mixture of shelf sand plain and shelf coarse sediment plain with weak tide stress. This pair includes areas that are used by up to eight commercially important species as nursery areas and up to seven species for spawning. The sites are clearly important for multiple species during vulnerable life stages and protecting either of them will help to rebuild fish stocks.

Pair 4 (blue): All planning units belong to the same cluster group, when the area is split into 15 groups or less, showing a high degree of similarity. The habitats included are a mixture of shelf sand plain, shallow coarse sediment plain with weak tide stress and shallow sand plain. Both sites contain areas that are used for spawning by multiple species.

Pair 5 (purple): Three of the planning units in each site are from the same cluster when they were split into five groups. This pair is different from the other four in that they contain a variety of seabed habitats. Each site contains the following seabed landscape types: subtidal sediment banks; shelf coarse sediment plain with moderate tide stress; shallow sand plain; shallow coarse sediment plain with moderate tide stress; shelf sand plain; shallow coarse sediment plain with strong tide stress; and shelf coarse sediment plain with strong tide stress. The two sites cover areas that are used by multiple species for vulnerable life stages, especially for spawning.

4 Conclusions

This study shows that it is possible to design multi-functional marine reserve networks that should be able to simultaneously achieve multiple goals, including:

1) contributing to fishery sustainability;
2) protecting and recovering the full spectrum of marine wildlife; and
3) recovering the structure and integrity of marine food webs.

Meeting these objectives will create healthy marine ecosystems that will provide for human needs, including fish and shellfish production. Furthermore, rebuilding populations of commercial fish stocks and marine wildlife can be expected to increase resilience to environmental disturbances and climate change. Such goals require an extensive marine reserve network, which is why we designed example networks to protect 30% or more of marine habitats. The analyses showed a high degree of flexibility in choice of individual reserves for protection while still meeting targets for the network.

The above goals for the network cannot be achieved with piecemeal fishery closures that have more limited protection and management targets. Nor can they be achieved at the marine basin scale with small reserves or marine protected areas that receive only limited protection from exploitation. However, it is possible to reduce the impacts of reserve establishment on the fishing industry, and still meet most conservation targets, by excluding key fishing grounds from the network.

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Appendix 1: Targets set for the North Sea marine reserve network

Targets set and the actual amounts included

Feature	**Target**	**Amounts included in networks**	**Amounts included with high fishing effort areas excluded**
Ocean area	30% of North Sea	34.9-38.2%	37.3-41.1%
Seabed landscapes			
Aphotic rock	50% of area	50.4-75.3%	50-52.8%
Photic rock	50% of area	50.3-52.8%	55.2-58.2%
Shelf trough	50% of area	50.4-53.2%	50.4-53.6%
Barrier beach	30% of area	88.4-100%	88.4-100%
Bay	30% of area	31.8-37.4%	37.3-37.7%
Cold deep-water mixed sediment	30% of area	31.6-64.1%	31.6-51.1%
Cold deep-water mud plain	30% of area	31.6-37.6%	31.8-36.6%
Cold deep-water sand plain	30% of area	33.6-88.2%	54.6-61.9%
Continental slope	30% of area	30.6-36.3%	30.4-35.2%
Embayment	30% of area	67-70.5%	30.3%
Estuary	30% of area	30.3-33.6%	58.1-66.4%
Lagoon	30% of area	100%	100%
Sealoch	30% of area	59.4%	87.9-95.8%
Shallow coarse sediment plain–moderate tide stress	30% of area	30.7-36.7%	32.3-40.7%
Shallow coarse sediment plain–strong tide stress	30% of area	30.7-51%	30-33.7%
Shallow coarse sediment plain–weak tide stress	30% of area	30.1-38.1%	30-36.4%
Shallow mixed sediment plain–moderate tide stress	30% of area	30-64.7%	42.7-50.4%
Shallow mixed sediment plain–strong tide stress	30% of area	67.1-100%	36.4-69.3%
Shallow mixed sediment plain–weak tide stress	30% of area	34.6-58.1%	48.7-51.4%
Shallow mud plain	30% of area	40.7-82.1%	15.4%
Shallow sand plain	30% of area	30.3-54.9%	31.1-46.7%
Shelf coarse sediment plain–moderate tide stress	30% of area	42.5-73.3%	53.4-71.6%
Shelf coarse sediment plain–strong tide stress	30% of area	36.3-100%	33-65.5%
Shelf coarse sediment plain–weak tide stress	30% of area	35.1-44.6%	37.4-47.5%
Shelf mixed sediment plain–moderate tide stress	30% of area	61.5-92.5%	59.7-77.8%
Shelf mixed sediment plain–strong tide stress	30% of area	83-100%	68.5-85.5%
Shelf mixed sediment plain–weak tide stress	30% of area	30.4-48.9%	30.1-31.4%
Shelf mound or pinnacle	30% of area	100%	0%
Shelf mud plain	30% of area	30.1-37.7%	30.1-31.9%
Shelf sand plain	30% of area	32.9-38.9%	38-42.6%

Sound	30% of area	100%	100%	
Subtidal sediment bank	30% of area	30.6-82%	30.5-95.3%	
Warm deep-water coarse sediment plain	30% of area	41-65.3%	39.1-42.3%	
Warm deep-water mixed sediment plain	30% of area	79.5-100%	79.5%	
Warm deep-water sand plain	30% of area	82.3%	46.4-83.3%	
Topographic features				
Iceberg plough-marks	50% of area	53.9-67.3%	50.1-57.1%	
Pockmarks	50% of area	50-50.4%	28.4%	
Water column features				
Spring Estuarine water	30% of area	72.9-100%	76-100%	
Spring Weakly-stratified oceanic water	30% of area	30.3-57.3%	52.1-66.5%	
Spring Weakly-stratified (Region of freshwater influence) ROFI	30% of area	30.5-36.9%	28.9%	
Spring Weakly-stratified shelf water	30% of area	31.5-36.4%	38.8-43.7%	
Spring Well-mixed oceanic water	30% of area	31.1-42.6%	30.3-35.7%	
Spring Well-mixed ROFI	30% of area	34.7-53.5%	40.2-52.2%	
Spring Well-mixed shelf water	30% of area	32.3-46.2%	32.1-46%	
Summer Estuarine water	30% of area	72.5-100%	72.5-100%	
Summer Frontal oceanic water	50% of area	50.3-55.7%	51-64.8%	
Summer Frontal ROFI	50% of area	52.5-60.4%	13.2%	
Summer Frontal Shelf water	50% of area	50.4-56.6%	50.2-53.2%	
Summer Stratified oceanic water	30% of area	30.5-36.6%	30.2-31.5%	
Summer Stratified ROFI	30% of area	30.5-35.4%	30-32.7%	
Summer Stratified shelf water	30% of area	31.9 - 37.6%	37.6 - 41.5%	
Summer Weakly-stratified oceanic water	30% of area	65.8-89.4%	76.3-100%	
Summer Weakly-stratified ROFI	30% of area	30.3-46.9%	23.7%	
Summer Weakly-stratified shelf water	30% of area	41.8-63.2%	54.2-60.6%	
Summer Well-mixed ROFI	30% of area	30.1-54.3%	43.9-56.7%	
Summer Well-mixed shelf water	30% of area	30.3-64.1%	30.1-78.4%	
Autumn Frontal oceanic water	50% of area	62.9-73%	73-84.9%	Well-mixe
Autumn Frontal ROFI	50% of area	61.2-100%	0%	
Autumn Frontal shelf water	50% of area	50.2-59.4%	16.5%	
Autumn Stratified oceanic water	30% of area	30.3-62.7%	56.3-67.8%	
Autumn Stratified ROFI	30% of area	36.3-87.8%	30.7-53.3%	
Autumn Stratified shelf water	30% of area	30-30.8%	30-31.6%	
Autumn Weakly-stratified oceanic water	30% of area	31-36.8%	31.2-36.6%	
Autumn Weakly-stratified ROFI	30% of area	31.5-64.6%	18.4%	
Autumn Weakly-stratified shelf water	30% of area	30.3-34.8%	46.8-55.9%	
Autumn Well-mixed oceanic water	30% of area	46.6-69.8%	51.2-65.1%	
Autumn Well-mixed ROFI	30% of area	36.3-50%	35.7-48.5%	
Autumn Well-mixed shelf water	30% of area	41-50.8%	43.3-57.5%	
Winter Estuarine water	30% of area	70-100%	73.7-100%	
Winter Weakly-stratified ROFI	30% of area	30.6-44.6%	26.6%	
Winter Weakly-stratified shelf water	30% of area	30.4 - 59.35%	30.1-35.3%	
Winter Well-mixed oceanic water	30% of area	31.1-33.2%	33.8-36.4%	
Winter Well-mixed ROFI	30% of area	39.2-54.7%	41.3-50%	

Winter Well-mixed shelf water	30% of area	33.3-37.7%	37.9-44.4%
Nursery and spawning areas			
Nursery areas			
Blue whiting	30% of area	30.1-35.4%	34.5-39.1%
Cod	30% of area	30.2-39.6%	30-33.5%
Haddock	30% of area	33.6-41.3%	38.6-49%
Herring	30% of area	44.2-59.4%	38.6-44.5%
Lemon sole	30% of area	35-42.1%	39.3-53.8%
Mackerel	30% of area	30-36.4%	35.9-44.2%
Nephrops	30% of area	30.2-42.7%	40.2-47.5%
Norway pout	30% of area	30.1-40.9%	33.7-45.1%
Plaice	30% of area	32.4-50.1%	31.6-35.4%
Saithe	30% of area	34.1-45.5%	48.2-52.7%
Sandeel	30% of area	33.8-40%	40.9-49.6%
Sole	30% of area	45.8-60.7%	53.7-63.2%
Sprat	30% of area	35.3-41.8%	42.9-48.1%
Whiting	30% of area	31.1-45.9%	30.1-49.2%
Six or more nursery grounds	50% of area	50.1-50.8%	50-50.5%
Spawning areas			
Cod	30% of area	30.2-40.4%	30.4-62.9%
Haddock	30% of area	30-31.8%	39.4-43.6%
Herring	30% of area	37.3-44.9%	40.8-42.9%
Lemon sole	30% of area	33.2-44.2%	39.9-52.3%
Mackerel	30% of area	41.1-49.2%	30.2-40.5%
Nephrops	30% of area	30.2-40%	40.2-44.9%
Norway pout	30% of area	30.1-40.9%	33.7-45.1%
Plaice	30% of area	31.9-44.8%	43.3-53.3%
Saithe	30% of area	30-33.5%	35.4-37.8%
Sandeel	30% of area	33.3-38.7%	39.9-48.2%
Sole	30% of area	43.1-57%	51.8-60.8%
Sprat	30% of area	31.8-39.8%	31.1-41%
Whiting	30% of area	31.2-44%	46.8-54.7%
Six or more spawning grounds	50% of area	50.1-60.5%	55.4-61.4%

Appendix 2: Data layers used

Data used to set targets

Seabed habitats

Detailed biological information for offshore regions is hard to obtain. Surrogates for biological information, such as geophysical data, can be used to identify broad-scale marine habitats, as they are strong determinants of biological community type (Roff, Taylor et al., 2003). In order to represent marine habitats in the North Sea we used UKSeaMap seabed landscapes, along with data on the location of pockmark fields and iceberg plough-mark zones. We then set a target to protect 30% of the area of each seabed marine landscape apart from those deemed highly vulnerable to damage by fishing – namely: aphotic rock, photic rock, and shelf troughs – which received a higher protection target of 50%. These seabed types are especially vulnerable to destruction by fishing practices such as trawling.

Topographic features

Iceberg plough marks and pockmark fields were mapped and we then set a target of representing 50% of the area of each in the network. These features cause the seabed to be more complex so they can play host to a greater variety of ocean life and are vulnerable to fishing practices that destroy the structure of the seabed, such as trawling.

Water column features

The character of the water column influences its ecology and there is a high degree of change in the water column throughout the year. We used four seasonal maps – spring, summer, autumn and winter – which show the location of different water features. We aimed to include 30% of the area of each of the majority of water column features, for each season, within a reserve network in order to represent the variety of features present throughout the year. Certain features are particularly important in supporting marine life, such as frontal regions that form boundaries between water masses and support tidally driven increases in primary productivity. Frontal systems tend to concentrate plankton, including eggs and larvae. They also attract forage fish species, such as herring, bringing in predators like cetaceans, seals and sharks. To protect the concentrations of life they support, we set a higher representation target for frontal features.

Nursery and spawning areas

In order to increase fish stocks, protection during critical life stages is needed, which allows greater numbers to survive and reach maturity. Spawning is a critical life stage and increased protection of spawning sites should allow greater numbers of fish to spawn. Protecting nursery areas will allow greater numbers of fish to reach marketable sizes and attain maturity, thus increasing the spawning stock. We used maps of nursery areas for 14 species, and spawning areas of 13 species (see Appendix 1 for a list of species).

Data sources

Seabed landscapes

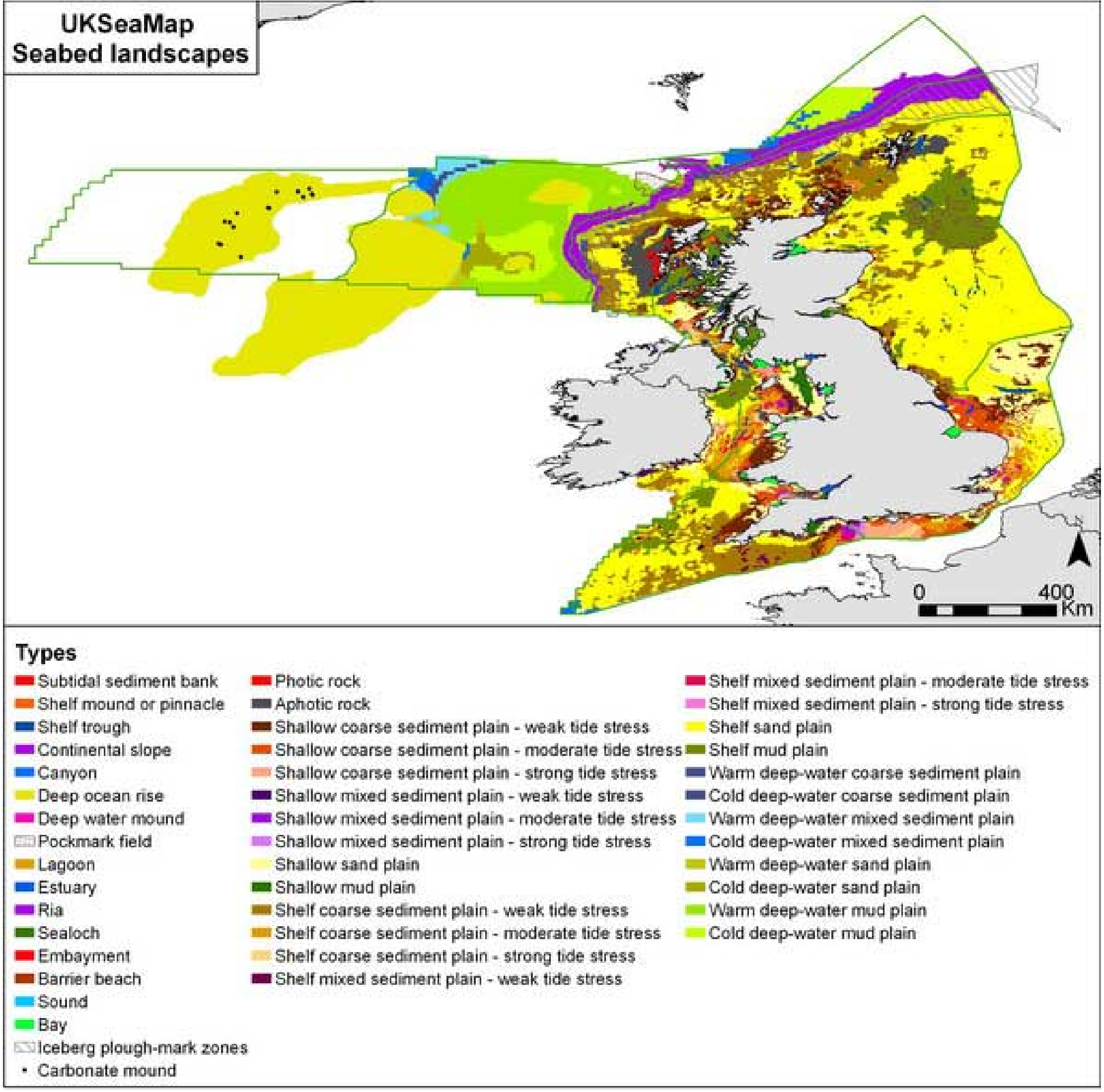
North Sea seabed landscapes were obtained from JNCC (Joint Nature Conservation Committee). There are 36 types identified for the North Sea area. To classify the seabed the following data were used:

- Bathymetric slope data
- Coastal physiographic features
- Seabed substratum
- Light attenuation
- Depth
- Bottom temperatures
- Wave-base
- Near-bed stress

To test the validity of the seabed landscape map, biological sample data was used by JNCC. Around 32,000 samples were collated form a variety of sources. Each sample was then assigned to a habitat. The expected correlation between the habitat type and the seabed landscape type was calculated, and then used to test the observed relationship.

Connor, DW, Gilliland, PM, Golding, N, Robinson, P, Todd, D and Verling, E (2006) *UKSeaMap: the mapping of seabed and water column features of UK seas*. Joint Nature Conservation Committee, Peterborough.

Figure 1: Marine landscapes map from JNCC



The UKSeaMap Funding Partners accept no liability for the use of this data or for any further analysis or interpretation of the data.

Topographic features

High species diversity can often be linked to high habitat complexity because of the greater refugia, variety of living opportunities, and quantity of food that complex habitats offer. To identify areas of likely complex bottom habitat in the North Sea we used the distribution of two topographic features: pockmark fields and iceberg plough-zones. These were identified by BGS (British Geological Survey) and obtained from JNCC SeaMap WebGIS (www.jncc.gov.uk/page-3663, accessed on 01/05/07). We digitised an image of the features and geocorrected it to use in our analyses. Pockmarks are near-circular depressions usually 100m across, though some are up to 500m in diameter, and 1 to 4 metres deep. They are mainly found on continental shelves and occur over large areas. Iceberg plough-zones are ridges of boulders and cobbles that have been formed by the ploughing movement of icebergs through the seabed during the last ice age. These ridges are 10s to 100m wide and comprise turbated sediment often with boulders exposed on their berms.

Connor, DW, Gilliland, PM, Golding, N, Robinson, P, Todd, D and Verling, E (2006) *UKSeaMap: the mapping of seabed and water column features of UK seas*. Joint Nature Conservation Committee, Peterborough.

The UKSeaMap Funding Partners accept no liability for the use of this data or for any further analysis or interpretation of the data.

Water column features

Water column features were obtained from JNCC in the form of four shape files, one for each season, owing to the significant changes in the water column over the year. To classify the water column, data layers of salinity, surface to seabed temperature differences, and frontal probability were used in the classification. These data layers were thought to represent the main hydrographic parameters that influence ecological character. To validate the resultant classification, JNCC used biological distribution data of plankton taxa to validate the results.

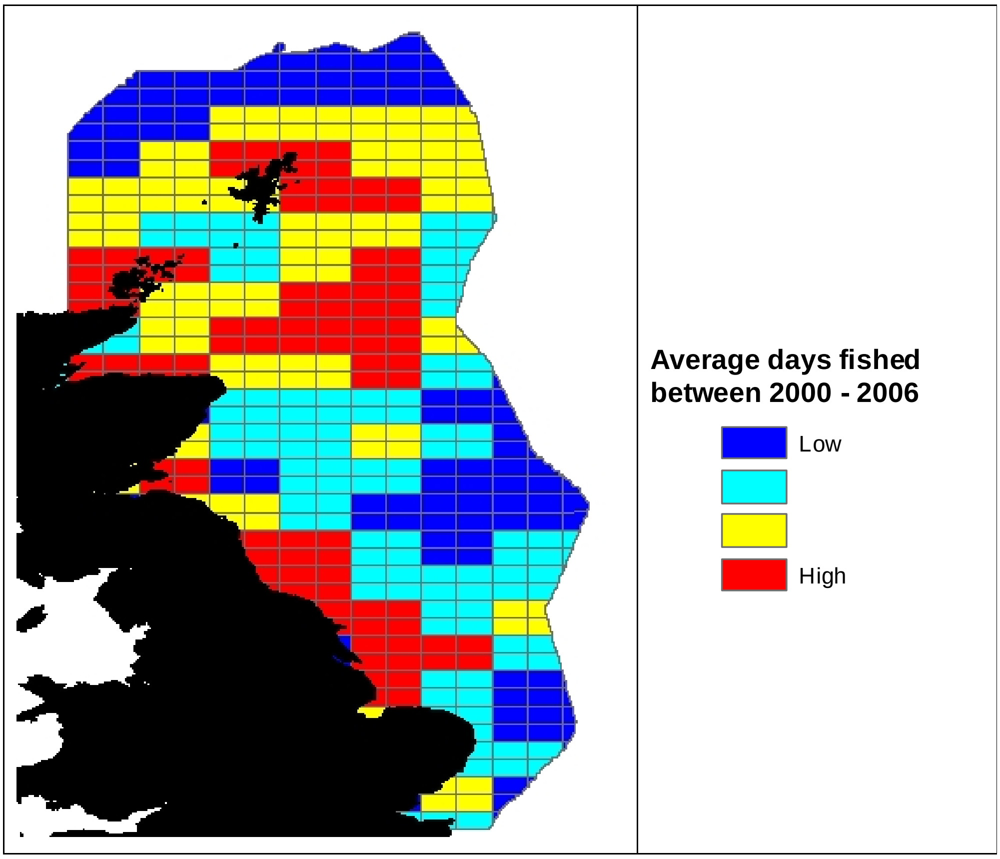
Connor, DW, Gilliland, PM, Golding, N, Robinson, P, Todd, D and Verling, E (2006) *UKSeaMap: the mapping of seabed and water column features of UK seas*. Joint Nature Conservation Committee, Peterborough.

The UKSeaMap Funding Partners accept no liability for the use of this data or for any further analysis or interpretation of the data.

Fishing effort data

Fishing effort data were obtained from the Marine Fisheries Agency (April 2007) in the form of a spreadsheet giving the number of days fished per ICES rectangle, subdivided by fishing gear type. The data is for UK registered vessels over 10 metres in length, and excludes fishing by vessels from other EU countries in UK waters.

Figure 2: Distribution of total fishing effort by the UK fleet. The data has been split into quartiles

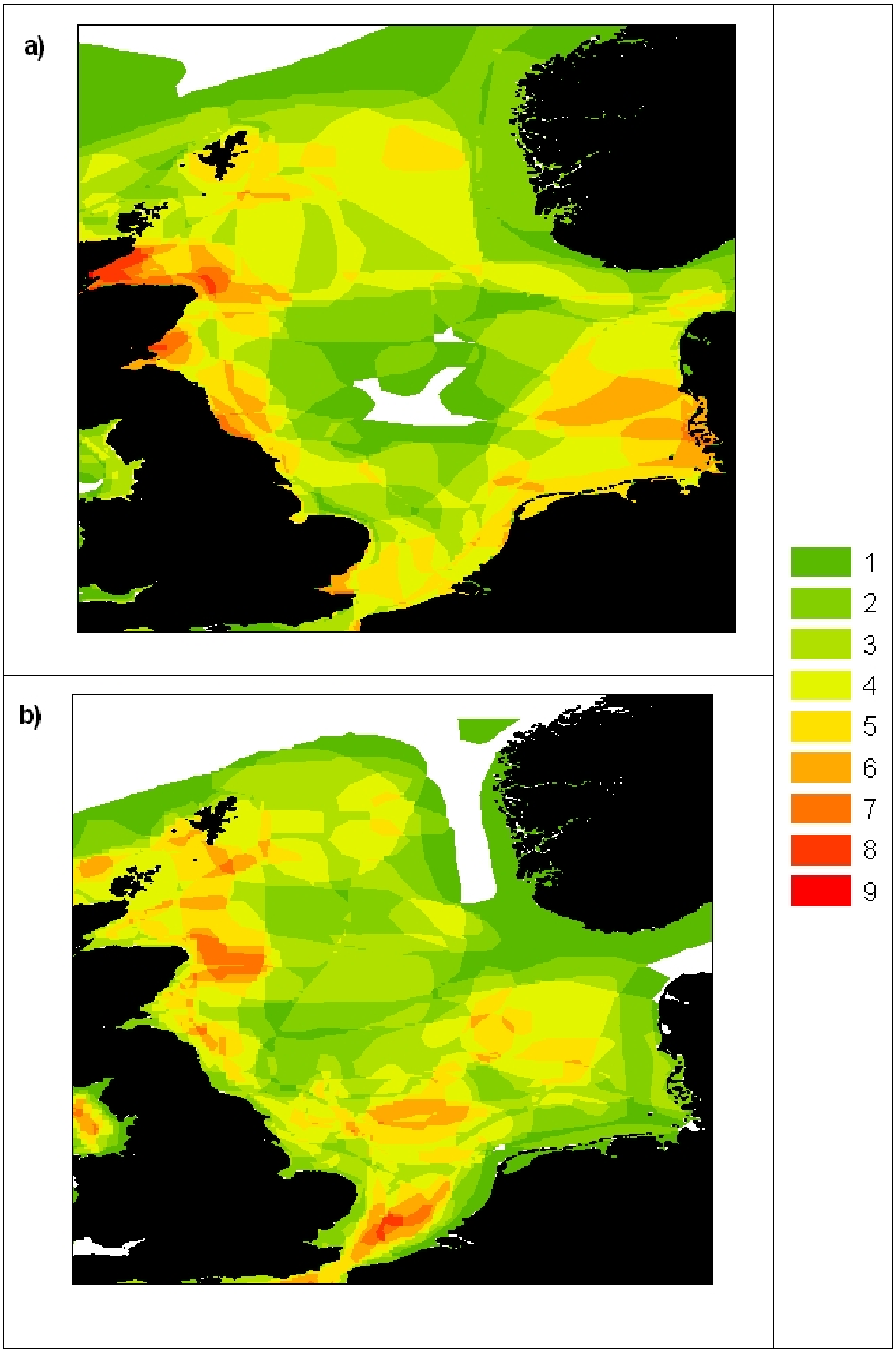


Nursery and spawning areas

Maps of nursery and spawning areas of commercially important species were digitised. As well as being used individually, the distribution of nursery and spawning areas for all species were overlaid to give two maps, one for nursery areas and one for spawning areas, to show places that are important for multiple species. The data used to create the original maps came from multinational research vessels, which collect details on the distribution of eggs, larvae and size of fish.

Coull, KA, Johnstone, R, and Rogers, SI. 1998. *Fisheries Sensitivity Maps in British Waters*. Published and distributed by UKOOA Ltd.

Figure 3: Composite maps of (a) Nursery areas for blue whiting, cod, haddock, herring, lemon sole, mackerel, *Nephrops*, Norway pout, plaice, saithe, sandeel, sole, sprat and whiting; (b) Spawning areas for cod, haddock, herring, lemon sole, mackerel, *Nephrops*, Norway pout, plaice, saithe, sandeel, sole, sprat and whiting



Appendix 3: How *Marxan* works

Marxan was developed at the Ecology Centre at the University of Queensland, Australia (Ball and Possingham, 2000; Possingham, 2000). It is the most widely used decision support software for designing networks of marine reserves and was instrumental in re-zoning the Great Barrier Reef Marine Park in Australia (Fernandes, 2005). *Marxan* works by selecting sites for protection to create efficient reserve networks that meet user-defined conservation targets while trying to minimise costs. The costs include parameters that are generally proxies for real financial costs and include measures of the area and the total boundary length of reserves within the network.

To use *Marxan*, the region being considered for protection has to be divided into units of area, referred to as planning units. Features to be represented in the reserve network are then mapped, such as habitat types and species occurrence. Human uses and impacts can also be mapped, such as fishing intensity or pollution levels. For each planning unit the amount of each feature is calculated. The *Marxan* user then sets a target for how much of each feature is required in the reserve network. If the network does not meet a particular target then a user-set penalty is applied. Any penalties are ultimately added to the total cost for a reserve network. Hence network designs that do not meet the conservation targets can be considered as expensive options.

The ‘cost’ of reserving each planning unit is decided by the user and can reflect real costs that might be incurred. Examples of costs include area, as bigger sites cost more to include in an MPA network. Costs of inshore planning units can be set higher than offshore ones to reflect that they cost more to police if included in a reserve network, due to the high number of coastal resource users (Balmford et al., 2004). Alternatively, all the planning units can be given the same cost.

Costs generally increase with the size of the area to be protected, but there are economies of scale that can be achieved by creating fewer, larger reserves, compared to many small reserves that cover the same area (Balmford et al., 2004). In *Marxan* a ‘Boundary Length Modifier’ (BLM) can be set that determines the extent to which reserve networks are clumped. This forces the program to seek less expensive network solutions with fewer, larger marine reserves rather than many small areas. The more clumped the reserves are, the less total boundary there will be for a given area protected, and so the less expensive the network is to create and manage.

Each run of *Marxan* produces a network design. At the outset of a *Marxan* run, sites for protection can be locked in, and undesirable areas locked out. The program starts with a ‘seed solution’, which is usually a random pick of planning units. It then adds and subtracts planning units in a pre-determined number of iterations (usually several thousand). For each iteration, the cost of the network is calculated, which is the area, plus the boundary, plus any penalty for not meeting the conservation targets. In this way the program seeks to meet the conservation targets with the lowest cost network through trade offs made between meeting targets, and efficiency in the costs of area and the boundary lengths. The simulated ‘annealing’ algorithm used by *Marxan* allows both ‘good’ and ‘bad’ changes to be accepted near the start. But as the algorithm progresses, the frequency with which ‘bad’ changes are accepted decreases. This unique feature of simulated annealing allows different options to be explored by not optimising locally too early on in the process.

Marxan can be run many times to provide alternative marine reserve network designs for any given set of targets. From these, a selection frequency, or ‘irreplaceability value’, can be calculated for each planning unit, indicating its relative importance to meeting the given targets. This value may be useful in deciding which planning units are high priorities for protection.

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WWF-UK
Panda House, Weyside Park
Godalming, Surrey GU7 1XR
t: +44 (0)1483 426333
f: +44 (0)1483 426409