Recovering Scotland's Marine Environment

Report to Scottish Environment LINK
October 2009

Photo: George Brown

David Hughes & Thom Nickell

Scottish Association for Marine Science Internal Report No. 262

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Foreword by Scottish Environment LINK Marine Task Force

Recovering Scotland's Marine Environment is an independent report by Dr David Hughes and Dr Thom Nickell from the Scottish Association for Marine Science.

Focusing on features for which there is good evidence of decline, the report makes a strong case that Scotland's marine environment is in a far from pristine state and is in real need of recovery. Many habitats and species have been seriously depleted over a long period as a result of human activities, fragile habitats are particularly vulnerable to some mobile fishing gear, while the discharge of organic waste and water-borne chemical contaminants can also lead to the depletion of certain species. Unsustainable fishing practices have led to the decline of some fish stocks.

There is no doubt that a healthy marine environment is an ecologically and economically productive one. Therefore the case studies presented in the report, including the destruction of seabed habitats like oyster and maerl beds, that once supported entire ecosystems and provided nursery grounds for scallops and fish, have ultimately damaged the engine house of our marine economy including fisheries.

The report highlights some good examples of improved marine management, such as ongoing work to reduce fish farm impacts. A number of Scottish fisheries have also adopted technical conservation measures including selective gear and closed areas, reducing discards and enabling vulnerable species to show signs of recovery, and many fisheries are now MSC accredited, with several more under assessment. Scottish fisheries management has taken a leading role in Europe towards species recovery by adopting Long Term Management Plans (LTMPs) for certain species or through the Conservation Credits Scheme.

Ecosystems can recover, however these first steps need to be supported by a strong national framework of action for recovery across all of Scotland's marine environment. Restoring even a fraction of that lost abundance and prosperity will require co-ordination of effort, planning that takes account of the needs of the environment, use of sustainable fishing methods and the long-term protection of keystone habitats and species.

The Marine (Scotland) Bill is the best chance in our lifetimes to unite all our efforts to restore Scotland's seas to better health, abundance and productivity.

But the Marine Bill as it stands will only manage the *status quo*. It will not bring about any improvement in the wider seas outside marine protected areas.

To support the restoration of healthy and productive Scottish seas the Marine Bill must be strengthened to include:

- **Recovery** - A duty on Scottish Ministers to improve the health of Scotland's seas, in line with international commitments.
- **Planning** - A duty on Scottish Ministers to prepare and adopt a national marine plan. A duty to ensure that Scottish Marine Regions cover the whole Scottish marine area (0-12nm). Scottish Ministers must ensure that regional plans are produced for all areas where there are conflicting uses and planning and/or management is required. A clear description in law of what plans must deliver.

- **Protection** - A duty on Scottish Ministers to create an ecologically-coherent network of Marine Protected Areas
- **Targets** - A duty on Scottish Ministers to set out the environmental targets marine plans must deliver – marine ecosystem objectives.

Fisheries - in addition, the UK and Scottish Marine Bills must be implemented in a manner that delivers improved joined-up operations between the Marine Bills and fisheries legislation to help deliver restoration.

Scottish Environment LINK is the umbrella body for Scotland's voluntary environmental organisations, representing around 500,000 members. Scottish Environment LINK's Marine Task Force and its campaign for a Scottish Marine Bill is supported by:

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EXECUTIVE SUMMARY

The effects of human exploitation

Human exploitation of Scotland's seas dates back at least 10,000 years. We do not have the data to calculate the full extent of human impacts on the marine environment, but it is unlikely that there are any 'pristine' ecosystems left on the Scottish continental shelf. Natural variability and climate change are known to play a role in the decline of certain species. Nevertheless, research on the relatively few marine features for which data is available provides evidence that human activities have resulted in significant ecological depletion in the seas around Scotland.

Catch records from whaling stations leave no doubt that the abundance of all large whales in the north-east Atlantic was drastically reduced by commercial whaling.

Fishing has caused the significant decline both of certain target species and of species caught as bycatch. There is a large body of data that demonstrates that fishing, particularly bottom trawling and dredging, has profoundly altered ecosystems in heavily-fished coastal seas. Major changes include the replacement of creatures that form 'living crusts' on the seabed, like oyster, fileshell, maerl and fanshell, with smaller mobile worms and fish that inhabit sediments. Offshore, fishing in the deep Rockall Trough is believed to be seriously depleting slow maturing deep water fish species.

Case Studies of how human activities have impacted the marine environment

Herring - During the late 20thC Scottish herring stocks experienced a catastrophic decline, with landings in the North Sea falling from around 650,000 tonnes a year in the 1950s and early 1960s down to almost zero in the 1970s. In the Clyde, once the centre of a major herring fishery, landings peaked at 40,000 tonnes in the early 1930s, but had declined to almost zero by the 1980s. For recovery of herring to take place incidental fishing effort would have to be radically reduced.

Cod - Landings in the North Sea have declined from a peak of around 800,000 tonnes in 1980 to near zero. The inshore cod fishery has declined from a peak of 2300 tonnes in 1998 to around 300 tonnes in 2008. Bycatch of young cod by prawn trawlers remains a concern. Despite the recent EU Cod Recovery Plan, cod spawning stocks west of Scotland remain close to their lowest historical levels, although there is some evidence that plans are beginning to have a positive effect in the North Sea. On the west coast it is believed that natural mortality and environmental variability combined with fishing mortality are likely to be hindering cod recovery.

Skates and rays - Once common, these fish mature and reproduce slowly. Inshore landings have declined from around 465 tonnes in 1997 to less than 150 tonnes in 2008. Both bycatch and target fisheries are found to be at the root of this decline.

Maerl – This very slow-growing (1mm a year) coral-like red algae is an important Scottish species. Maerl beds are reservoirs of biodiversity, important both as nursery grounds for young scallops and young fish. Studies show that organic waste from fish farms significantly reduces live maerl and that scallop dredging has profound and long-lasting impacts. Scallop dredging on a maerl bed has been found to kill over 70% of live maerl, with no discernable recovery over the following four years. Recovery of maerl beds would be expected to require many years without disturbance.

File shell – These can form dense beds which stabilize loose sediment and can support hundreds of other species. They have disappeared from several areas where they were once common. Scallop dredging and use of TBT-based antifoulant on salmon farm nets, are known to kill file shells. A recent study estimated that complete recovery of a 7.5m wide strip cleared by the passage of a typical assemblage of Newhaven scallop dredges would take 117 years. In one case recovery from TBT antifoulants took 9 years.

Fan shell – Once common, this is now a scarce Scottish species, a decline attributed to physical damage and smothering by bottom trawling and dredging. It is believed that patches of fan shells act as an 'ecosystem engineer' and can supply up to 80% of the nutrients to plant plankton in the water column. Natural recovery is limited by the scarcity of individuals, but artificial populations in protected areas could be beneficial to ecosystem recovery.

Native oyster – Once widespread in dense beds, these are now rare around Scotland. They are known to be important in filtering water, preventing algal blooms and supporting ecosystem health. The Firth of Forth once supported over 166km^2 of oyster beds, with beds at Newhaven alone yielding around 60 million oysters a year. Native oysters may now be biologically extinct in the Firth of Forth. There is conclusive evidence that overexploitation is at the root of this collapse. It is believed that restoration will be impossible without effective legislation and enforcement to prevent unlawful gathering.

Demersal (bottom dwelling) fish communities in the northern North Sea – Research using data since 1925 has shown that the more intensive the fishing pressure the fewer fish species and smaller and younger the fish present. Results suggest that the total biomass of today's North Sea fish community is 38% lower than in the absence of exploitation. The biomass of large fish in the 4-16 kg and 16-66 kg size classes is estimated to have been reduced by 97% and 99% respectively compared with the pre-fishery state.

Examples of ecosystem recovery

The Clyde Estuary – This was so polluted that by the 1870s fish were virtually extinct. Since the improvement of sewage treatment in the late 1960s 34 fish species have been recorded, including salmon.

Marine cage farming – Organic waste from salmon farming reduces biodiversity and changes the type of species present in a limited area around the cages. Site rotation and more exposed sites are being used to encourage recovery, although full recovery has been found to take several years.

A strategy for marine ecosystem recovery

A strategy for marine ecosystem recovery would combine the management of fishing and other activities to ensure that they are at sustainable levels and do not cause long-term environmental damage, the use of protected areas both for marine biodiversity and to assist fisheries management, monitoring and effective enforcement. Recovery of all degraded Scottish habitats should be a component of the Marine Bill, with attention paid to the declining species highlighted in the case studies.

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1 Overview of human depletion of marine ecosystems in Scotland

1.1 The growth of historical marine ecology and its application to Scotland

The announcement in April 2009 of the discovery of 14,000-year old stone tools near Biggar in South Lanarkshire pushes the earliest known human presence in Scotland back to the end of the last Ice Age (BBC, 2009). Little is known of the lifestyle of these earliest settlers, but remains from the later Mesolithic period (ca. 8000 – 4000 BC) are much more numerous and show that human communities living around the coast made extensive use of marine resources. Stable isotope analysis of human bone from Oronsay, Inner Hebrides, indicates that more than 50% of dietary protein came from marine sources (Richards & Hedges, 1999), while the many shell middens found around the Scottish coastline testify to the importance of marine molluscs in the hunter-gatherer economy (Pollard, 1994). Fishing, mainly for shallow-water, inshore species continued throughout the Neolithic, Bronze and Iron Ages, and from the Viking Age onwards there is evidence for increased offshore fishing for large gadoids, possibly connected with the growth of an export trade in dried fish (Barrett et al., 1999). Within the period covered by historical records fishing became increasingly important to the Scottish economy, a tradition extending from the mediaeval herring fishery to the industrial fisheries of the 19th and 20th centuries, and continuing to the present day. Besides fishing, industrialization and population growth in Scotland have generated additional human pressures on the marine environment through the growth of aquaculture, coastal development, pollution, oil and gas extraction and the introduction of non-native species.

Human exploitation of Scotland's seas thus extends back at least 10,000 years. The extent of this human "imprint" must be assessed in the context of changing scientific perspectives on our capacity to modify and damage marine ecosystems. Although concerns about the dangers of overfishing are nothing new, as late as 1955 a book could still be written entitled *The Inexhaustible Sea* (Daniel & Minot, 1955), expressing a belief in the inability of humans to significantly deplete the ocean's living resources. In 1971, the great Danish marine biologist Gunnar Thorson argued that exploited marine fish were at no risk of extinction, since declining returns would render fisheries economically unviable long before populations were reduced to biologically unsafe levels (Thorson, 1971). By the end of the 20th century these optimistic assessments had been conclusively disproven by the many documented cases of stock declines driven by overfishing, the most notable recent example being the collapse and enforced closure of Canada's Grand Banks cod fishery in 1993 (Myers et al., 1997). Around the same time, dwindling populations of large oceanic predators forced scientists to consider the possibility that overexploitation could drive some marine fish species to biological extinction (Casey & Myers, 1998; Myers & Worm, 2003). From the late 1980s onwards a large body of data from studies around the world has demonstrated that fishing, particularly bottom-trawling and dredging, is a source of massive disturbance to the marine environment, with the result that the ecological functioning of the most heavily-fished coastal seas has probably been profoundly altered (Jennings & Kaiser, 1998; Hall, 1999; Kaiser & de Groot, 2000; Kaiser et al., 2006). In a landmark paper Jackson et al. (2001) proposed that human overfishing was a significant ecological force long before the industrial age, and that modern conservation biologists therefore need a much longer historical perspective to identify the "natural" state of coastal marine ecosystems (Jackson, 2001). Jackson's analysis did much to accelerate the subsequent growth of historical marine ecology as a scientific discipline, making use of evidence from archaeology, written records and photographic archives to reconstruct the history of human impacts on the oceans (Schrope, 2006; Roberts, 2007; McClenachan, 2008; Rick & Erlandson, 2009).

1.2 Evidence from archaeology

Obstacles to a comprehensive assessment of human impacts on Scotland's marine ecosystems include the (so far) limited analysis of the archaeological record, our still-incomplete knowledge of the country's marine biodiversity, and the difficulty of assigning a human causation to some observed changes. The ecological impacts of human activity over the past 2000 years have been reviewed for the Dutch Wadden Sea and the wider south-eastern region of the North Sea (Wolff, 2000; Lotze, 2005; Lotze et al., 2005). No comparable historical analysis has yet been carried out for Scotland's seas, but archaeology provides some evidence for faunal depletion in prehistory and during the early historic period. Bones of walrus (*Odobenus rosmarus*) occur in Bronze Age deposits at Jarlshof, Shetland, suggesting that this large pinniped formed part of the Scottish marine fauna at that time (Yalden, 1999). Remains of the extinct great auk (*Pinguinus impennis*) are quite common in archaeological sites from

Orkney, the Western Isles and the Inner Hebridean island of Oronsay (Serjeantson, 2001). On Sanday, Orkney, bones of this large flightless seabird decline in abundance from the Neolithic through the Bronze and Iron Ages, and are extremely rare by the 1st millennium AD. This is consistent with a process of human overexploitation that continued into historic times, leading to the last Scottish record of the species at St. Kilda in 1840, shortly before its global extinction in 1844. The abundant remains of fish and marine molluscs in many Scottish archaeological sites (Barrett et al., 1999) offer rich potential for analysis of changes in coastal ecosystems. In a study of marine resource use in northern Scotland during the first millennium AD, Milner et al. (2007) noted a decline in average size of limpet (*Patella* spp.) shells in middens at Quoygrew, Orkney, from the 10th to the 13th centuries. Limpets are believed to have been collected for use as fish bait, and their declining size is consistent with heavy exploitation as offshore cod fishing became a major economic activity in the early historic period. These examples are still few and scattered, but they suggest that human impacts on Scottish marine ecosystems extend far back into prehistory and that a detailed analysis of archaeological and historical data could yield much more information.

1.3 Mapping Scotland's marine biodiversity: what is "natural"?

For a country of modest size Scotland has a huge coastline, recently estimated at ~16,500 km, and an extensive territorial sea area (~88,600 km^2 within the 12-mile limit) (figures cited in Saunders, 2004). Although marine science has a long and distinguished history in Scotland, much basic information on the distribution and characteristics of marine habitats has been gained only recently, and our knowledge is still incomplete. The west coast sea lochs were surveyed by scientifically-trained scuba divers of the Marine Nature Conservation Review in 1988-1992 (Howson et al., 1994). Many of their stations have not been visited by scientists since and very few have been the subject of regular monitoring. Assumptions that the biotopes and species recorded by the MNCR represent the natural state for particular sites are vulnerable to the "Shifting Baseline" syndrome first defined for marine fisheries (Pauly, 1995; Pinnegar & Engelhard, 2008), but equally applicable to benthic ecosystems. In this case, the biotope and species composition first recorded by scientific observers is assumed to be natural, and is used as a baseline to evaluate subsequent changes. The historical perspective taken by Jackson et al. (2001) suggests that this assumption is dubious and that there are likely to be few if any pristine coastal environments in a country with Scotland's long history of marine resource exploitation.

Advances in acoustic technology and benthic habitat discrimination software have made it easier to survey large areas of seabed and map the broad-scale distribution of benthic environments (e.g. Brown et al., 2005; McGonigle et al., 2009). However, ground-truthing by video observation, scuba or remote sampling is still required to fill in the details of species composition in habitat maps produced in this way. Recent surveys in Scottish inshore waters have provided new records of distinctive and important benthic biotopes, including cold-water coral (*Lophelia pertusa*) reefs off Mingulay in the Outer Hebrides (Roberts et al., 2005) and tubeworm (*Serpula vermicularis*) reefs in Loch Teacuis, Morvern (Dodd et al., 2009). These examples demonstrate that Scotland's coastal waters are still far from completely explored and further unexpected discoveries are possible.

1.4 Ecological impacts of bottom-trawling and dredging

Some forms of anthropogenic damage to Scottish marine ecosystems can be inferred from work done outside Scotland. Experimental studies in Scottish waters have contributed to the global dataset on the ecosystem effects of mobile fishing gear (Tuck et al., 1998; Hall-Spencer & Moore, 2000a; Hauton et al., 2003), but the most detailed information on the long-term benthic impacts of commercial dredging comes from the scallop grounds of the Isle of Man (Hill et al., 1999; Kaiser et al., 2000; Veale et al., 2000; Bradshaw et al., 2001, 2002). Experimental dredging, comparison of fished and closed areas, and analysis of historical data demonstrate clearly that six decades of scallop dredging have signficantly degraded the seabed habitats and communities in this area of the Irish Sea. Major ecological changes include the loss of seabed habitat diversity and a shift in community dominance from large, sessile epifauna to smaller, opportunistic species inhabiting the bottom sediments. The extent of observed change is proportional to the length of time a site has been fished (Bradshaw et al., 2002). These Irish Sea results are supported by data from scallop grounds in Iceland (Garcia et al., 2006), New England (Collie et al., 2000) and Greece (Kefalas et al., 2003), while analysis of a global dataset on benthic fishing impacts ranked scallop dredges as the most destructive form of towed gear (Kaiser et al., 2006). This weight of evidence supports the contention of Hall-Spencer & Moore (2000a, discussed below) that commercial dredging has had damaging ecological impacts on Scottish scallop grounds.

In addition to Mingulay, Roberts et al., (2005) surveyed three other areas of the western Scottish shelf with historical records of *Lophelia pertusa* but found no evidence for its continued presence. Extensive trawl damage to *L. pertusa* reefs has been observed off the coast of Norway (Hall-Spencer et al., 2002), and it is possible that cold-water coral distribution in Scottish inshore waters has also been reduced by trawling. An example of ongoing ecological depletion by trawling in Scottish waters (although outside the 12-mile territorial limit) is the deep-water fishery in the Rockall Trough and adjacent waters along the shelf edge (Gordon, 2001). The life histories of most deep-water fish species are characterised by slow growth and late age-at-maturity, a combination making them intensely vulnerable to fishing pressure (Koslow et al., 2000). Populations of some exploited species in the northwest Atlantic are believed to have been reduced by 97-99% since the onset of fishing (Devine et al., 2006). In the Porcupine Seabight, south-west of Ireland, fish abundance has been significantly depressed at depths far below the current maximum limit of commercial fishing at ~ 1600 m, indicating that the impacts of the fishery extend deeper than previously thought (Bailey et al., 2009). In consequence there is little doubt that the current deep-water fishery in the Rockall Trough is unsustainable (Gordon, 2003). Trawl scars are routinely visible to depths of over 1000 m in seabed photographs from the continental margin west of the Hebrides (Roberts et al., 2000) but the wider impacts of this disturbance to the deep-sea ecosystem are still unknown (Roberts, 2002).

1.5 Ecosystem change: natural or anthropogenic?

There are several documented examples of population decline in marine organisms in Scotland where the link to human activity is tenuous or uncertain. These cases illustrate the fact that it is not always easy to identify the causative agents of observed changes, and that human impacts, where present, usually operate against a background of natural variation.

1.5.1 Tubeworm reefs

Reefs of the calcifying tubeworm *Serpula vermicularis* are a defining feature of the Loch Creran Marine Special Area of Conservation and occur in the shallow sublittoral around most of the loch's periphery (Moore et al., 2009). In his popular account of life around Loch Creran in the late 19th century William Anderson Smith (1887) recorded seeing "*bunches of serpulae tubes, from six inches to near a foot in height*" growing amongst eelgrass (*Zostera marina*) at low tide. This is the earliest written record of tubeworm reefs in Loch Creran. A change in the ecology of the loch is indicated by the fact that nowhere today do the reefs exist in such shallow water, or in association with eelgrass. It is also uncertain whether tubeworm reefs have been present continuously in Loch Creran since Anderson Smith's time. *Serpula vermicularis* reefs were recorded in the Linne Mhuirich arm of Loch Sween, mid-Argyll, in the 1980s, but were found to have died out when the area was re-surveyed in 1994 (Hughes et al., 2008). No recovery has taken place since (D.J. Hughes, personal observations). Although the cause of their disappearance is not known, it is most likely to have been a natural event unrelated to human activity. Tubeworm reefs in Loch Creran have sustained local damage as a result of dredging and mooring scour (Moore et al., 2009), but neither of these processes could have operated in Linne Mhuirich. The discovery in July 2006 of what appear to be incipient reefs in Loch Teacuis, Morvern (Dodd et al., 2009), where none were recorded in 1996, raises the possibility that *S. vermicularis* reefs in sea lochs may be relatively transient features, forming and disappearing on a decadal timescale for unknown natural reasons.

1.5.2 Seabirds

In recent years there has much concern about the reproductive output and population numbers of seabird species breeding in Scotland. A summary of the available data (Parsons et al., 2006) found that the aggregate trend for 13 species was relatively stable from 1986 to 1991, but showed a steady decline from 1991 to 2004. Sandeel specialists such as the kittiwake (*Rissa tridactyla*), Arctic tern (*Sterna paradisaea*) and Arctic skua (*Stercorarius parasiticus*) were particularly hard-hit, these three species declining by 29-63%. Sandeel recruitment is sensitive to ocean climate and has been impacted by a recent warming trend in the North Sea (Arnott & Ruxton, 2002). The North Sea industrial fishery has also been implicated in the decline of sandeel-dependent seabirds (Frederiksen et al., 2004). Human activity (via fishing) may therefore play an indirect role in the decline of some Scottish seabirds, but its importance relative to oceanographic changes is still uncertain.

1.5.3 Cetaceans

Whalebone has been recorded from many archaeological sites in Atlantic Scotland and cetaceans were probably a valuable resource to prehistoric communities living around the coast (Mulville, 2002). It is not known when active hunting of whales and dolphins (as opposed to utilization of strandings) began in Scotland, and the archaeological record cannot give any indication of cetacean abundance in early times. Catch records of the whaling station at Loch Tarbert, Harris, show that large whales were common in Scottish waters well into the 20th century. During the periods when the station was active (1904-1928 and 1950-1951), 2423 whales of seven species were caught, including 1538 fin (*Balaenoptera physalus*), 378 sei (*B. borealis*) and 316 blue (*B. musculus*) whales (Thompson, 1928; Brown, 1976). It is not possible to translate these catch statistics into population estimates, but there is no doubt that the abundance of all large whales in the north-east Atlantic was drastically reduced by commercial whaling. Fin and sei whales are still encountered in small numbers to the north and west of Scotland, particularly in the Faeroe-Shetland Channel (Weir et al., 2001; Macleod et al., 2003).

Scientific study of smaller cetaceans (dolphins and porpoises) is a relatively recent development in Scotland and so far we have little information on changes in abundance. The famous bottlenose dolphins (*Tursiops truncatus*) of the Moray Firth have only been monitored since 1989 (Thompson et al., 2006), not long enough to identify population trends in such highly mobile, long-lived animals. Study of dolphin populations off the Scottish west coast is even more recent.[1] Sea areas of greatest importance for harbour porpoises (*Phocoena phocoena*) have been identified in the North Sea (Hammond et al., 2002) and to the north and west of Scotland (Weir et al.,

[1] http://www.scottishdolphins.info

2001) and may provide a baseline for future population monitoring. Unlike the large whales, dolphins and porpoises were not intentionally hunted in Scottish waters in recent times. Some incidental mortality in fishing nets does occur in Scotland (Parsons et al., 2000) but its significance for cetacean numbers is not known. Other potential human influences on dolphin and porpoise populations (e.g. pollutant effects, depletion of prey species) will be indirect and therefore difficult to detect and quantify. Shifts in the relative abundance of dolphin species currently taking place off north-west Scotland (MacLeod et al., 2005) appear to be driven by oceanographic factors rather than human influence.

2 Case studies of ecosystem decline or depletion in Scottish waters

The following section presents brief accounts of species and ecosystems in Scottish waters (within the 12-mile limit) which meet the following conditions:

- Documented evidence of a reduction in numbers/distribution, or of ecological depletion
- They are in their present condition as a direct result of human activity
- They have the potential for population recovery or improvement in ecological condition

We have only considered cases where there is strong evidence of decline due to man's influence; for the purpose of this report that is to say where there is documented evidence of abundance/distribution in the form of baseline or historical data, and subsequent data on temporal change. Scotland has a number of important marine species, habitats and landscapes (eg. subtidal rocky reefs, maerl beds and cold water corals), but until very recently the extent and abundance of these has not been mapped or monitored. For this reason, most of the case studies presented below deal with commercially fished species, as there have been reasonably accurate landings data on these species for some time. Specific marine habitats have not been quantitatively assessed either until recently, except for maerl beds discussed below, therefore attention has been focussed on areas where data are available. In addition, while there may be well-evidenced cases of decline or recovery beyond the 12 mile limit, they have not been addressed as they are beyond the scope of this report.

Likewise, the authors have only considered cases of recovery of inshore species or habitats where there is good evidence. There may well be more of these cases in Scottish waters, but in the absence of published data, the authors do not feel able to comment.

2.1 Case study 1: Herring (*Clupea harengus*)

2.1.1 Scottish herring – the wider picture

There has been a herring fishery in Scottish inshore waters since the 15th century (Rorke, 2005), but during the late 20th century Scottish herring stocks experienced a catastrophic decline. There is a great deal of published literature on the decline of North Sea herring, and specifically those located inshore (the Forth, Moray Firth, Shetland and West Coast fisheries). Sub-populations of North Sea herring spawn at different times and can be found spawning in almost any month although the stock is dominated by autumn spawners. Three major populations can be identified: Buchan/Shetland herring, spawning off the Scottish and Shetland coasts during August and September; Banks or Dogger herring, spawning in the Central North Sea and off the English coast from August until October; and the Southern Bight or Downs herring, spawning in the English Channel from November until January. For most of the year the different populations mix, but during the spawning season they migrate to their separate areas. Because the herring mix outside the breeding season it is difficult to track the status of these individual stocks and overall catch statistics are usually reported from the whole North Sea. In addition there is often difficulty in ascribing causality to declining fish stocks since many factors are involved. In particular, recruitment success in many stocks is highly variable and a run of a few poor years can lead to relatively rapid declines in adult biomass. However, if an exploited fishery is seen to collapse, and after a period of closure, the fishery recovers, it can reasonably be argued that the collapse was primarily due to the fishery.

2.1.2 North Sea herring

Bailey & Steele (1992) provide catch data for North Sea herring (total international catch) and show that following the complete collapse of the fishery and its closure in 1977, after a four year moratorium the fishery had begun to recover (Figure 1). Although changes in total landings should be interpreted cautiously as some of the changes will be due to changing fishing effort, it is reasonable to assume that such large scale fluctuations reflect stock status with some time lag. While other variables including physical factors (change in climate), variability in recruitment and fecundity may have played a role (Bailey & Steele, 1992), man's influence was assumed to be a major factor in the decline of the North Sea herring stocks (Saville & Bailey, 1980).

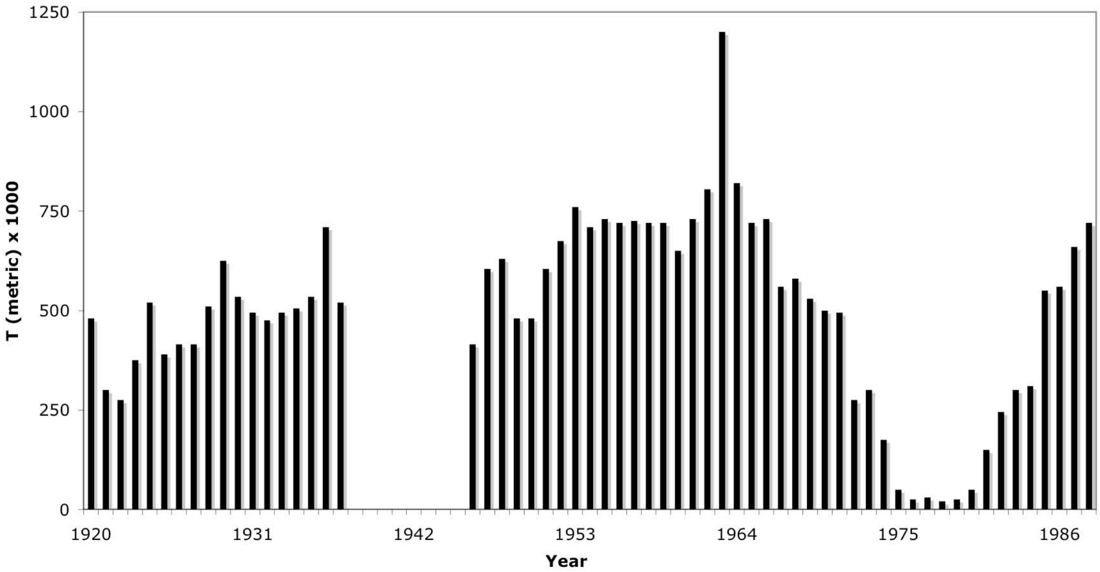

Figure 1. Total herring landings from the North Sea 1920-1988 (redrawn from Bailey & Steele, 1992).

2.1.3 Scottish inshore herring

The data above are aggregated across the whole North Sea and this can make the Scottish inshore fishery component difficult to interpret, but FRS data collected from individual boat logbooks reveal the fishing effort in inshore areas (Greenstreet et al., 1999). To take pair trawling as an example, effort from 1960-1980 was concentrated in the inshore waters of the Moray Firth (10,000-16,000 hours), followed by the Tay and Forth, with some effort locally in Shetland (Figure 2). By the 1990s this effort had declined to 0-10 hours fishing; the reason was the depletion of the stock in the Moray Firth, and the increasing use of pelagic purse seines, with the major effort shifting to the Shetland and Aberdeen areas (Figure 3) (Greenstreet et al., 1999).

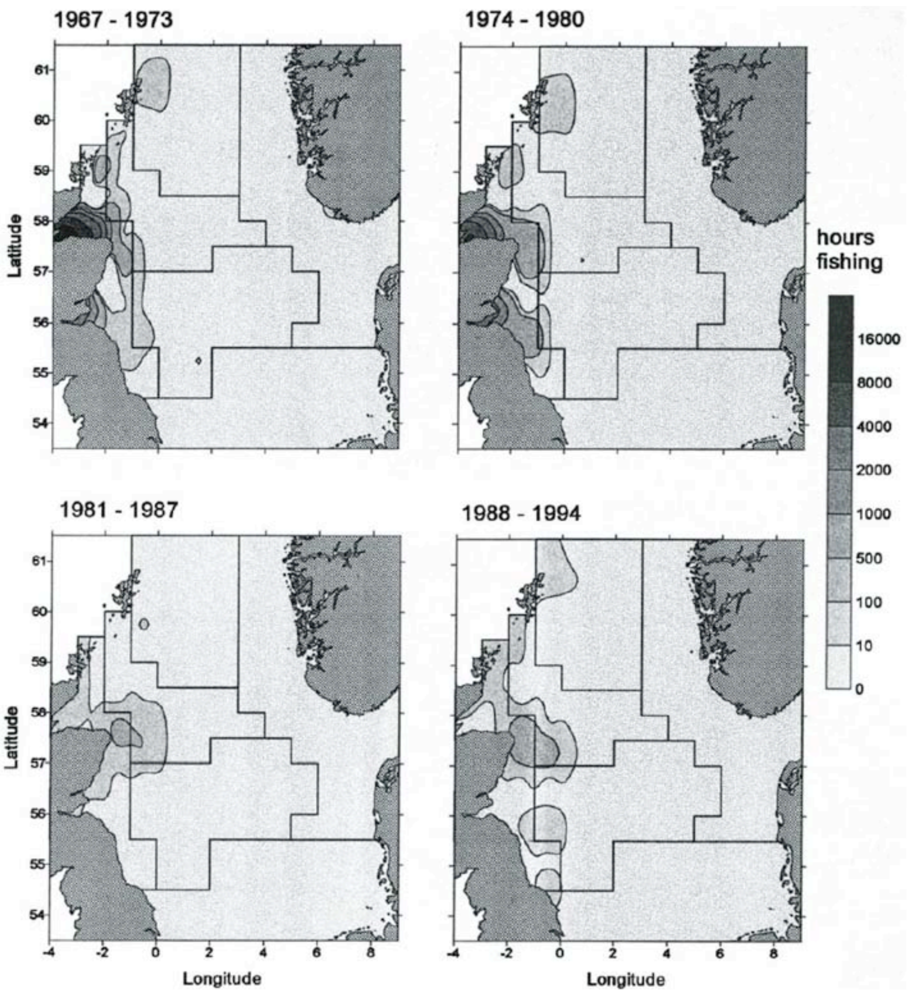

Figure 2. Changes in pelagic pair trawling fishing effort over time. Taken from Fig. 5 in Greenstreet et al., 1992.

Atlantic herring stocks are quite discrete (Iles & Sinclair, 1982), and the pressures exerted on one stock may not be experienced by all stocks around Scottish coasts. One difficulty in managing North Sea herring, however, is the fact that while there are a number of separate breeding stocks, the juveniles and adults merge together at other times of the year. For the Scottish North Sea herring fishery, the two main inshore spawning areas are the northern coast to Orkney and Shetland, and off the Aberdeenshire coast. The nursery areas for some of these stocks are the Moray Firth and the Firths of Forth and Tay, while many herring larvae drift eastward across the North Sea. Many of the herring from the West Coast spawning grounds also drift across into the North Sea to mature (Bailey & Steele, 1992).

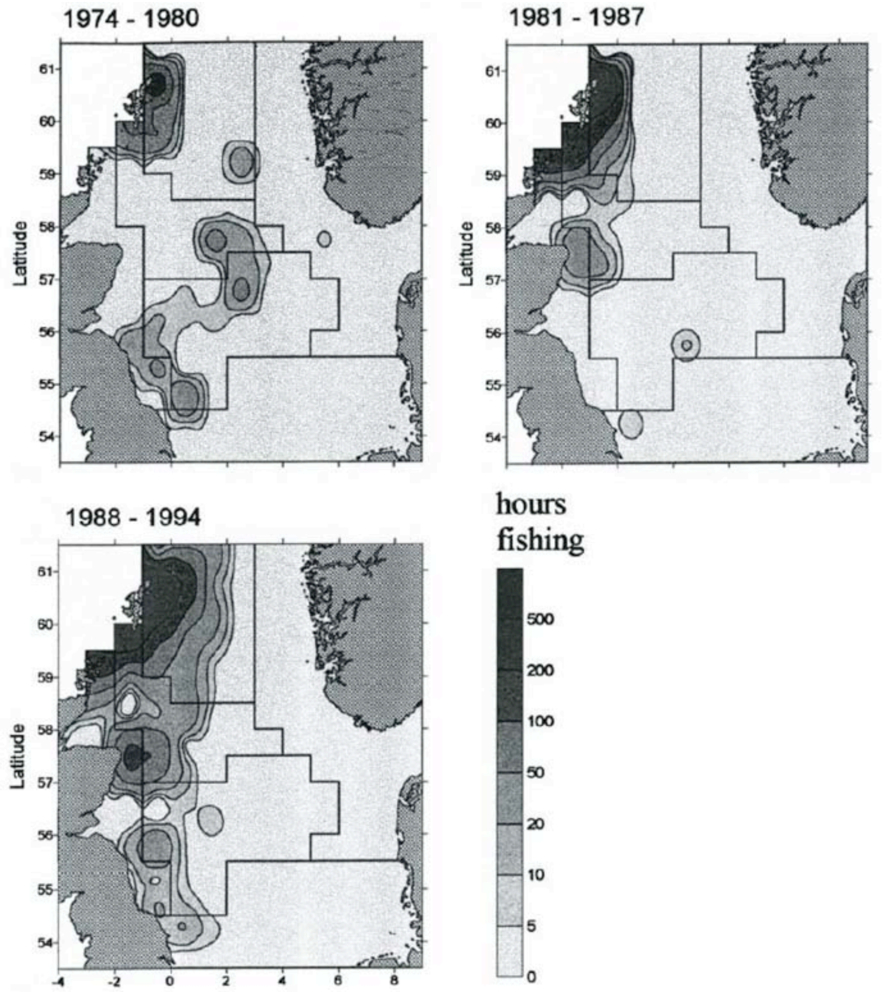

Figure 3. Changes in pelagic purse seining fishing effort over time. Adapted from Fig. 6 in Greenstreet et al., 1992.

From Figure 1 it is apparent that post-war landings until the 1960s were relatively stable at the 650,000 t level. While recruitment was sufficient during this period, there was a massive decline in spawning stock biomass (SSB), and increase in fishing mortality (Bailey & Steele, 1992). Whereas recruitment was sufficient during the 1960s, by the 1970s, however, this situation had altered drastically. The above factors are heavily suggestive that overfishing in the 1960s caused the depletion of the adult stock to the point where the subsequent lack of recruitment in the 1970s led to stock collapse (Nichols, 2000).

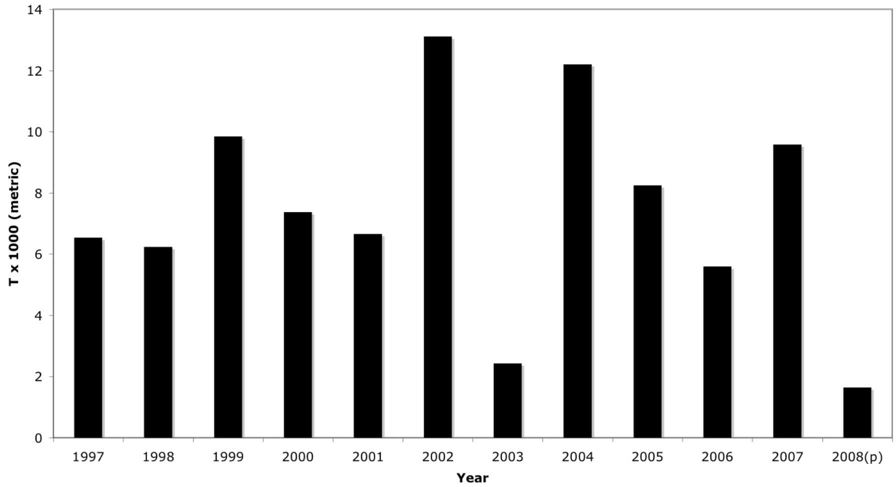

Figure 4. Inshore landings of herring for all Scottish ports, 1997-2008 (provisional data for 2008) from Marine Science Scotland (2009).

Taking Scottish landings as a whole, the inshore herring catch in recent years is seen to be extremely variable (Marine Science Scotland, 2009) (Figure 4). Looking at one particular inshore fishery, e.g. the Clyde, a picture similar to the North Sea emerges. Once the centre of a major herring fishery, the Clyde has seen landings decline to almost zero (Marine Science Scotland, 2009) (Figure 6). The principal fishing method for Clyde herring historically was ring-net or anchored drift nets; more recently either pelagic pair trawl or mid water pair trawl have been used (Bailey et al., 1986).

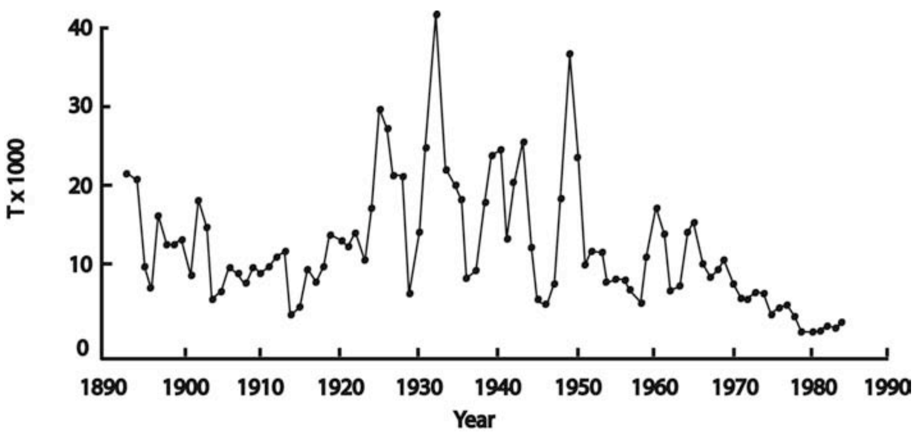

Figure 5. Clyde landings for herring from 1890-1988. Redrawn from Fig. 3, Bailey et al., 1986.

2.1.4 Scottish West coast herring fisheries – the Clyde

Historically, landings from the Clyde spring-spawning herring fishery averaged ca. 14,000 t per annum through the 20th century until the late 1960s, at which time the stock began to collapse (Bailey et al., 1986) (Figure 5). The reasons for the collapse of the Clyde herring are not clear cut; although there are multiple stocks that comprise the Clyde fishery almost all of the Clyde stock was being fished within the Clyde. As with North Sea stocks, declining spawning stock biomass, fishing mortality and eventual lack of recruitment may well have been causative (Bailey et al., 1986).

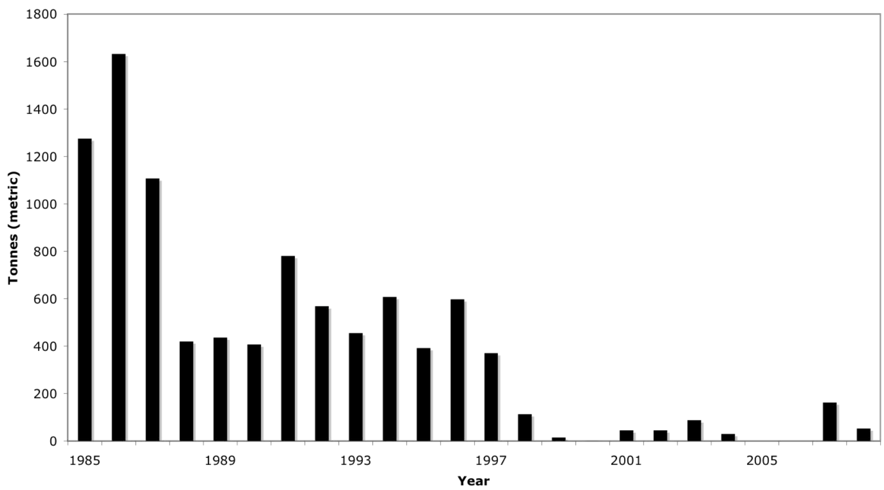

Figure 6. Landings of herring for all Clyde ports, 1985-2008. Data from Marine Science Scotland (2009).

2.1.5 Potential for recovery

After the collapse of the North Sea herring fishery in the 1970s, and the subsequent closure of the fishery, there was a marked increase in landings into the 1980s. The current state of the fishery, however, does not lead to hope for herring recovery. The latest ICES advice for spring spawning herring stocks is that "current fishing mortality rates are expected to lead to reduction of stock" and for autumn spawned herring in the North Sea, the stock is over fished, and there should be no fishing in 2009 (ICES, 2008). As stocks have shown previous recovery, clearly, for a lasting recovery of herring to take place, fishing effort must be radically reduced.

2.2 Case study 2: Cod (*Gadus morhua*)

2.2.1 Scottish cod – the wider picture

Cod are present in all Scottish waters, from shallow rocky coastal areas to water deeper than 200 m. Historically they have formed an important part of the Scottish diet, and since the Viking age they have been fished extensively from the Orkneys and Shetland (Barrett et al., 2001). They are fished throughout the North Sea and West Coast, and 7000-8000 t were landed at all Scottish ports in 2007 and 2008 (Marine Science Scotland, 2009). The North Sea spawning grounds are mainly in the south near Dogger Bank (Fox et al., 2008) with juveniles migrating eastwards to develop; the main inshore Scottish spawning grounds are in the outer Moray Firth, the waters around Lewis/Harris, and the entrances to the Firths of Lorn and Clyde (Fisheries Research Services, 2007) (Figure 7). As in other areas of the North Atlantic, cod stock structure around the UK is relatively complex and individual spawning populations may be at least partially genetically isolated (Hutchinson et al., 2001; Wright et al., 2007; Metcalf et al., 2009). Cod on the west of Scotland may migrate north and form part of the west of Shetland population, while in contrast, cod in the Clyde may remain there year round (Fisheries Research Services, 2007). However, cod in the Clyde may also move into the North Channel (at the northern end of the Irish Sea) and if caught here may be recorded as having come from ICES Area VII.

Cod take several years to mature, and while some fish may be reproductively mature at 2 years, nearly all are by the age of 6. In UK waters cod grow rapidly compared to other areas such as the Barents Sea and they may be large enough to be captured by their first or second year. The removal of reproductively immature cod from the population has implications for recruitment to the population (Longhurst, 1998). Cod SSB in both the North Sea and west of Scotland is close to historical minima triggering stock re-building management plans under the Common Fisheries policy (Figure 9) (ICES, 2009). There is some limited evidence that these plans are beginning to have an effect with apparent declines in effort in the North Sea and some indications of a halt in the decline of SSB (but see Section 2.2.4 below).

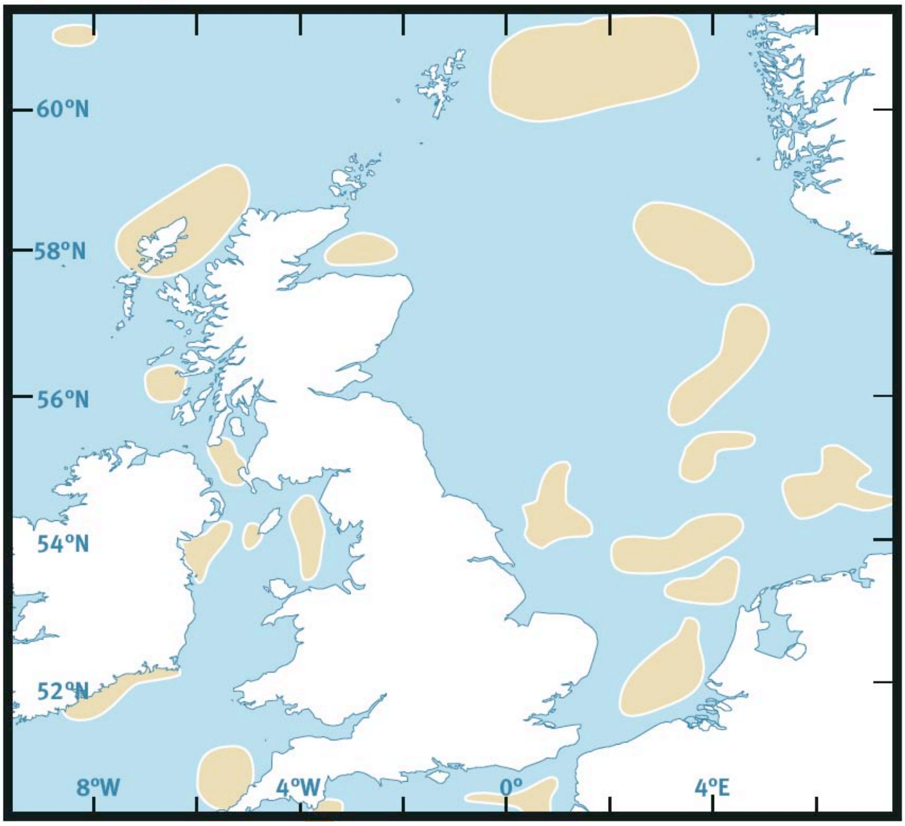

Figure 7. Cod spawning grounds in British waters. Taken from Fisheries Research Services (2007).

The depletion of North Sea, West Coast, and indeed many Northeast Atlantic cod stocks is well documented. The major cause of these declines is generally agreed to be fisheries pressure although recent environmental changes may have negatively affected recruitment leading to even greater pressure on the stock as a whole (O'Brien et al., 2000; Beaugrand et al., 2003; Clark et al., 2003). Total catches throughout the North Sea have been declining to near-collapse from a peak in 1980 of ca 600,000 t, to the extent that closure of the fishery was recommended in 2003 (ICES, 2009) (Figure 8). The latest ICES advice for 2009 was that in terms of spawning stock biomass in relation to precautionary limits, the stock had reduced reproductive capacity; there was an increased risk of fishing mortality in relation to precautionary limits; and that the stock was over-fished.

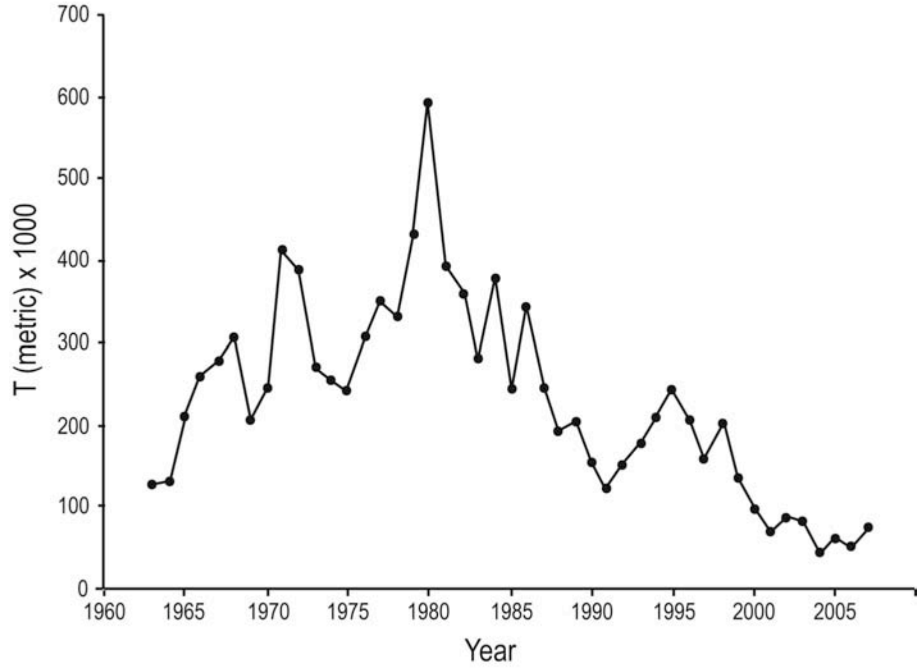

Figure 8. Total North Sea landings of cod 1963-2005. Data from ICES (2009).

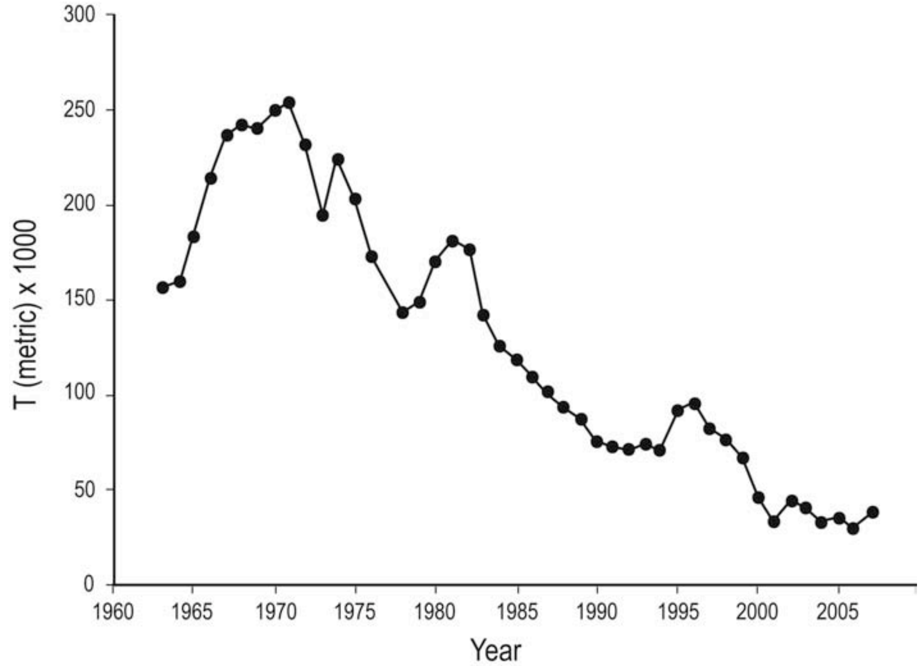

Figure 9. North Sea spawning stock biomass of cod 1963-2005. Data from ICES (2009).

2.2.2 Inshore Scottish cod fishery

The inshore Scottish cod fishery is in a similar situation to the wider North Sea. Figure 10 clearly shows the decline in the inshore fishery from a peak of 2300 t in 1998 to an estimated 300 t in 2008. Spawning area fidelity is known to occur in cod

(Wright et al., 2006a), with recent work suggesting that between 67-97% of inshore cod remain within 100 km of their spawning grounds (Wright et al., 2006b). The offshore cod are thought to migrate over larger distances. Thus while cod stocks are assessed as single units for management purposes, they are likely to be isolated sub-populations that are genetically distinct (Holmes et al., 2008). Excessive exploitation of the sub-populations may have profound effects on the genetic diversity of the stocks (Hutchinson et al., 2003) with resultant collapse of the sub-populations and prolonged prevention of recovery (Hutchinson, 2008).

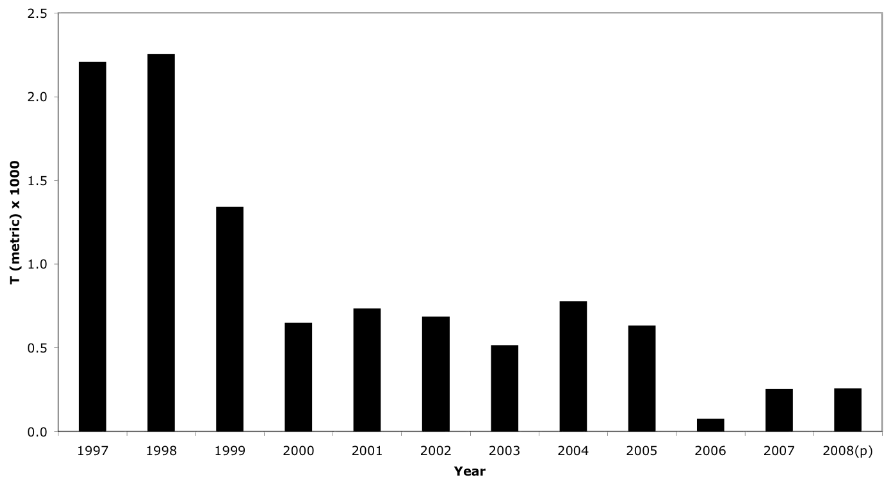

Figure 10. Inshore (<12 nm) cod landings for all Scottish ports, 1997-2008 (provisional data for 2008) from Marine Science Scotland (2009).

2.2.3 The Clyde cod fishery

With the above knowledge on sub-populations in mind, it is interesting to look at one such stock, the Clyde. Until 1985 the annual Clyde catch averaged ca 1500 t (Figure 11); thereafter, however, the catch has declined to virtually zero (Figure 12). The collapse of the Clyde cod fishery led to the closure of the southern Clyde in 2001 and limitations on the *Nephrops* fishery, which includes cod as a bycatch.

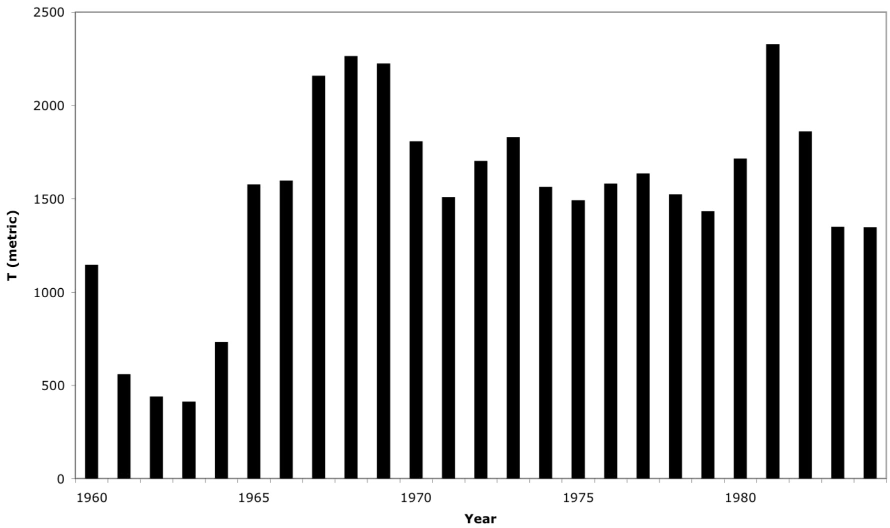

Figure 11. Landings of cod for all Clyde ports, 1960-1984. Department of Agriculture and Fisheries Scotland data, in Hislop (1986).

In response to the complete collapse of the Clyde and West Coast stocks, the EU maintained this area closure scheme, most recently in 2004, and introduced a limit on fishery effort. Additional technical measures such as increased mesh sizes were introduced; all these measures had the effect of changing target species from cod to *Nephrops*. Bycatch of juvenile gadoids in the trawl-based *Nephrops* fisheries remains a concern; measures such as mandatory 120 mm square mesh release panels are now required to reduce bycatch. ICES has recommended a zero catch for the entire West Coast cod fishery since 2004, and the recommendation for 2010 is the same.

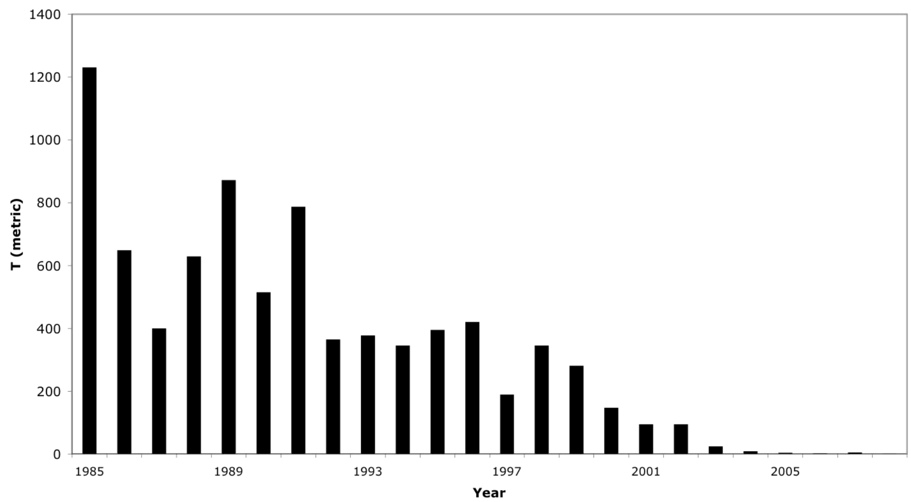

Figure 12. Landings of cod for all Clyde ports, 1985-2008. Data from Marine Science Scotland (2009).

2.2.4 Potential for recovery

The European Commission enacted the Cod Recovery Plan as a Council Regulation ((EC) No. 423/2004), which sought to increase cod stocks by increasing the SSB, decreasing fishing mortality, and limiting changes in the Total Allowable Catch (TAC) by ±15% (ICES, 2008). For the North Sea stocks, ICES concluded that on the basis of SSB and fishing mortality the stock is "suffering reduced reproductive capacity"; the recommendation in 2008 was that the EU Cod Recovery Plan was not adaptive in nature and that the cod fishery should be closed until the recovery of the SSB could be ensured.

For West Coast and Clyde cod stocks, ICES advice for 2008 was that on the basis of SSB, the stock is "suffering reduced reproductive capacity", and that "total mortality is probably high but cannot be accurately partitioned into fishing mortality and natural mortality" (ICES, 2008). An assessment of the performance of the Cod Recovery Plan on the West Coast stocks (Clark & Holmes, 2008) concluded that:

> We found that if the West of Scotland stock and fishing mortality are accurately assessed, with negligible additional unallocated mortality, the cod recovery plan will perform as expected, with the stock recovering in a few years. However, additional unallocated mortality is one of the biggest obstacles to the success of the recovery plan, or any similar.
>
> The recent performance of the West of Scotland cod stock suggests that the stock will take much longer to recover than predicted by the idealised simulations described here. The most likely causes of the difference are additional mortality not accounted for in the current stock assessment, poor estimation of annual recruitment, or environmental variability.

Thus, uncertainty in the model due to poor reporting and other factors do not lead to encouragement in the short term for cod recovery, at least on the West Coast. A full implementation of ICES recommendations may yet show cod recovery in Scottish inshore waters.

2.3 Case study 3: Skates and rays

2.3.1 Scottish skates and rays – the wider picture

The common skate *Dipturus batis* (synonym *Raja batis*) is a long-lived elasmobranch that matures slowly, grows quickly, and was once common throughout the North and

Irish Seas (Walker & Heessen, 1996, Walker & Hislop, 1998). While traditionally targeted by longline, it is now largely a bycatch of the demersal fisheries (Holden, 1973). From a peak catch of nearly 6,000 t in 1960, Scottish landings averaged ca 3,900 t per annum, although the catch was gradually declining (Figure 13). Unfortunately, catches of all skates and rays were aggregated in landings data until 2009, so that individual species' information is obscured. Additionally, quotas have not been set for elasmobranchs, with TACs only coming into force for these species in 1999.

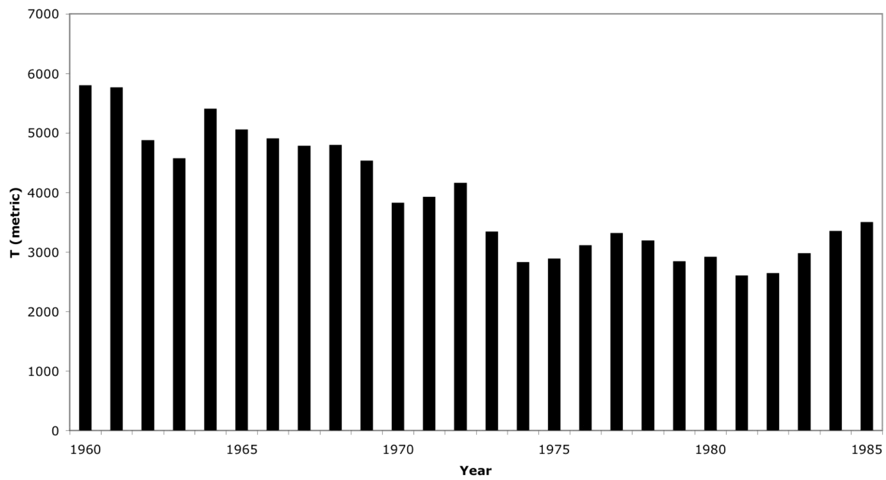

Figure 13. Total Scottish landings of skates and rays for all ports, 1960-1985. Department of Agriculture and Fisheries Scotland data, in Hislop (1986).

Common skate have several life history features which make them particularly susceptible to fisheries exploitation: a) their large size at hatching (22 cm) (Brander, 1981) and quick growth, coupled with the presence of wings and spines ensures they are caught in most demersal gear; b) slow rate of maturity and c) low fecundity (Walker & Hislop, 1998). Female skate in the Celtic Sea, for example, while reaching a maximum length of 237 cm, are only sexually mature at 180 cm (Wheeler, 1978), by which time they are 11 years old (Du Buit, 1976). Coupled with this slow maturation is low fecundity, with only 40 egg cases per year being laid (Du Buit, 1976).

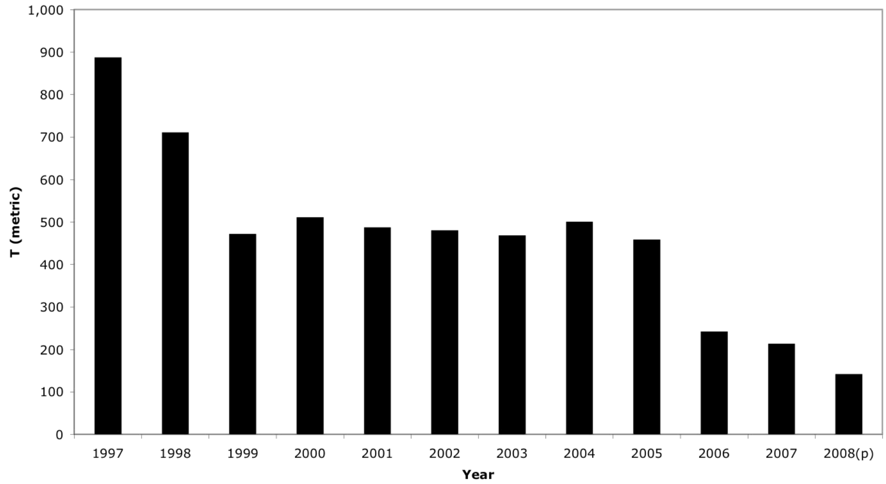

Figure 14. Total landings of inshore skates and rays into Scottish ports, 1997-2008 (2008 data provisional). Data from Marine Science Scotland, 2009.

2.3.2 Inshore skates and rays

While the average annual catch from 1997 for all skates and rays in inshore Scottish waters was 465 t, the landings have decreased steadily such that less than 150 t in total are now being caught (Figure 14). The status of skates and rays in the Clyde is even more serious. Landings in the Clyde totaled 206 t in 1968, and averaged 108 t per annum until 1984 (Figure 15); only 0.71 t were landed in 2008 (Figure 16).

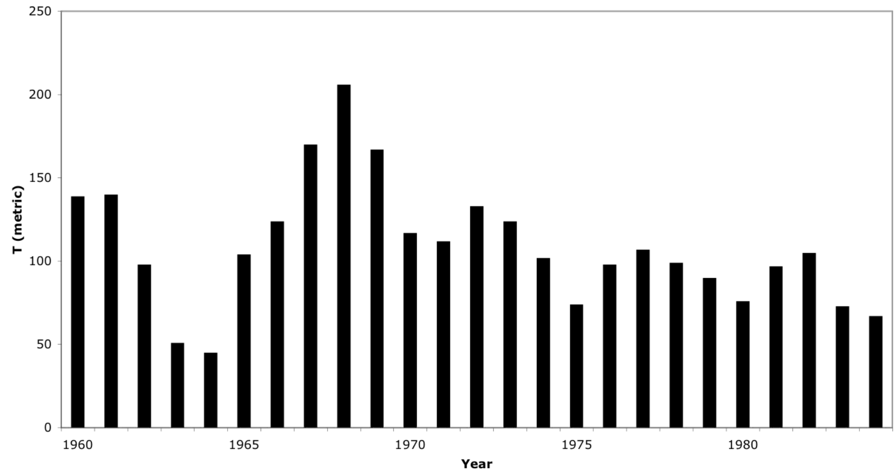

Figure 15. Landings of skates and rays into all Clyde ports, 1960-1984. Department of Agriculture and Fisheries Scotland data.

2.3.3 Clyde skates and rays

The Clyde stocks of common skate may not quite be at the state of extirpation reported for the Irish Sea (Brander, 1981), however without accurate stock assessments, the status of this species in inshore Scottish waters is uncertain.

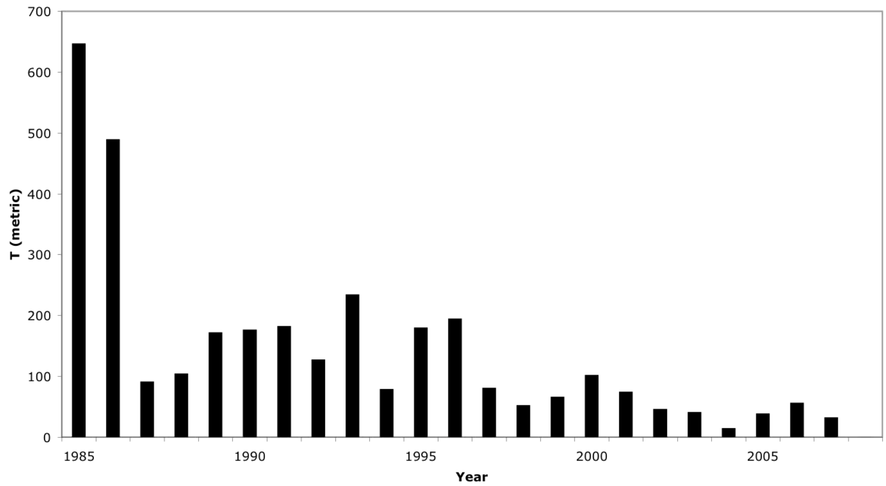

Figure 16. Total landings of skates and rays in Clyde ports 1985-2008. Data from Marine Science Scotland, 2009.

2.3.4 Potential for recovery

The latest ICES advice regarding the common skate in the North Sea and the West of Scotland is that the stock is "depleted" and that "target fisheries for these species should not be permitted and measures should be taken to minimise bycatch." (ICES, 2008). As the major skate and ray species have only recently been identified to species in landings data, it will take at least five years before it is known whether the setting of TACs and decreased effort has worked (ICES, 2008). Additionally, a decrease in the market for these species may also encourage recovery (ICES, 2008).

2.4 Case study 4: Maerl beds

2.4.1 Ecosystem description and characteristics

"Maerl" is a collective term used for calcified red seaweeds (Rhodophyta) growing as unattached nodules or branching twig-like structures on the seabed (Birkett et al., 1998; Barbera et al., 2003; Hall-Spencer et al., 2008). In favourable conditions maerl can occur in extensive beds, with the skeletons of dead plants accumulating to form deep, calcareous deposits overlain by a surface layer of living plants. Maerl beds are typically found in areas such as tidal rapids, straits and entrance channels to sea lochs, which combine vigorous tidal currents with shelter from the destructive effects of wave action. The living plants require light for growth and maerl is therefore confined to relatively shallow (< 20 m) water depths. The hard, calcareous nodules of maerl provide an attachment surface for non-calcified seaweeds and sessile animals, while the lattice formed by the loosely-packed branches provides a habitat for a wide range of small invertebrates. The high biodiversity associated with maerl beds has led to them being classed as a Priority Habitat in the UK Biodiversity Action Plan[2] and the Scottish Biodiversity List.

2.4.2 Occurrence in Scottish waters

In Scotland the two principal maerl-forming species are *Phymatolithon calcareum* and (less-commonly) *Lithothamnion glaciale.* Maerl beds are relatively common along the west coast (including the Clyde Sea area), in the Western Isles, Orkney and Shetland, but they are entirely absent from the east coast of Scotland. Scott and Moore (1996) reported over 100 sites with maerl in Scotland, more than in any other European country.

2.4.3 Evidence for depletion or damage as a result of human activity

Two human activities - salmon farming and scallop dredging - have been shown to cause damage to maerl beds in Scottish waters.

2.4.4 Effects of salmon farming

Hall-Spencer et al. (2006) cited data from SEPA showing that in 2003 there were 16 salmon farms in Scotland (out of 346 farms operating at the time) situated above maerl beds. These authors used diving surveys and core samples to study the impacts of salmon farming on the maerl habitat at three localities – North Sandwick, Yell, Shetland; Puldrite Bay, Wide Firth, Orkney and North Bay, Loch Sheilavaig, South Uist. At all three sites, organic waste derived from fish cages was visible on the seabed up to 100 m from cage edges and was associated with significant reductions in live maerl cover. Near-cage sediment samples showed significantly reduced

[2] http://www.ukbap.org.uk/UKPlans.aspx?ID=40

invertebrate biodiversity, particularly of small crustaceans, and a faunal composition dominated by polychaete worm species typical of organically-enriched environments. At the Shetland site, scavenging amphipod species feeding on organic waste were significantly more abundant close to the salmon cages (Hall-Spencer & Bamber, 2007). In laboratory experiments, maerl plants have been shown to be highly sensitive to smothering and burial (Wilson et al., 2004), and the Scottish field study demonstrates that the strong tidal flows characteristic of maerl habitats offer little protection from the detrimental impacts of organic waste deposition.

2.4.5 Effects of scallop dredging

Maerl nodules are rigidly calcified, brittle, and therefore highly susceptible to breakage. The physical impacts of dredging for scallops or other commercially-exploited shellfish are regarded as one of the main threats to maerl beds throughout Europe (Hall-Spencer et al., 2003). Repeated dredging can lead to loss of structural complexity, reductions in biodiversity and long-term degradation of the maerl habitat. Hall-Spencer & Moore (2000a) compared the effects of experimental dredging at a previously-unfished site (Creag Gobhainn, Loch Fyne) and a site used by scallop fishermen for four decades (Stravanan Bay, south-west Bute). Sediment cores were taken to estimate the cover of live maerl prior to experimental dredging at both sites. The plots were then monitored bi-annually over a four-year period. Experimental dredging at Stravanan Bay, where live maerl was very sparse, had no measurable effects on population density. However, at the previously-unfished Loch Fyne site, dredging led to a > 70% reduction in the density of live maerl, with no discernible recovery over the following four years. The ridges and troughs left by the passage of the dredge remained visible on the seabed for up to 2.5 years. Hall-Spencer & Moore concluded that scallop dredging has profound and long-lasting impacts on maerl habitats. Supporting evidence was provided by samples from the Tan Buoy, south-west of Great Cumbrae island in the Clyde. Historical samples collected in the 1885-1891 period (before the onset of scallop fishing in the area) contained abundant maerl plants, alive when collected, up to 58 mm in length. Repeated surveys in 1995-1997 yielded only 16 living *Phymatolithon calcareum* plants, all much smaller (< 20 mm) than the specimens collected a century before. The degradation of the Tan Buoy maerl ground was attributed to the cumulative effects of intensive scallop dredging carried out in the area from the 1960s onwards.

2.4.6 Potential for recovery

The dredging impact study of Hall-Spencer & Moore (2000a) indicates that maerl beds are highly sensitive to physical disturbance and have a very low regenerative capacity. The low recovery rate is a consequence of the very slow growth (approximately 1 mm per year) of individual maerl plants (Blake & Maggs, 2003; Bosence & Wilson, 2003) and their high sensitivity to smothering by fine sediment (Wilson et al., 2004). Where salmon farming is carried out in close proximity to maerl beds it may be advisable to forego the relocation of cages carried out as part of the "fallowing" procedure as this may simply increase the total area of impacted seabed with no compensating recovery in the original cage "footprint" (Hall-Spencer et al., 2006; Hall-Spencer & Bamber, 2007).

2.4.7 Ecological importance

Maerl beds support a wide range of seaweed and invertebrate species, some of which may be unique to this habitat (Keegan, 1974; Hall-Spencer et al., 2003; Steller et al., 2003). In Scottish coastal waters, maerl beds are therefore important reservoirs of marine biodiversity. Protection of healthy maerl grounds can also have beneficial consequences for coastal fisheries. The structural complexity and associated fauna of maerl beds make them important feeding areas for juvenile fish, including commercially-important species such as cod (*Gadus morhua*) (Hall-Spencer et al., 2003). Maerl beds are also believed to be important nursery grounds for juvenile queen scallops (*Aequipecten opercularis*). In laboratory and field experiments, juvenile scallops showed higher rates of survival among maerl plants than on bare gravel, an effect attributed to the refuge from predation offered by the interlocking maerl branches (Kamenos et al., 2004).

2.5 Case study 5: File shell (*Limaria hians*) beds

2.5.1 Ecosystem description and characteristics

The gaping file shell (*Limaria hians*) is a small (shell length up to 4 cm) bivalve mollusc distinguished by long, filamentous orange tentacles extending from the mantle edge, which is continuously exposed due to the inability of this species to retract its fleshy structures within the shell valves (Tebble, 1966). *Limaria hians* lives buried just below the sediment surface and forms a "nest" of seaweed, shell fragments or other debris bound together in a mass of secreted byssal threads. At high densities, the nests of *Limaria* may coalesce to form semi-continuous reef-like structures covering several hectares of seabed and extending up to 20 cm above the botttom (Hall-Spencer and Moore, 2000b). Dense *Limaria* beds may support over 700 individuals m^{-2} (Hall-Spencer & Moore, 2000b). *Limaria hians* beds are listed as a Priority Habitat in the UK Biodiversity Action Plan and the Scottish Biodiversity List.

2.5.2 Occurrence in Scottish waters

Limaria hians has been recorded along the west coast of mainland Scotland, from Kintyre and the Clyde Sea to north-west Sutherland. There appear to be no records from the Western Isles or the Scottish east coast. Typical habitat consists of mixed muddy gravel or sands in weak to moderately strong tidal streams. Knowledge of current distribution and status is very limited but extensive beds have been described from recent diving surveys off Creag Gobhainn, Loch Fyne (Hall-Spencer and Moore, 2000b) and Port Appin, Argyll (Trigg and Moore, 2009).

2.5.3 Evidence for depletion or damage as a result of human activity

Hall-Spencer & Moore (2000b) summarised the limited information available on *L. hians* in Scottish waters and concluded that the species has disappeared from several areas where it was formerly common, including Skelmorlie Bank, Ayrshire, and Stravanan Bay, Isle of Bute. *Limaria hians* nests were present among maerl samples collected in 1885 from Tan Buoy, Great Cumbrae, but only dead shells were found when the site was re-surveyed in 1995-1997 (Hall-Spencer & Moore, 2000a). The decline of *L. hians* in the Clyde Sea was attributed to the destructive effects of scallop dredging by Hall-Spencer & Moore (2000b), as already discussed in relation to the associated maerl habitat. Direct observations of fishing impacts were recorded by

Hall-Spencer & Moore (2000b) at Creag Gobhainn, where a commercial scallop boat towed through the *Limaria* bed in October 1999. The *Limaria* nests were ripped apart and torn from the seabed along the dredge track. *Limaria hians* has a thin, delicate shell, and damaged individuals dislodged from their nests were rapidly consumed by fish, crabs and other scavengers (Hall-Spencer & Moore, 2000b).

The growth of the aquaculture industry along the Scottish west coast may also have contributed to the decline of *L. hians*. In Ireland, Minchin et al. (1987) showed that the use of tributyl tin (TBT) as an antifouling agent on salmon nets led to a dramatic reduction in spat settlement of *L. hians*, with beds close to a salmon farm being reduced to less than 2% of their former extent.

2.5.4 Potential for recovery

Trigg & Moore (2009) investigated the rate of regrowth of a *Limaria* bed off Port Appin, Argyll, following experimental disturbance. *Limaria* “nests” were cleared by a diver from 10 seabed plots (0.25 m^2) and the surface raked to simulate the passge of a scallop dredge. Nest regrowth was monitored after 6 and 12 months. Regrowth occurred mainly by extension of the periphery of neighbouring, undamaged areas. After 12 months, half the treated plots showed less than 25% cover of *L. hians* nests, and none had reached a thickness comparable to the undisturbed beds. At the measured linear regrowth rate of 3.2 cm $year^{-1}$ it was estimated that complete recovery of a 7.5 m-wide strip cleared by the passage of a typical assemblage of Newhaven scallop dredges would take 117 years. Regeneration of *L. hians* beds following physical disturbance is therefore likely to be extremely slow, especially if areas are dredged repeatedly.

Minchin (1995) reported that an Irish bed of *L. hians* had fully recovered nine years after use of TBT-based antifoulants had ceased. This finding suggests that the species is more resilient to the effects of chemical contaminants than to the physical impacts of scallop dredging.

2.5.5 Ecological importance

Limaria nests support a rich fauna of small invertebrates and provide attachment surfaces for algae and larger sessile animals. Hall-Spencer & Moore (2000b) recorded 19 algal and 265 invertebrate species from just six nests collected in Loch Fyne. *Limaria* beds are therefore likely to make an important contribution to total benthic biodiversity in the areas where they are found.

2.6 Case study 6: Fan shell (*Atrina pectinata*)

Note: This species is normally referred to as *Atrina fragilis* (formerly *Pinna fragilis*), but *A. pectinata* (Linnaeus, 1767) is now the valid scientific name.

2.6.1 Species description and characteristics

Atrina pectinata is the largest bivalve in the British marine fauna (Tebble, 1966), with a shell up to 40 cm in length. The species is found in mud, sand and gravel habitats and is typically found buried in the seabed with the upper 25-50% of the shell protruding above the sediment surface. It is the subject of a UK Biodiversity Action Plan[3] and is also named on the Scottish Biodiversity List.

2.6.2 Occurrence in Scottish waters

Woodward (1985) summarised the historical records of *A. pectinata* in Scotland, showing a scatter of occurrences along the west coast from Kintyre and the Clyde north to Wester Ross, and a larger number of records from north-east Scotland, Orkney and Shetland. Information on current distribution is very limited, but *A. pectinata* is now considered to be scarce throughout UK waters (Solandt, 2003). A 2004 summary by the Marine Conservation Society lists anecdotal reports of fan shells collected by fishing boats off Skye and Canna, and a sighting by divers in the Sound of Mull (Marine Conservation Society, 2004). Isolated living specimens are known in Loch Carron (Solandt, 2003) and Loch Alsh (Marine Conservation Society, 2006). However, a targeted diving survey of the Oberon Bank and Sound of Arisaig SAC, funded by Scottish Natural Heritage in 2003, found no *Atrina pectinata* (Seasearch, 2003). These few recent records suggest that *A. pectinata* still exists locally, probably at very low density, in the waters of the west coast and around the

[3] http://www.ukbap.org.uk/UKPlans.aspx?ID=123

Inner Hebrides. Solandt (2003) states that "considerable numbers" of *Atrina* are still being found in the Western Isles, but provides no reference to the source of this information. There appears to be no information on the current status of the species in north-east Scotland or the Northern Isles.

2.6.3 Evidence for depletion or damage as a result of human activity

The decline in abundance of *Atrina pectinata* throughout the UK is attributed to the destructive impact of bottom trawling and dredging. The relatively thin, fragile shell of *Atrina pectinata,* which in life projects above the seabed, is extremely vulnerable to damage by towed fishing gear. Solandt (2003) cites anecdotal reports of *Atrina* shells being regularly collected by trawlers in the Irish Sea in the 1970s, with decks sometimes being "covered with the broken fragments of this species". Although detailed information for Scotland is lacking, there is no reason to doubt that the same factor is responsible for the extreme scarcity of *Atrina* across most or all of its former range. The closely-related New Zealand fan shell (*Atrina zelandica*) shows reduced feeding efficiency and a significant decline in physiological condition when exposed to elevated suspended sediment concentrations (Ellis et al., 2002; Safi et al., 2007). It is therefore possible that in heavily-fished areas surviving *A. pectinata* individuals might suffer adverse effects of increased water turbidity even if they escape direct physical damage.

2.6.4 Potential for recovery

If substantial surviving populations of *A. pectinata* can be located in Scottish waters, restrictions on the use of towed bottom-fishing gear will be essential to protect these localities as sources of recruits for depleted areas. Mature fan shells collected as bycatch in trawls can survive transplantion back into a suitable benthic habitat (Solandt, 2003), so the potential exists for deliberate creation of artificial populations in protected areas to enhance reproductive output, which may be currently limited by the low density of surviving individuals.

2.6.5 Ecological importance

The ecology of the fan shell has not been studied in UK waters, but work carried out in New Zealand provides an insight into the role that *A. pectinata* may have played in benthic ecosystems before its population decline. The New Zealand fan shell *A. zelandica* has been shown to exert an important influence on benthic community structure and ecosystem function in coastal soft sediment habitats. Patches of these large bivalves add to the physical structure and complexity of otherwise homogenous sediment habitats, reflected in the contrasting communities of small sediment-dwelling invertebrates found inside and outside the *A. zelandica* patches (Warwick et al., 1997; Cummings et al., 1998). Like most suspension-feeding bivalves, *A. zelandica* produces copious quantities of pseudofaeces, and local enrichment of the sediment by these biodeposits causes fan shell patches to function as “hotspots” of nutrient flux from the sediment to the overlying water (Hewitt et al., 2006). The importance of this nutrient transfer was demonstrated in Mahurangi Harbour, New Zealand, which supports extensive beds of *A. zelandica* and is also a major site of oyster culture. Nutrient fluxes from fan shell beds were much higher than from bare sediment and were shown to account for up to 80% of the nutrient supply required for phytoplankton production in the water column (Gibbs et al., 2005). *Atrina zelandica* beds were thus of major importance to the sustainability of aquaculture in the harbour. These studies demonstrate the capacity of large bivalves to act as “keystone” species or “ecosystem engineers”. Dense populations modify the physical structure and biogeochemical cycling of the habitat, with major effects on local biodiversity and ecosystem functioning (Norkko et al., 2001). It is unlikely that any remaining *A. pectinata* populations in Scottish waters exist at densities able to exert signficant ecosystem effects, but the New Zealand studies suggest the beneficial consequences that could follow from their restoration.

2.7 Case study 7: Native oyster (*Ostrea edulis*) beds

2.7.1 Ecosystem description and characteristics

The native or flat oyster (*Ostrea edulis*) is a sessile suspension-feeding bivalve characteristic of productive estuarine and shallow coastal habitats sheltered from wave action, with sediments ranging from mud to gravel. In favourable conditions oysters can form dense beds, with dead shells making up a considerable fraction of the substratum and providing an attachment surface for new recruits. The species is widely distributed around European coasts and was formerly abundant in British coastal waters. However, extensive oyster beds are now found only in a small number of localities in the UK, mainly in southern England and western Ireland.[4] Owing to their rarity, native oyster beds are included in the UK Biodiversity Action Plan[5] and the Scottish Biodiversity List.

2.7.2 Occurrence in Scottish waters

The history and status of the native oyster in Scotland have been comprehensively reviewed by UMBS Millport (2007). Historical records and archaeological evidence (Pollard, 1994) show that oysters were once widespread and abundant around the Scottish coasts, including Orkney and Shetland, and were an important food resource for human populations from Mesolithic times onwards. Native oysters now occur mainly in small, scattered populations fringing the west coast sea lochs, usually at low population density. The summary by UMBS Millport (2007, Table 3.5) of existing data on the status of *O. edulis* in Scotland shows that the species appears to be completely extinct in some former localities, with populations in many other areas reduced to remnants. Only Loch Ryan in Galloway still supports oyster beds large enough to sustain commercial harvesting.

2.7.3 Evidence for depletion or damage as a result of human activity

The review of the history of Scottish oyster fisheries by UMBS Millport (2007) leaves no doubt that the decline and disappearance of oyster populations can be attributed to human overexploitation. Oysters were an important food source for Mesolithic hunter-gatherers and their shells are often abundantly represented in coastal middens (e.g. Myers & Gourlay, 1991). Oysters continued to be exploited through mediaeval times, with commercial fisheries supplying a European market in operation by the 18th century. Around the full extent of the Scottish coastline, the history of oyster fisheries since the 1700s is one of rapid growth, overexploitation and collapse. The Shetland fishery was exhausted by the late 19th century, while the once-prolific Orkney oyster beds were commercially extinct by 1918. Landings from the Moray and Cromarty

[4] http://www.marlin.ac.uk/habitatsbasicinfo.php?habitatid=69&code=1997
[5] http://www/ukbap.org.uk/UKPlans.aspx?ID=495

Firths peaked in 1884, followed by rapid decline and exhaustion. The Firth of Forth once supported the largest and most valuable oyster beds in Scotland, covering an area of over 166 km^2 along the southern shoreline of the firth. Commercial fisheries grew rapidly during the 1700s, punctuated by numerous unsuccessful attempts at regulation in an effort to protect the stocks. In 1834-36, the Newhaven beds alone yielded ~ 60 million oysters per year, with up to 60 boats pursuing the fishery. By the 1870s, beds were being abandoned due to exhaustion and commercial fishing had ceased by 1920. Native oysters may now be biologically extinct in the Firth of Forth (UMBS Millport, 2007).

2.7.4 Potential for recovery

UMBS Millport (2007) reviewed the effectiveness of management measures for remaining Scottish oyster populations and the feasibility of artificial restoration. Low population densities limiting regenerative capacity and the continuation of unlawful collecting were identified as the two key issues to be addressed. Measures such as provision of shell substratum ("cultch") to promote larval settlement and artificial transplantation of adult oysters into protected areas have the potential to enhance stocks, although recovery to anything approaching former levels of abundance would take many years to achieve. Recent attempts to restore oyster (*Crassostrea virginica*) reefs in Chesapeake Bay, Virginia, USA, appear to be showing some success (Stokstad, 2009). However, the experience from management of remaining Scottish and Northern Irish oyster populations suggests that restoration will be impossible without effective legislation and enforcement against unlawful gathering (Smith et al., 2006; Smyth et al., 2009).

2.7.5 Ecological importance

The former economic importance of the native oyster in Scotland is apparent from the fishery records, but extensive beds of suspension-feeding bivalves can also have important effects on water quality and ecosystem health. The destruction of oyster reefs in Chesapeake Bay and other estuaries along the eastern seaboard of the USA during the 19th and early 20th centuries has been held responsible for subsequent eutrophication, hypoxia, increased turbidity, harmful algal blooms and other environmental problems associated with the uncontrolled growth of phytoplankton

(Kemp et al., 2005). Although the capacity of bivalve populations to limit phytoplankton concentrations has been questioned (Pomeroy et al., 2006), a recent review (Coen et al., 2007) argues strongly that dense oyster beds provide beneficial services to coastal ecosystems including filtration of suspended matter, enhanced nutrient cycling, creation of feeding habitat and refugia from predation for mobile animals, and provision of substratum for other sessile species. Restoration of native oyster beds should therefore be seen as a desirable goal in the wider context of improving the health of coastal marine ecosystems in Scotland.

2.8 Case study 8: Demersal fish communities of the northern North Sea

The North Sea is one of the world's most important fishing grounds and has been heavily exploited for well over a century (Jennings et al., 2000). Over much of this period the biology, life history and population dynamics of the major commercial fish species have been subjects of continuous research in an effort to understand the factors controlling stock sizes and contribute to more effective management of the fisheries. However only in the past 10-15 years has much attention been paid to the effects of intensive fishing on the North Sea ecosystem as a whole. This broader perspective on the North Sea forms part of a global research effort which over the past two decades has demonstrated beyond any reasonable doubt that fishing, particularly bottom-trawling, dredging and other activities impacting the sea floor, has profound effects on marine ecosystems beyond reductions in the stock size of the exploited fish species (Jennings & Kaiser, 1998; Hall, 1999; Kaiser & de Groot, 2000; Kaiser et al., 2006).

Information on changes in the demersal fish communities of the northern North Sea has come from comparing results of the August Groundfish Survey (AGFS), carried out annually by Scottish fishery research vessels since 1980, with archived data from earlier surveys extending back to 1925. Data were obtained from four areas of the northern North Sea, including an inshore zone extending roughly from Whitby, Yorkshire north to Orkney and covering the entire eastern Scottish mainland coast (Greenstreet & Hall, 1996; Greenstreet et al., 1999a). Species diversity changes in the groundfish community over the full study period were subtle, and mostly resulted from small differences in the relative abundance of rare species such as the grey gurnard (*Eutrigla gurnhardus*) and spurdog (*Squalus acanthias*). However, comparing data from 1925-1996, only the least-fished of the four study areas showed no detectable decline in species diversity of the total groundfish assemblage. Along the Scottish east coast, the most heavily-fished area (Greenstreet et al., 1999b), a decline in diversity was apparent among the non-target subset of groundfish species (Greenstreet et al., 1999a). From the same dataset, Jennings et al. (2002) showed that the mean and maximum individual body mass of the demersal fish community fell declined significantly between 1925 and 1996. Human impacts on North Sea demersal fish were shown most comprehensively by Greenstreet & Rogers (2006), who analyzed trends in 12 indicators of community health over the 1925-1997 period in sea areas categorised as experiencing low, medium and high fishing pressure. The authors took a hypothesis-based approach, predicting for example, that areas most affected by fishing would show the lowest mean fish body weight, lowest proportion of large fish, lowest species richness and diversity, and lowest size and age at maturity. The results were overwhelmingly in line with the authors' predictions. In heavily-fished areas the expected temporal patterns were seen in 11 out of 12 community indicators, compared with 9 out of 12 in areas of medium fishing intensity and only 1 out of 12 in lightly-fished areas.

The studies discussed above are based on data extending back only to 1925, long after the start of industrial fishing in the North Sea. The North Sea was heavily-fished by 1900, with landings at that time having already reached approximately one million tonnes per year, probably corresponding to about 10% of the fish standing stock biomass (Daan et al., 1990). The 1925 baseline therefore describes a fish community already subjected to significant fishing pressure and cannot be taken to represent a natural or unexploited state. Jennings & Blanchard (2004) applied a theoretical model of fish community size structure (the relationship between fish body mass and abundance) to contemporary data from the North Sea to estimate the structure of the community in its unexploited, pre-fishery state. Results suggest that total biomass of the contemporary North Sea fish community is 38% lower than it would be in the absence of exploitation. Fish at the upper end of the size spectrum have been particularly depleted. Current biomass of large fishes in the 4-16 kg and 16-66 kg size classes is estimated to be have been reduced by 97% and 99% respectively, compared with the pre-fishery state. This finding is in line with the common marine fisheries pattern where large, old individuals are rapidly lost from the population, which then comes to be dominated by younger and smaller size classes (Jennings & Kaiser, 1998). Recent research thus provides strong evidence that the demersal fish communities of the northern North Sea are in an ecologically-depleted state, and that the degree of impact is proportional to the regional intensity of fishing pressure.

It should be emphasised that the above case studies focussing on the decline of species as a result of commercial fishing are the best evidenced examples of decline in inshore Scottish marine species. The authors do not wish to imply that they are the only examples of decline; due to the scarcity of historic data on other species, the commercially exploited species (most noticeably those caught by mobile gear) will always be the outstanding examples of decline.

3 Case studies of ecosystem recovery in Scottish waters

The following section presents brief accounts of species and/or ecosystems in Scottish waters (within the 12-mile limit) and outwith MPAs which meet the following conditions:

- Well-evidenced examples of marine habitats, species and ecosystems in specific geographical locations in Scottish waters where increases in biodiversity or species abundance or improvements in habitat or ecosystem health have been recorded as a result of reduction or removal of human-induced pressures.

3.1 The Clyde Estuary

The Clyde Estuary was once known as a salmon habitat; prior to the Industrial Revolution, the river and its tidal reaches were relatively clean (Doughty & Gardiner, 2002). By the 1860s, however, manufacturing and human sewage had brought about an enormous change. The Ordnance Gazetteer of Scotland of 1884 describes what had happened to the once clean estuary (Groome, 1884):

> The river improvements are credited with having destroyed one industry - the salmon fishing that flourished once above Dumbarton. Even to-day the Clyde Trustees pay upwards of £200 a year to the burgh of Renfrew for damage done to its fisheries. It seems questionable, however, whether the fish could have survived another hurtful agency - that pollution, namely, which has formed the subject of Reports by Dr Frankland and Mr Morton in 1872, Mr M'Leod in 1875, and Sir John Hawkshaw in 1876. According to Mr M'Leod, nearly 100 miles of natural and artificial sewers, within the bounds of Glasgow city alone, conveyed to the Clyde, by 42 outlets (33 of them below the weir), the sewage of 101,368 dwelling-houses and 16,218 sale shops, warehouses, factories, and workshops, whilst 31 factories discharged their waste outflow by private drains directly into the river. Experiments made with floats in 1857-58 by Messrs Bateman and Bazalgette showed that sewage entering the river at the centre of the city, when the volume of water was small, travelled only 2½ miles a week; and this slow progress can hardly have been quickened by the levelling of the river's bed below Glasgow, or by the large abstraction of water caused by the River Supply Works at Westhorn, 2½ miles above the city, which, with two reservoirs, each holding 400,000 gallons, were completed in 1877 at a cost of £30,000. So that, "in summer weather, the time during which the river is made to loiter on its way to the sea is more than sufficient to establish in full operation those processes of putrefactive fermentation - inevitable whenever the thermometer exceeds 55° Fahr. - to which the formation of sewer gas and other filthy products of this fermentation is due." Glasgow is the chief, but by no means the only

> offender; the paraffin oil, iron, coal, paper, cotton, and dye works, of New Lanark, Blantyre, Airdrie, Coatbridge, and other seats of industry all helping to swell the liquid mass of pestilence.

Water quality in the estuary became so bad that hydrogen sulphide in the water was corroding the iron and copper-bound hulls of moored ships, and steam vessels could no longer take Clyde water into their boilers (Mackay et al., 1978).

Indeed, by the 1870s, fish in the Clyde were virtually extinct (Rivers Pollution Commission, 1872). The introduction of sewage treatment works in the 1890s improved the situation somewhat (Mackay et al., 1978); following effective pollution reduction legislation and the formation of the River Purification Boards in the 1960s (Mackay et al., 1978; Doughty & Gardiner, 2002) salmon returned to the Clyde Estuary in the 1980s (Curran & Henderson, 1988).

Estuaries are recognised for their importance as nursery areas for fish, and the state of the fish habitat in the estuary may be regarded as an indicator of the general health of the ecosystem (Henderson & Hamilton, 1986; Power et al., 2002; Whitfield & Elliott, 2002). One of the main requirements of fish in an estuary is oxygen supply; high organic loads reduce the available oxygen and prevent fish recolonising previously polluted areas. Mackay et al. (1978) detailed the decrease in biochemical oxygen demand in the Clyde Estuary as a result of improved and new sewage treatment works from 1968, with a corresponding increase in dissolved oxygen. This increase in water quality, especially the dissolved oxygen levels, was attributed by Henderson & Hamilton (1986) as the primary reason for the return of fish species to the Clyde Estuary. Table 1 reproduced from Henderson & Hamilton (1986) shows the numbers of species returning.

The fish fauna in the Clyde is now monitored 4 times annually by trawling, and data provided by SEPA show that since 2000, there are on average 18 fish species in the lower estuary on an annual basis (the upper estuary is not sampled due to obstructions on the bottom) (Table 2).

Table 1. Fish species recorded in the Clyde Estuary between Glasgow and Woodhall 1978-1985. Table 1 in Henderson & Hamilton (1986).

	1978/79	1980/81	1982/83	1984/85
Salmo salar	+	+	+	+
Salmo trutta (sea trout)	+			
Chelon labrusus	+			
Sygnathus typhle	+			
Taurulus bubalis	+	+		
Gasterosteus aculeatus	+		+	+
Limanda limanda	+	+	+	+
Platichthys flesus	+	+	+	+
Pleuronectes platessa	+	+	+	+
Gadus morhua	+	+		
Pollachius virens	+	+	+	+
Agonus cataphractus	+	+	+	+
Anguilla anguilla	+		+	+
Zoarces viviparus	+		+	+
Pomatoschistus minutus	+		+	+
Sprattus sprattus	+		+	
Clupea harengus	+		+	
Trisopterus esmarkii	+		+	
Ammodytes tobianus		+	+	+
Eutrigla gurnardus		+		
Pholis gunellus		+	+	+
Merlangius merlangus		+	+	
Pollachius pollachius		+	+	
Hippoglossoides platessoides		+		
Scophthalmus rhombus		+		
Zeugopterus punctatus				
Myoxocephalus scorpius			+	+
Spinachia spinachia			+	
Perca fluviatilis			+	+
**Esox luscius*			+	
**Salmo trutta* (brown trout)			+	
**Cyprinus carpio*			+	
Trisopterus luscus				+
Liparis liparis				+
Cumulative species total	18	25	32	34

*Single occurrence of these freshwater species

When the Royal Commission delivered its Third Report on Environmental Pollution, it considered two main criteria sufficient for recovery of an estuary to be established (Royal Commission, 1972):

> There are two simple biological criteria for the management of estuarial waters: (a) ability to support on the mud bottom the fauna essential for sustaining sea fisheries, and (b) ability to allow the passage of migratory fish at all states of the tide.

While the above definition may fall short in its quantitative classifications, clearly, under most notions of recovery, the Clyde Estuary has undergone enormous improvement since the middle of the 19th century, to the stage where it is classed again as a salmonid river under the Designated Sites Under the Surface Waters (Fishlife) (Classification) (Scotland) Direction 1999. Indeed the recovery of the Clyde is mirrored by those of other major Scottish estuaries, such as the Forth and Tay, which have seen similar reductions in pollution in the 20th century and concomitant improvements in habitat quality.

Table 2. Fish species/number of individuals collected by trawl in the Clyde Estuary from Dumbarton Rock to Bowling, 1986-2007. Data from SEPA, unpublished.

	Year/Number of individuals																					
Species	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Platichthys flesus	243	382	418	334	292	226	184	259	268	891	255	67	118	79	886	542	464	1331	1051	1498	284	613
Pholis gunnellus	8	12	1	2				1	1	1					29	40	39	61	32	63	26	1
Limanda limanda	3	1		7	8	4	6	10	5	6	8	3	2	1	35	200	94	92	211	92	135	12
Myoxocephalus scorpius	1	15	10	39	1	5	4	4	1		1	1	5		5	60	49	29	67	3	7	14
Taurulus bubalis	5	16	1	1	16	4	1	3	1	10	1			1		85	20	102	114	67	37	29
Pleuronectes platessa	17	30	28	11	6	4	12	1	2	16	9	3	1	1	116	83	74	71	296	147	249	48
Agonus cataphractus	7	36	12	7	8	1		1	4	6	2	1	2	5	1	85	29	20	72	11	48	41
Pollachius virens	2					1									1		10	50	38	4		
Zoarces viviparous		1			1					1			1		32		135	132	144	129	11	12
Liparis liparis		1													1							
Ammodytes sp.		2														1	3		1	1		
Gadus morhua		2											3		12	1	1	19	54	6	59	1
Salmo trutta					1										1							
Scyliorhinus canicula							1															
Anguilla anguilla								1							1		1					
Solea solea															1	2		1	3	2	15	1
Syngnathus rostellatus										2						28	3	15	22	7		2
Pollachius pollachius															1	10	2				1	1
Callionymus lyra															3	13	3	4	1			
Clupea harengus															10	2		91	8	22		
Hippoglossoides platessoides															2		13	148				
Pomatoschistus minutus															1	304	284	140	279	275		16
Sprattus sprattus sprattus															1	7	5	29	6	17		
Merlangius merlangus															16	11	1	7	6		2	
Trisopterus minutus															1	21					51	
Spinachia spinachia																1			6			
Eutrigla gurnardus																	1					
Lampetra fluviatilis																		1				
Gobius niger																				2		
Trisopterus luscus																					1	
Total species	8	11	6	7	8	7	6	8	7	8	6	5	7	5	21	19	20	19	19	17	14	13

3.2 Marine cage farming

The impacts of marine cage farming on the sea bed, primarily in the form of organic enrichment from uneaten feed and fish faeces, are well established (c.f. Black, 2001). There is a large body of regulations controlling these environmental effects, both European and national (Henderson & Davies, 2000), one aspect of which is the notion of the Allowable Zone of Effects, or AZE (Read & Fernandes, 2003). The concept of the AZE is such that conditions that might normally breach the Environmental Quality Standards for that particular water body may not apply; in the case of marine cage farming, this is normally the effect of organic enrichment from the fish farm on the benthic community in the immediate vicinity of the farm. The concept of an AZE is an explicit admission that deleterious environmental effects will be taking place, but in a very limited area (which in Scotland is delimited by mathematical modelling of the dispersal of wastes) (Cromey et al., 2002). In terms of the benthic macrofaunal community, the effect will typically be a reduction in the number of species present in the sediment, a shift in species composition to opportunistic/pollution tolerant taxa, and high individual abundances of these fewer opportunistic species (Black, 2001; Borja et al., 2009, Nickell et al., 2009).

It is an accepted practice in Scottish aquaculture for sites to be taken out of production and allowed to recover (Pereira et al., 2004) - this is known as “site rotation”, and should not be confused with the practice known as “fallowing”, which is of a short period, on the order of weeks, intended to break a fish disease cycle. This practice has been in place in Scotland for a number of years, and although it has been the subject of several scientific studies, the period of time that the sea bed needs to recover has not yet been quantified. In their study of three salmon farming sites on the Scottish West Coast, Nickell et al. (1998) showed that all sites exhibited recovery of species numbers after one year but took two years to recover in terms of indicator taxa in the most impacted site. Similarly, Pereira et al. (2004) observed that 15 months after the cessation of production, recovery was evident at the station nearest to the former fish cage site, but the sediment was still highly impacted, and opportunistic species still dominated the fauna.

Looking at the problem of benthic recovery from aquaculture activity outside of the Scottish context, workers in Canada have reported a very wide range of recovery rates from a few weeks to more than six years (Brooks et al., 2003; 2004). Brooks et al. (2004) proposed two definitions of recovery:

chemical:

> the reduction of accumulated organic matter with a concomitant decrease in free sediment sulfide ($S^{=}$) concentrations and an increase in sediment redox potential under and adjacent to salmon farms to levels at which more than half the reference area taxa can recruit and survive.

biological:

> the restructuring of the infaunal community to include those taxa whose individual abundance equaled or exceeded 1% of the total invertebrate abundance at local reference stations. Recruitment of rare species representing <1% of the reference abundance is not considered necessary for complete biological remediation.

Macleod and co-workers have studied recovery processes at salmon farms in Tasmania over several years and have reached some interesting conclusions:

1) macrobenthic recovery was slower than chemical recovery, so chemical methods were not sufficient to define ecological recovery (Macleod et al., 2004).
2) recovery of macrobenthic community function (from analysis of life history attributes of dominant fauna) is more rapid than return to community equivalence at reference stations, and may be a more useful measure of benthic recovery (Macleod et al., 2007).
3) macrobenthic recovery was faster at a more quiescent site than a more exposed site, which was attributed to the greater resilience of the species typically found at such sites and differences in larval supply (Macleod et al., 2006; Macleod et al., 2007).

Since the earlier Scottish studies (Nickell et al., 1998; Pereira et al., 2004), salmon aquaculture has changed significantly: cages are bigger, average farm size has increased, more exposed sites have been developed and the in-feed sea lice medicine

Slice (emamectin benzoate) has become widely used. Although a recent study did not find a relationship between Slice in sediments and community changes at active sites (Black et al., 2005), its potential to retard recovery has not been studied. Copper is also widely used in aquaculture as an antifoulant and has been detected at very high concentrations in fish farm sediments in Loch Craignish (Dean et al., 2007). It has been proposed that copper in enriched sediments is likely to be bound as sulphides and therefore not bioavailable (Brooks & Mahnken, 2003; Brooks et al., 2004), but recovering sediments may release this copper back into pore waters with the potential to affect recolonisation.

More recent approaches to modelling inputs to the sea bed from cage farming have yielded an improved understanding of effects on the macrofaunal community. The DEPOMOD model has a benthic component (Cromey et al., 2002) which at present predicts likely impact from increasing/decreasing amounts of carbon. Morrisey et al. (2000) had some success in predicting remineralisation of carbon and concomitant recovery rates in New Zealand when using the Findlay-Watling oxygen supply model (Findlay & Watling, 1994); they also noted the potential for increased recovery times due to the presence of heavy metals in the sediment.

It can safely be said, therefore, that recovery of these coastal marine muddy habitats in the vicinity of fish cages does occur, and has been recorded. It does remain, however, for the process to be quantified; a project funded by the Scottish Aquaculture Research Forum is presently engaged in this work.[6]

4 Components to be included in a strategy for marine ecosystem recovery, and potential for monitoring

Of the ecologically-depleted species and ecosystems discussed above, the demersal fish communities, which include cod and skates/rays, are already regularly monitored under the groundfish survey programme of FRS, Aberdeen, while herring stocks are monitored as part of the pelagic fisheries programme. The four benthic species/biotopes differ in their potential utility as components for monitoring of ecosystem recovery. There are so few living specimens of the fan shell *Atrina*

[6] http://www.sams.ac.uk/research/departments/ecology/ecology-projects/aquaculture-environment-interactions/researchproject.2007-03-15.2135392058

pectinata currently known in Scotland that they can be observed and monitored individually. These specimens may be useful in generating publicity and raising awareness of their species but in such small numbers they can make no significant contribution to population recovery. Surviving fan shells appear to exist at such low density that even locating them has proved difficult. Monitoring would only become an option in the event of fortuitous discovery of a viable population at a depth accessible to scientific divers or ROV deployment. Maerl beds are already surveyed as part of Site Condition Monitoring programmes in Marine SACs where they are an important feature (for example, the Sound of Arisaig). In localities where beds are known to have been damaged by fish farm discharges or scallop dredging, the value of regular monitoring is limited by the extremely slow growth of the maerl plants. At growth rates of ~ 1 mm per year, measurable regeneration might only be detectable on a timescale of decades. It would probably be more useful to implement the recommendations of Hall-Spencer et al. (2006) regarding placement of salmon farms and to consider restrictions on use of mobile fishing gear on maerl beds, while recognising that recovery from these impacts will be a very protracted process.

Dense *Limaria hians* beds are currently known from only a few sites in Scotland. As noted previously, linear regeneration of these features is also slow, but still an order of magnitude faster than recorded for maerl. Regular monitoring of surviving beds could therefore probably detect any changes in condition, as indicated by the percentage cover and thickness of *L. hians* nests. The known examples at Creag Gobhainn, Loch Fyne and off Port Appin are at depths accessible to divers, making this an option for detailed study of small-scale experimental plots. For wider-scale surveys, an ROV or video camera suspended from a slow-moving boat could be used. A towed video sled would not be appropriate owing to the damage this would cause to the biotope.

Owing to the former abundance of *Ostrea edulis* in Scotland, and its likely importance as a keystone species in shallow-water ecosystems, the species should certainly be included in any strategy for marine ecosystem recovery. Population monitoring of surviving native oyster beds has already been conducted by UMBS Millport in several west coast sea lochs, so that sites, methods and baseline data are already well-established.

5 Implications with regard to emerging Scottish policy and legislation

The overview of evidence for human-induced depletion of Scottish marine ecosystems, together with the specific case studies, have two broad implications for future marine policy in Scotland:

1. Humans have been exploiting the living marine resources of Scotland for at least 10,000 years. This fact, considered alongside the emerging perspectives from historical marine ecology, mean that all coastal ecosystems in Scotland should probably be regarded as having been modified by human activity to some degree. It is unlikely that there remain any "pristine" (i.e. completely natural and free from human influence) ecosystems on the Scottish continental shelf, and even the deep waters beyond the shelf edge are now subject to significant human impacts in the form of deep-water trawling.

2. The case studies from Scottish waters support the general scientific consensus that use of mobile fishing gear, particularly bottom-trawls and dredges, is the most pervasive form of human disturbance to the seabed environment and the most significant cause of ecosystem degradation in coastal seas. Other processes, such as discharge of organic waste and water-borne chemical contaminants can be locally important, but are of much lower overall impact than the use of mobile fishing gear.

It therefore follows that control and regulation of fishing activity must be central to any strategy intended to promote marine ecosystem recovery in Scotland. This issue is currently being addressed in many parts of the world through the creation of networks of Marine Protected Areas (MPAs), which are intended to both protect marine biodiversity and promote the sustainability of fisheries. With respect to the case studies discussed here, regulation of bottom-fishing activity will be essential to the conservation and recovery of demersal fish communities, maerl and *Limaria hians* beds, and to *Atrina pectinata* if any viable populations of this species still exist. Recovery of native oyster beds will require more effective policing and enforcement of laws to deter illegal harvesting, possibly supplemented by artificial restoration in suitable areas if the necessary level of protection can be applied. Indeed, recovery of all degraded Scottish marine environments should be a component of the Marine Bill, and attention paid to the declining species highlighted in this report.

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