RESETTING MARINE ENVIRONMENTAL BASELINES FOR THE UNITED KINGDOM: WHAT HAVE WE REALLY LOST?

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Abstract

The systematic collection of data on fish stocks now used to inform fisheries management began only a few decades ago, however, these data do not provide a true picture of change as commercial fishing began many centuries earlier. Historical information such as that found within old photographs, naturalists' records, witness testimonies, government data and nautical charts can be used to reconstruct past environments thus providing a baseline from which to judge the state of the seas today. This study explores both historical and modern data for fish stocks and habitats around the United Kingdom and documents some of the changes that have occurred as a result of fishing, as well as investigating the potential of non-consumptive activities to degrade marine environments. Witness testimonies from the 1860s and 1880s reveal that bottom trawling had a devastating and immediate impact upon marine habitats as it expanded around the British Isles. Data sets of demersal fish landings from the 1880s to the present day reveal that technological improvements have masked fish stock decline and that the UK fishing fleet now has to work 17 times harder to catch the same quantity of fish. Comparisons of historical records with the results of recent survey activities show that bottom trawling has fundamentally altered shellfish habitats and extirpated oyster populations at several sites around the UK. At a global scale, wild fish landings have been in decline since the late 1980s. However, growth of the global human population means that wild fish availability per capita has in fact been decreasing since 1970, raising concerns regarding meeting nutrition requirements for those countries dependent upon fish protein. A rapid growth in aquaculture is currently compensating for declines in wild fish availability, however this current rate of increase is unlikely to be sustained in the future. Highly protected marine reserves (HPMRs) are spatial tools that aim to protect habitats and marine wildlife within their boundaries from the direct effects of extractive and depositional activities. HPMRs provide a picture of the marine environment in the absence of activities such as fishing, and offer another way of establishing environmental baselines. However, these areas are often used for non-consumptive activities which may also negatively impact upon habitats and wildlife if inadequately managed. An examination of 91 HPMRs from around the world show that many permit potentially damaging non-consumptive activities, such as SCUBA diving or motorised boating, with few regulations in place. Recommendations are made on how to mitigate or manage for these activities so that HPMRs can provide the high levels of ecosystem protection intended whilst still allowing people to use and enjoy these areas. This thesis demonstrates that reliance on recent fisheries data alone is flawed and that knowledge of marine ecosystems prior to fishing is necessary to evaluate the true success of marine management efforts and to set appropriate baselines for recovery.

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For Chapter 3, Simon Brockington collated historical landings statistics in parallel with me as part of a separate project, although this was unknown to us both at the time. Once we discovered this, we elected to publish a paper together. However I continued to use my own data to provide the analysis.

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Chapter 1: Introduction

1.1 SHIFTING BASELINES

Changes to the environment often go unnoticed due to a phenomenon called the 'shifting baseline syndrome' (Pauly 1995). These are intergenerational changes in the way we perceive our environment (Roberts 2007). Over time human activities such as fishing can degrade habitats and reduce targeted populations, altering the structure and functioning of marine ecosystems. However, as many of these effects are gradual or difficult to observe, each new generation perceives the altered environment that they are familiar with as 'natural', whilst older generations and their memories are forgotten. This creates problems for restoration targets as it is often difficult to know what a pristine, or less altered ecosystem should look like, particularly when major impacts upon the environment occurred before living memory. It is therefore necessary that shifting environmental baselines are recognised and evidence for large scale change is provided, in order for appropriate management and restoration targets to be set.

Jackson et al. (2001) showed that impacts of overfishing likely preceded other types of human disturbance in coastal ecosystems. In addition Pandolfi et al. (2003) found that most coral reef ecosystems had been substantially degraded before 1900, most likely due to overfishing. As threats such as climate change and pollution become increasingly significant for marine ecosystems (Harley et al., 2006; Hughes et al., 2003), our understanding of the true extent of degradation from long-term human disturbance is far from complete. The effect of the shifting baseline syndrome means that more recent generations fail to appreciate gradual changes that over time have dramatically altered the marine environment.

Research by Saenz-Arroyo et al. (2005) found that significant intergenerational changes occurred within just three generations of fishers in the Gulf of Mexico. Older fishers remembered greater abundances and sizes of Gulf Grouper, whilst younger fishers rarely caught this species. Ainsworth et al. (2008) came to similar conclusions using fisher interview data from eastern Indonesia, finding that older fishers remembered greater abundances of fish than younger fishers. These studies illustrate that even with memories of past abundance still alive, an appreciation of the extent of decline by younger generations was simply not there (Roberts 2007).

Around the UK many fishers can recall times when abundances of fish were significantly higher than today (COAST 2006). However, even the most long-term of these memories will still be affected by the shifting baseline syndrome as fisheries around the UK have been intensively exploited for many generations. In addition, advancing technology often masks declines in marine populations caused by fishing due to vessels improved catching power and ability to find and exploit new fishing grounds. An important example of this occurred in the 1880s when UK fishing vessels began to use steam power. This dramatically improved their fishing abilities by allowing them to fish further offshore and in weather that was not suitable for sail vessels. Steam power quickly became the dominant mode of fishing, particularly for vessels that used demersal (bottom) trawls. As a result, demersal landings soared thereby masking the decline of inshore fish populations (Garstang 1900).

The intensification of fishing and adoption of gears that could alter seabed habitats happened before living memory. Greater information on long-term changes to UK marine ecosystems is needed so our seas can be managed appropriately.

1.2 HISTORICAL MARINE ECOLOGY

Currently most fisheries and conservation management measures fail to account for the impact of long-term human disturbance. Most fisheries management and marine conservation efforts focus upon the last 20 to 50 years when technological improvements enabled improved scientific monitoring of marine communities and fisheries (Lotze and Worm 2008). For most areas, ecological monitoring came long after the start of intensive human activities. Since activities such as fishing are not distributed evenly throughout the marine environment and in many cases have occurred for long periods of time (Jennings et al., 2001), it is difficult to determine the full extent of change using recent data. During the past decade a number of studies have aimed to reconstruct and create awareness of past changes as a result of human activities, in order to reset our baselines and help us understand the extent to which we have altered the marine environment. Throughout the world, researchers have used a variety of techniques and sources to piece together descriptions of past habitats and species abundance. Despite the assortment of different methods used and the large geographical scope of research completed, studies consistently show that humans have indeed significantly altered and impacted upon marine communities around the world, much of this long before scientific monitoring began (Jackson et al., 2001; Pandolfi et al., 2003; Roberts 2007).

The field of historical marine ecology first emerged with the work of Jeremy Jackson during the 1990s. Initially Jackson (1997) used hunting and carrying capacity data alongside historical accounts to calculate likely population sizes of Caribbean green turtles during the pre-Columbus era. Several assumptions had to be made due to a lack of data (namely, percentage of female nesting turtles captured, number of nesting rookeries and total area of sea grass cover) and different methods produced varying estimates. For example, hunting data showed an estimated Caribbean population of 33-39 million green turtles, whilst carrying capacity data provided an estimate of 660 million. Despite the differences in population estimates, Jackson showed that turtles and other large vertebrates in parts of Caribbean coastal ecosystems were heavily depleted by 1800. Consequently keystone species were lost before scientific studies began, with this loss impacting and altering all levels of the coral reef ecosystem (Jackson 1997).

During the last decade, several research initiatives have been underway to gather historical data. For example, the History of Marine Animal Populations (HMAP) was initiated in 2000 as a global research programme to study human impacts upon the oceans and the status of past marine life (ICES 2008). The Sea Around Us project, based in Canada, began in 1999 and aims to analyse the impacts of fisheries – both past and present – upon marine ecosystems (Pauly and MaClean 2003). Findings from this project have dramatically improved our knowledge of our past and current impacts on fisheries and the marine environment. Studies initiated by the program include estimates of the worldwide extent of illegal fishing (Agnew et al., 2009) and the potential for zoning of the high seas to provide protection from fishing activities (Sumaila et al., 2007).

Some studies have used a variety of data to illustrate changes over time. Lotze (2007) combined archaeological, historical, fisheries, and ecological records to reconstruct the ecological history of the Wadden Sea and show past species occurrence, changes in species composition over time and trends in relative abundance of species. She found that while some species such as harbour seals and seabirds have shown a recovery during the 20th century as a result of protection from hunting and conservation of habitat, others have shown long-term decline due to human impacts such as exploitation, habitat alteration and pollution.

Lotze and Milewski (2004) integrated archaeological, historical and more recent data (including fisheries statistics and historical descriptions) to derive information on ecological changes in the Quoddy Region of the Bay of Fundy, Canada. They showed that a range of human influences including exploitation, habitat destruction from bottom trawling and river damming, pollution and introduced species had impacted at all levels and across a number of species groups. On this basis they estimated that higher trophic level species were at least 10 times more abundant before European colonisation in the late 1700s, and that declines had accelerated during the last 150-300 years. Despite these worrying trends, they also found that conservation efforts had slowed or reversed declines for some species (Lotze et al., 2006).

Palomares et al. (2006) used qualitative observations of early naturalists to create a relative abundance scale of functional groups of species in the Falkland Isles, cross-referenced with independent sources of numbers or weight of animals killed by hunters. Over time (1650-1950), abundances of marine mammals and seabirds were perceived to have decreased. A paucity of observational data meant that perceived changes to the functional groups of marine algae and invertebrates were unable to be analysed. This study demonstrated that qualitative historical data is able to be transformed and ranked to show trends over time.

Global scale investigations have been conducted by Myers and Worm (2003), who used catch and effort data from research trawl surveys and commercial longlining data throughout tropical and temperate regions to show that industrialised fisheries typically reduce community biomass by 80% within the first 15 years of exploitation, and that large predatory fish biomass is about 10% of pre-industrial levels. Myers and Worm (2003) focused upon areas where catch and effort data were recorded from the beginning of the industrialised fishery, hence they were limited to trawl-vessel data from the Gulf of Thailand, two fishing banks in the northwest Atlantic and South Georgia in the Antarctic. Pelagic longline data was taken from data recorded from the Japanese longlining fleet from 1952-1999, and focused upon equatorial and southern ocean regions throughout the Atlantic, Indian and Pacific oceans as these were newly exploited areas at the beginning of the time series. Catch data were standardised spatially into grids. Trawl survey data were used to estimate changes in abundance of large demersal fish species such as cod and skate, whilst longline data focused upon oceanic species such as tuna, swordfish and marlin. Changes in catch per unit of effort (100 hooks) were used to approximate changes in relative biomass for longline-caught species. In a continuation of this work Ward and Myers (2005) collected observer data from longline fishing vessels on species body mass and abundance from the tropical Pacific and compared this with datasets from the same region 50 years earlier. Despite the later fishery deploying more hooks and targeting a wider depth range for longer periods of time, higher trophic level predators such as sharks and tunas showed declines in abundance (average 21%) and mean body mass. Overall the biomass of large predators had declined by a factor of 10 whilst smaller species increased in abundance.

The results from the analysis by Myers and Worm (2003) have been questioned by other scientists (e.g. Cox et al., 2002; Hampton et al., 2005; Sibert et al., 2006). Sibert et al. (2006) also analysed data from the Pacific industrialised longline fisheries to determine past and present biomass of four exploited tuna species. In doing so they supplemented longline fishery data with information from other tuna fisheries operating in the Pacific Ocean such as purse seine and troll and line fisheries. They analysed catch and effort data, tagging and size composition data to estimate fishery impacts upon tuna and the blue shark (*Prionice glauca*). Biomass estimates of the fished and unfished portions of the stocks were obtained using stock assessment methods, which use fishery data to reconstruct the size and age structure of exploited fish populations. This approach was different to Myers and Worm (2003) who analysed data from the Pacific, Atlantic and Indian Oceans and separated the pelagic fisheries data based on temperate, sub-tropical and tropical communities taken from the industrialised longline fishery alone.

Using their approach Sibert et al. (2006) found considerable variation between different stocks of the same species, with total biomass of each species ranging from 36-91% of the biomass predicted in the absence of fishing. Many stocks were estimated to be above levels of maximum sustainable yield. A similar study by Cox et al. (2002) also found declines in large predatory species, although the declines were less than those found by Myers and Worm (2003). Cox et al. (2002) also found that the biomass of two species of smaller tuna, the juvenile bigeye (*Thunnus obesus*) and skipjack (*Katsuwonus pelamis*), had increased relative to their biomass in the 1950s. Sibert et al. (2006) also showed that skipjack tuna and blue shark biomass had increased over time, possibly because other large predators had declined as a result of fishing. In addition, Sibert et al. (2006) found that changes to fishing methods altered the size of individuals that were caught, and that declines in average size were not just a result of exploitation. Cox et al. (2002) and Sibert and colleagues (2006) work shows that more in-depth studies can produce very different results to broad-ranging analyses of data, and show the inherent difficulties in attempting to accurately reconstruct past marine communities. However, all papers agreed that major changes had occurred within pelagic fisheries since the 1950s and used their findings to warn that management of these fisheries must improve.

The loss of top predators from marine ecosystems is likely to have led to further ecological consequences throughout marine communities (Heithaus et al., 2008). Declines in shark populations were investigated by Ferretti et al. (2008), who used generalised linear models constructed from historical data to show that five species of sharks had declined between 96 and 99.99% in the northwestern Mediterranean Sea relative to their former abundance. If the extent of this decline is accurate, significant wider ecosystem effects throughout the Mediterranean as a result of the loss of top predators may occur, as has been shown in other ecosystems (Ferretti et al., 2008). McClenachan and Cooper (2008) used archaeological and historical information to reconstruct historical population sizes of the now extinct Caribbean monk seal. The numbers of seals recorded in historical documents as killed or surveyed was compiled alongside natural population parameters from other monk seal species populations and modelled to determine the baseline population size of a 17th century breeding colony. These results were expanded to estimate the total population occurring throughout the Caribbean before intensive hunting occurred. Estimates suggest that numbers of Caribbean monk seals were between 233,000 to 338,000 individuals. The biomass of prey required to sustain such population sizes suggest that Caribbean reefs were 3 to 5 times more productive than typical coral reefs today (McClenachan and Cooper 2008).

Poulsen et al. (2007) examined changes in population dynamics of cod and ling in the northeastern North Sea since 1872, based on historical CPUE and catch data from the longline fishery. Data on catch and effort were assembled by Swedish fisheries inspectors from 1872 to 1886, and CPUE were derived by calculating numbers of fish caught per longline fisher per season. The authors showed that ling size has decreased since the late 19th century and that ling abundance in this area has likely declined. Cod spatial distribution had contracted over time as a result of fishing effort. Another historical study in the North Sea was done by Rijnsdorp et al. (1996) who looked at bottom trawling data to calculate changes in abundance of demersal fish species. Comparing 1906-09 and 1990-95, they found community shifts towards reduced diversity and reduced species evenness, whilst smaller sized species had increased in abundance.

Many historical studies have focused on larger-scale, industrial fisheries. However some research has shown that ecosystems can be significantly affected by low-level ‘artisanal’ fisheries before fisheries became industrialised. Hardt (2009) used archaeological reports, plantation records, Government reports and published historical accounts to show that artisanal fisheries of Jamaica caused declines in megafauna and finfish populations, and that analysis of these data are necessary to set realistic recovery goals. Mangi and Roberts (2006) demonstrated that artisanal fishing gear, usually assumed to be relatively benign, did damage coral reef habitats and cause reef degradation. Pinnegar and Engelhard (2008) found that low level artisanal fishing can affect higher trophic levels and that even on remote oceanic islands ecosystems may have been degraded for hundreds of years. By studying reef areas around six Caribbean islands with varying levels of fishing intensity, Hawkins and Roberts (2003) showed that fish populations declined and the structure of the reef altered as fishing levels increased. This has also been shown in reverse by the establishment of marine reserves, where populations of fished species have increased and structure of habitats and communities has altered upon cessation of fishing (Gell and Roberts 2002; Gell and Roberts 2003; Roberts et al., 2001; Halpern 2003).

Innovative techniques have also been used to illustrate changes over time. Roman & Palumbi (2003) used mitochondrial DNA sequence variation models to estimate whale population sizes prior to whaling, based on genetic diversity of North Atlantic whales today. This research suggested that historical whale populations were much larger than previously thought. In a study to explore the availability of fish species over time, Pinnegar et al. (2006) examined changes to seafood prices. They demonstrated how prices may be increased by declines in high trophic level species such as cod and hake, but also be affected by increases in species availability as a result of finfish aquaculture. Hence, economic factors alone cannot always illustrate decreases in species availability. McClenachan (2009) used photographs to document the loss of large trophy fish from the Florida Keys from 1956-2007. Over this period mean sizes of fish caught declined and species composition shifted from large groupers and sharks to small snappers. Edgar and Samson (2004) used sediment core samples to show that shellfish abundance and diversity along the eastern coast of Tasmania had declined since the onset of a commercial scallop fishery. Most of these declines had previously gone unnoticed.

Historical declines of benthic habitats are particularly hard to quantify as few references exist. Many shellfish beds such as horse mussels and oysters were decimated by the beginning of the 20th century by trawling and dredging, alongside other detrimental impacts such as habitat development, disease and invasive species (Beck et al., 2009; Airoldi and Beck 2007). Such beds are important to biodiversity because their hard substrate supports large numbers of species (Hiscock et al., 2005). Kirby (2004) reconstructed the history of oyster degradation throughout Australian and North American estuaries. Degradation was measured using four proxies; earliest documented regulation of a fishery, the beginning of importation of oysters to restock an area, peak in landings data and earliest evidence for bottom dredging. The results of this study showed that as oyster fisheries close to centres of population became overexploited, oyster beds further afield began to be fished until they too became overexploited.

Hall-Spencer and Moore (2000) also showed how benthic habitats were affected by fishing. A previously unfished area of maerl bed in the Clyde estuary (southwest Scotland) was experimentally fished using scallop dredges and monitored alongside control plots for the next four years. They found that scallop dredging led to a 70-80% reduction in live maerl and that no recovery occurred during the four years of monitoring. In addition to direct physical damage to the maerl, they also found that vulnerable species such as *Limaria hians* which build large byssus nests were affected as their nests were torn or removed from the substratum by the dredge. Maerl in the path of the dredge was dragged along or buried, whilst silt re-suspended by the action of the dredge settled 15 metres or more from the dredge tracks. Hall-Spencer and Moore (2000) also compared modern maerl (*Phymatolithon calcareum*) thalli with historical collections of the same species gathered between 1885 and 1891. In the historical collections, *L. hians* nests were common and contained over 100 large *P. calcareum* thalli. Surveys of the same maerl bed from 1995-1997 produced only 16 live *P. calcareum* thalli, all smaller than the historical samples and no live *L. hians*. This study provides important insights into the difference scallop dredging has made to vulnerable, slow growing habitats such as maerl.

The examples discussed above show the variety of techniques and historical information used to piece together long-term change. However, much work still needs to be done. Historical data are always open to interpretation and there is a need to explore new methods and datasets to improve the robustness of historical reconstructions. My research aims to address historical impacts of fishing throughout the UK, focusing in particular upon bottom-living communities and their associated habitats.

1.3 UK CONTEXT

Archaeological research has unearthed evidence that sea fishing in England rapidly increased in intensity around 1000 AD (Barrett et al., 2004), as human impacts reduced the productivity of freshwater ecosystems. Until the 18th century, the slow nature of pre-industrial transport and rapid deterioration of fish flesh meant that fish consumption was mainly limited to coastal areas. Exceptions included herring which were salted or smoked after capture and could therefore be transported large distances. Indeed, the main market for British herring was the European continent (Smylie 2004). Oysters were another popular seafood product and provided a cheap source of protein for the poor. In 1864 it was estimated that 700 million oysters were consumed annually in London alone (Philpots 1891).

Bottom trawling in the UK was first mentioned during the 14th century when a local dispute about the use of an early type of beam-trawl was documented as being destructive to the seabed habitat and small fish (Alward 1932, Roberts 2007). Before the development of railways easily accessible markets for large quantities of cheap fish were generally unavailable, limiting the development of bottom trawling. The building of the national railway network began in the 1840s and went on to change the face of the UK fishing industry. As railways spread across the country and transportation times decreased, markets for cheap fish opened in inland towns and cities (Robinson 1996).

Beam trawling caught large numbers of fish such as haddock and plaice hence trawling became an important cheap source of protein for inner city populations (Robinson 1996). By the 1860s trawlers were resident throughout major ports in England and were exploring waters throughout the North Sea (Alward 1932). By the end of the 19th century bottom trawling had been established around the whole of the UK (Roberts 2007; Wimpenny 1953). During the 1880s the introduction of steam power revolutionised the fishing industry and encouraged further growth of the fleet (Roberts 2007; Knauss 2005; Wimpenny 1953). As a result of both increased competition and demand, together with declines on inshore fishing grounds, trawlers started fishing further afield (Aflalo 1904; Cushing 1988; Robinson 1996; Report of the Commissioners 1885).

After World War II, the declines in inshore stocks together with a growing demand for food encouraged the growth of UK distant-water fleets which targeted rich fishing grounds in the Arctic and around Iceland (Cushing 1988). Increasing competition from other countries in international waters and decreasing fish stocks led to disputes over who should have access to lucrative fishing grounds (Roberts 2007). Consequently during the late 1970s countries extended their territorial waters to 200 nautical miles from shore (Pauly et al., 2005). Whilst this displaced many fishing fleets from what had become their traditional grounds, most countries simply replaced foreign fishing power with their own expanded fleets, thereby continuing to deplete fish stocks (Pauly et al., 2005).

Throughout the second half of the 20th century fish landings continued to rise, fuelling optimism that fish could continue to feed an ever-growing global population. However, during the late 1990s it was discovered by Watson and Pauly (2001) that global landings of fish had actually begun to decline during the late 1980s, but had been masked by systematic over-reporting by China. Pauly et al. (1998) also showed that during the late 20th century fishers had kept their catches high by targeting lower trophic-level species as predatory fish had declined in abundance. This process of ‘fishing down food webs’ had helped reduce the decline of overall landings of fish species, but hid the particularly dramatic decline of top level predators (Pauly et al., 1998).

1.4 FISHERIES TODAY

Today, marine capture fisheries appear to have reached a limit of 80-100 million tonnes per year (Garcia and Grainger 2005). Aquaculture is increasing in importance but has environmental costs (FAO 2009; Naylor et al., 2009), making it likely that its current rapid rate of increase cannot be sustained (Pauly et al., 2002). However, as the global human population has continued to rise, demands for animal protein have also escalated.

Fishing today is a globalised activity; approximately 50% of the world's fish harvest is internationally traded (Garcia and Grainger 2005), and the majority of fish eaten in the UK is derived from imports (Marine and Fisheries Agency 2009). This is a very different picture from the turn of the 20th century when the UK had a thriving herring export trade and obtained the majority of whitefish from its home fleets. Technological innovations have done little to halt overexploitation of fisheries and current measures to manage fish stocks rarely take historical changes to marine populations into account (Roberts 2007).

1.5 RESEARCH OBJECTIVES

This PhD aims to build up a picture of historical change to marine populations and seabed habitats around the UK. The resulting information will be useful to marine managers as it will provide them with more appropriate baselines on which to base quotas and set restoration and recovery targets.

Chapter two investigated the spread of bottom-trawling around the British Isles and its perceived effect upon inshore fisheries prior to the industrial revolution. During the period 1863-66, a Royal Commission of Enquiry was held throughout the British Isles, interviewing over 700 witnesses from 86 coastal ports and towns. Witness statements from commissions of enquiry carried out during the 1860s and 1880s were used to provide an analysis of perceptions of change related to the expansion of bottom trawling, including changes in catch rate and fishing effort.

Chapter three investigated the increase in fishing power and fish landings that were a consequence of the industrial era and the introduction of steam power. During this period, the collection of fishery statistics began on a nation-wide scale. These quantitative data allow research into changes in fishery landings over a period of nearly 120 years. Using these data alongside estimates of improvements in fishing power of bottom fishing gear, I created an index of landings per unit of fishing power, which provides greater information on the decline of demersal fish stocks than landings data alone.

Chapter four focused upon shellfish fisheries and their effects on seabed habitats. I conducted underwater surveys in three areas, the Firth of Forth in Scotland, Swansea and Caldey Island in South Wales to provide a picture of change compared to historical literature. Sediment cores were taken to estimate changes to shellfish communities over time as a result of fishing activities.

Chapter five investigated inconsistencies between UK Government health recommendations and global fish availability. Since the 1880s the UK population has almost doubled, yet overall fish landings by UK fleets have been in decline since the early 20th century. This chapter investigated the growing gap between domestic supply and demand and our increasing reliance upon imports. Fish availability per capita for the UK and the world was investigated and extrapolated to the year 2050 to determine whether there will be enough fish to provide recommended amounts per week.

The final data chapter assessed how recreational activities may impact upon marine environments and what damage they may do if left uncontrolled. Marine reserves, areas of no-take, have been acknowledged as an important spatial management tool in the recovery of marine biodiversity and associated fisheries (Gell and Roberts 2003; Halpern and Warner 2002; Roberts et al., 2001). However, marine reserves often become tourist attractions, increasing levels of activities such as scuba diving, walking and boating. High levels of recreational activities may impact negatively upon marine reserves, reducing their ability to recover to former baseline levels. I explored the risks posed by various activities to wildlife and habitats and made recommendations as to which activities should be excluded and which regulated within highly protected marine reserves to ensure that marine ecosystems can recover towards levels of former abundance.

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Chapter 2: Overfishing in the early 19th century: origins of the trawling controversy in the British Isles

2.1 ABSTRACT

The industrial revolution had as profound an impact upon fisheries as it did other trades. The growth in demand for cheap protein encouraged the spread of bottom trawling, which in turn provoked outcries from other fishers that valuable inshore stocks were being depleted. In 1863 a Royal Commission was dispatched to all areas of the British Isles to hear complaints and to decide on the best course of action. This chapter uses these minutes of evidence to investigate the early impacts of bottom trawling as it spread into new areas and what factors fuelled the widespread controversy that occurred. Despite widespread complaints of declines in inshore stocks, numbers of boats were increasing rapidly and fishers were exploiting new grounds, both of which contributed to increases in fish traded. The importance of fish as a supply to inland populations, plus the perception that fish stocks were indestructible fuelled the Commissioners beliefs that line and net fishers' complaints were unfounded. However this view changed just 20 years later when many trawlers also added their voices to the issue of inshore stock decline. Whilst the Royal Commissions failed to implement any meaningful protection for fish stocks, their findings did encourage the gathering of national fisheries statistics which still continues today.

2.2 INTRODUCTION

Beginning in 1863, a Royal Commission of Enquiry investigated complaints made against trawlers and allegations of overfishing in the United Kingdom (Report of the Commissioners 1866). Over a 19 month period, Commissioners visited 86 ports, posing nearly 62,000 questions to more than 700 witnesses drawn from all parts of the fishing industry including fishers, auctioneers, traders, carriers, boat owners and harbour authorities. They set out to determine whether the supply of fish from sea fisheries was increasing, stationary or diminishing, and whether any fishing methods involved wasteful destruction of fish or spawn.

By the time of the enquiry the industrial revolution had changed the face of Britain forever. Prior to the building of the national railway network, inland markets were limited to the few fish species able to withstand long journeys by road and fetch high enough prices to justify the large transportation costs (Robinson and Starkey 1996; Robinson 1996). However once the railway network began in the 1840s a swift and reliable means of transport opened up inland markets for fish.

In particular, the railways helped encourage the spread of bottom trawling. This fishing method typically caught large numbers of ‘offal’ fish such as haddock and plaice, which usually fetched lower prices than ‘prime’ species such as turbot and brill (Robinson 1996). Prior to the railways, trawling had mainly been a south coast activity. The increase in market demand encouraged its spread and by the 1860s trawlers were resident at major ports upon the northeast coast of England and were exploring grounds throughout the North Sea. This brought line, net and trawl fishermen into direct competition with each other for space at sea. In addition, trawl fishing impacted upon marine habitats in a way that line or net fisheries never had and was seen to be capable of bringing up large quantities of immature fish. This served to fuel opposition from different classes of fishermen who were horrified at what they perceived to be a wasteful method of fishing (Report of the Commissioners 1866). National outcry ensued.

During the enquiry’s three year duration the Commissioners heard testimony from over 700 witnesses, mainly fishermen, but also from others connected to the industry. Despite much evidence given that trawling destroyed young fish and damaged the seabed, the Commissioners found it hard to make sense of the environmental effects of a rapidly changing fishing industry. The many conflicting interests between different types of fishermen and their varied views, compounded by a lack of statistics, prevented firm conclusions. The Commissioners concluded in their report that,

"The allegations that trawling in the open sea has exhausted any trawling grounds, and that trawlers have been obliged permanently to leave any trawling ground on account of such exhaustion, are [...] devoid of foundation."

They also stated,

"...fishing by the use of the beam-trawl is the source of by far the greatest and most progressive supply of fish, other than herring, to the principal markets of this country; that certain descriptions of fish, such as soles and plaice, could not be largely supplied by any other mode of fishing; that it engages the largest capital, employs the most numerous body of hardy fishermen, is the least under the control of the weather, and obtains the greatest returns of fish for the labour and capital employed."

Despite hearing evidence to the contrary, the Commissioners found it difficult to believe that marine fisheries could be in decline as evidence from railways and inland trade figures showed rapid rates of increase in the quantities of fish transported from coastal towns. Part of this problem of conflicting evidence came from a lack of data, which the Commissioners called for in their recommendations, but which was duly ignored. In addition, changes in practises, such as a reduction in discarding of lower priced fish as markets had opened up had occurred within recent years. This made it difficult for fishers and the Commissioners to make suitable comparisons between past years and the present time. Witnesses were also usually heavily biased against methods of fishing which were not their own. Whilst some fishers saw declines in catches from inshore bays and estuaries, trawlers often targeted new grounds and were unable to see any signs of exhaustion (Robinson 1996). The Commissioners responded to this bewildering array of contrasting opinion and the fact that most sea fisheries legislation was unknown or ignored by fishermen, by stating, *"Beam trawling in the open sea is not a wastefully destructive mode of fishing, but is one of the most copious and regular sources of the supply of eminently wholesome and nutritious fish. Any restriction upon this mode of fishing would be equivalent to a diminution of the supply of food to the people; while there is no reason to expect present or future benefit from that restriction."*

They then recommended *"unrestricted freedom of fishing to be permitted."* After the enquiry concluded in 1866, the majority of fisheries legislation was removed.

Unsurprisingly, removal of restrictions did not end the problems of declining coastal fish stocks or conflict between trawl and line fishermen. Consequently in the early 1880s, another enquiry was called to investigate the effects of trawling. By this time, sail trawling was well established in most parts of England but was relatively new to the east coast of Scotland. Steam trawling had also begun but was in its infancy. During the second commission evidence that trawling affected local inshore fish stocks was beginning to grow, but at the same time trawling was also now an established method of fishing that was seen to provide an important supply of cheap fish to a growing population (Report of the Commissioners 1885).

In the last century, British sea fisheries have undergone a transformation that would never have been thought possible by the Commissioners of these enquiries. British sea fisheries once dominated the North Atlantic, but towards the end of the 20th century, technological advances could no longer mask the problem of dwindling fish stocks, whilst the management of fisheries moved from a national to European level. However, the actions taken as a result of the 1866 enquiry still haunt fisheries management today. If the Commissioners had been able to see beyond the subjective and narrow accounts of local fishermen, to the wider problem, then the history of British sea fisheries may have been very different.

In this report I aim to reconstruct the early history of industrial fishing and document the effects of trawling on fisheries and the marine environment. I collate information from the 1866 and 1885 Royal Commissions to build up a picture of what changes took place to fisheries during the early trawling years and how this affected the marine environment around the UK, as well as people's livelihoods and communities. In doing so I try to answer the following questions:

(1) What were the first signs of fishing impact on fish populations in the late 18th and early 19th century?

(2) How did people adapt to changes in demand for and availability of fish?

(3) When and where did the bottom trawling controversy resurface (following phases of controversy centuries earlier), and what were the triggers?

(4) What were the first signs of fishing impact on habitats in the late 18th and early 19th century?

2.3 METHODS

2.3.1 Quantitative perceptions of change to coastal fisheries

The report of the Royal Commission of 1866 contains 1379 pages of evidence from interviews with over 700 witnesses. I scanned this evidence and extracted all quantitative statements which related to beam trawling. Data on inshore shrimp trawling was not included as it was often unclear if the 'trawls' were operated by hand from shore rather than from boats in shallow inshore waters. In total I found 119 quantitative statements on changes to catch rate, 74 statements on change in fishing effort, 17 statements on change in price and 11 statements on change in size of fish. Statements that spoke of general declines or increases but did not provide a quantitative measure were not used unless the witness stated that a previous fishery no longer existed, or that no fish were caught. In such circumstances I then used these and assumed catches to have declined by 95%. No information was used if witnesses contradicted themselves during the interview or if they spoke of increases as they moved to unexplored fishing grounds. Where a statement included a range of values e.g. ‘20 years ago an average take was 20 to 30 stone, today it is 2 to 3 stone’, I took the median value. I then grouped statements according to species and also used a general “whitefish” category since many quotes used this term rather than giving a species name.

Having done this I then compared changes in catch rate of whitefish between the south and the northeast coasts of England. The reason for this was that by the 1860s a number of ports in the south of England had had resident beam trawlers working off the coast for over 60 years, therefore residents and fishers had known of their presence for their entire lives. However in the northeast of England trawling had only recently been established. For the two regions, each quantitative statement made by a witness was converted to percentage change over the period of time that the witness could recollect. Perceived percentage changes for all witnesses from each region were then plotted graphically to determine whether any overall trends existed in witnesses perceptions of change. The same method was used to interpret perceptions of change in fishing effort, but was compared for the whole of the British Isles because of a lack of data.

The procedures described above were also applied to a Government enquiry that took place in 1883-4 (Report of the Commissioners 1885). This was a smaller event than the 1866 enquiry, and focused upon places where numerous and persistent complaints were being made about the effects of trawling. In particular the Commissioners concentrated on the northeast of England and the east coast of Scotland. Trawling had been established for a number of years on the northeast coast of England by this time, but was still a recent phenomenon in Scotland. The Commissioners also interviewed a number of witnesses from London and Brixham where trawling was well established. They also took statements from related occupations such as fishery inspectors, scientists, local magistrates and fish merchants. From this report, I found 48 quantitative statements regarding changes to catch rate, 18 statements on changes in fishing effort and 14 statements about changes to the price of fish.

2.3.2. Perceptions of beam trawling

Witnesses perceptions of beam-trawling were collated from the 1866 and the 1885 enquiry. A Likert Scale was used to categorise people's perceptions of trawling, from very positive through to very negative (see Box 1 for descriptions used).

Occupations of the witnesses were split into: trawlers (included full-time, part-time and ex-trawlers, also owners of trawls), other fishers (fishers not connected with trawling e.g. net or line fisher), or other (e.g. fish buyer, seller, or non-fisher). Where witnesses expressed a negative view of trawling, the reasons for their negativity were logged. These fell into the following categories; destruction of small fish, destruction of fish (e.g. over-fishing of an area or wasteful destruction of adult fish), habitat destruction, destruction of spawn, competition with other fishers (at sea), competition with other fishers (within markets) and loss of gear. If the witness detailed more than one trigger for unhappiness against trawling these were all recorded.

Box 1: Perceptions of trawling

Very positive:
Witness refers to positive features or impacts of trawling (e.g. trawling improves the supply of fish to the population), and/or witness appears passionate about trawling and its importance within the context of the questions posed by the Commissioners. Witness does not make any negative statements about impacts from trawling, or when questioned about these, does not agree that any negative impacts may arise from trawling, such as the destruction of immature fish.

Positive:
Witness refers to the positive impacts that trawling has had (e.g. trawling has increased the supply of fish to inner city areas and forms an important source of cheap protein). The witness may profess that trawling has some negative impacts such as increased competition with line fishers upon the same grounds, but that problems such as these do not negate the need for trawling to continue.

Neutral:
Witness refers to trawling or answers a question posed about trawling, but no preference is stated as to whether trawling and its impacts are positive or negative. They do not advance their own opinion on the subject. Within the context of the questions posed, the witness' language is passive, and they may only describe a situation or account what they have been told by others, whilst professing to have no knowledge on the subject of trawling themselves.

Negative:
Witness refers to negative impacts of trawling, but appears reluctant to ascribe all localised fishery problems to trawling alone. Other factors are recognised or referred to (e.g. the witness may state that fish stocks were declining before trawling arrived, but that trawling has increased this decline). Witness is critical of trawling but does not appear passionate about its impacts.

Very negative:
Witness makes strongly worded statements about the impacts of trawling, such as rapid declines in fish stocks, destruction of spawn or great loss of gear occasioned by line fishers. Witness may make passionate statements regarding the negative impacts of trawling (e.g. they will see the end of fishing should trawling continue).

Pass:
Trawling and its impacts are not mentioned in the context of the interview.

2.4 WHAT WERE THE FIRST SIGNS OF FISHING IMPACT ON FISH POPULATIONS?

In this section I explore the changing experience of fishing through witness testimonies, using statements that indicate changes in population size as a result of fishing and how people adapted to these changes, either by altering their fishing grounds or improving their gear. The extent and significance of effects such as perceived changes in fish populations are examined and compared to the increase in quantities of fish carried by railway.

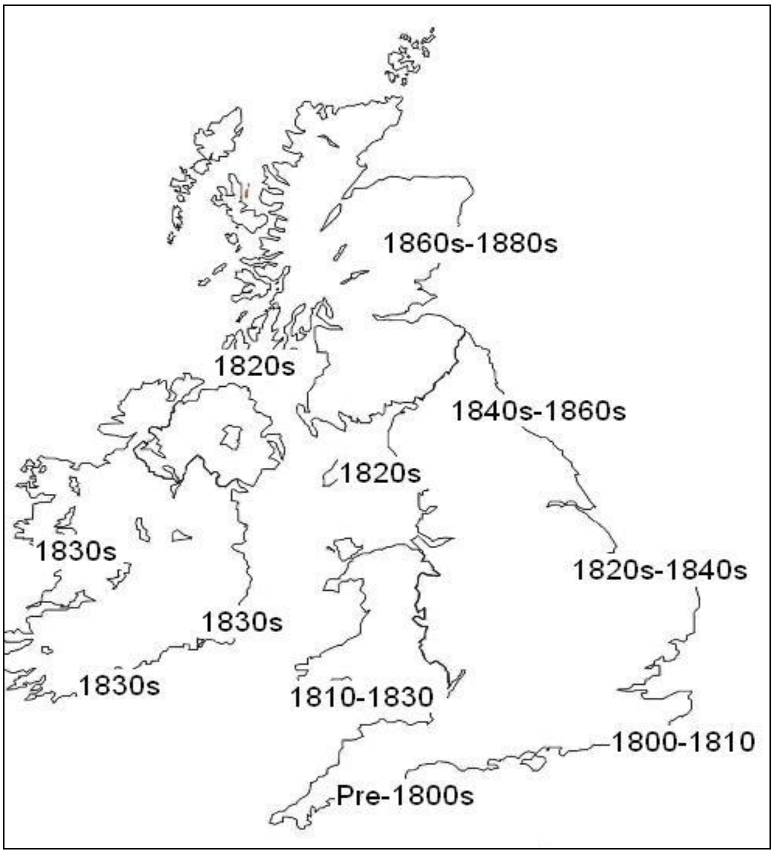

Figure 1. Approximate dates that sail trawling began around coasts of the UK in the areas indicated (Source: witnesses' testimony from Royal Commission of 1866 and Alward 1932).

Figure 1 shows that trawling began on the southwest coast of England prior to the 19th century. The origins of the beam trawling industry is attributed to Brixham or Barking from the 1670s onwards (Alward 1932) (see Figure 2 for areas visited by the Commissioners) and spread from there along the Channel and up into the North Sea during the early 1800s. This spread was facilitated by the introduction of the national railway system from the 1840s which increased demand for trawl-caught fish (Robinson 1996).

Figure 2. Locations of the major towns and ports around the British Isles and Ireland visited by the Royal Commission of Enquiry (1866).

2.4.1 Changes in catch rate

During the 1866 enquiry, the geographical extent and number of people interviewed led to a wide variety of statements and recollections reflecting the diversity of species targeted, gears used and areas fished, i.e. coastal versus offshore. In general fishers did not pinpoint exact fishing grounds although some offshore areas were mentioned specifically, namely the Silver Pits, California and Dogger Bank, all well-known fishing grounds in the North Sea. Different species were mentioned but in the main fishers referred to their catch as ‘whitefish’ (this would have consisted of a variety of species such as cod, haddock and whiting). Therefore I analysed changes to the statements which referred to whitefish.

Two regions were compared to one another, the northeast of England (n = 20) and the south of England (n = 15). Quantitative statements from witnesses from these regions were converted to percentage increase or decline for the number of years back in time they stated they were able to remember (see Table 1 for examples of statements compiled). On the south coast, one witness recollected back 60 years, whilst the earliest recollection stated to the Commissioners on the northeast coast was 55 years prior to the enquiry. Figure 3 shows people’s perceptions of change on the northeast coast of England, and Figure 4 shows perceptions of change on the south coast. A number of fishers on both coasts perceived declines of fish, however, perceived rates of decline were more common in the northeast, and often their perception of decline was greater than on the south coast. On average, south coast fishers believed that whitefish had declined by 9.8% in the past 60 years (S.E. 9.7%), while northeast fishers perceived a 64% decline (S.E. 8.4%) in the past 55 years (when calculated without the outlier present in Figure 3).

In the northeast of England (Figure 3) most fishers agreed that there had been some decline in fish stocks, although there was little agreement between fishers as to the extent of decline. This probably stemmed from the use of different gears and knowledge of different fishing grounds. There is little evidence to show that fishers with longer experience felt that there had been a greater decline in fish stocks than fishers who had been fishing for less time.

Table 1. Examples of witness statements used for perceptions of change.

Name	Occupation	Port	Description
1866 Royal Commission			
B. Simpson	Ex-line fisher	NE England	"[Off Spurn Point] twenty years ago we used to get 600 or 700 head of fish a day there; now they cannot get above 20 head, or 3 or 4 score at the outside."
T. Fell	Line fisher	NE England	"[20 years ago] a boat would get 58 or 60 stone of cod, haddock, and other fish. They would average that each boat. [Today they average] sometimes 12 or 15 stone […] sometimes a boat will go out and only get 2 or 3 stone."
T. Bulmer	Line fisher	NE England	"On the average, we brought ashore 3 quarters or a ton of fish in a boat […]. Now, on the average, 15 or 16 stones will be the outside."
R. Stibbs	Ex-trawler	SW England	'40 years ago there were 30 trawl vessels, now there are 64.'
C. Abbs	Council member	NE England	"I could buy haddocks formerly at 3*d*. and I have now to pay 6*d*. Cod […] I could formerly get for 1*s*. and 1*s*.8*d*. I am now obliged to pay 2*s*.6*d*. and 3*s*.6*d*."
1885 Royal Commission			
G. Morrice	Line/net fisher	NE Scotland	"[7 years ago] boats here can say they have got half a ton, 12 cwt, and as high as 14 and 15 cwt [haddocks], but the highest catch we had last year was 5.5 cwt, at about, I may say, 6 miles farther offshore than formerly."
G. Milne	Line fisher	NE Scotland	"We have landed at Port Erroll as 1000 to 1100 cod in the winter season [5 years ago]. [Last year we landed] 150."
R. Rowntree	Line fisher	NE England	"I have been going [to sea] 34 years […] and when I commenced we would get from 40 to 50 stone of fish, and now […] we cannot get over 4 or 5."
A.W. Ansell	Trawl fisher and owner	NE England	"Up to 1855, a vessel would capture as much as 60 stones in a night from the Silver pits […] it is unusual now to get more than 6 or 8 stone, which is a good haul."
D. Cole	Line/net fisher	NE England	"[When first began fishing, we went] 25 to 30 miles, and now we have to go 60 and 70."

Upon the northeast coast, the majority of people interviewed were line fishers who fished from cobles (small sail and rowing boats that typically held 3 to 5 people). These were limited to the distance they could fish offshore to a few miles and were unable to exploit grounds further afield when inshore stocks declined. Witnesses from this area who perceived increases in catches included a trawl fisher who was able to transport fish he previously threw overboard to other markets using the railway network, and fish-curers who were dealing with greater quantities of fish than they did in the past (S. Decent, trawl fisher from Hull; H. Wyrill, fish merchant from Scarborough).

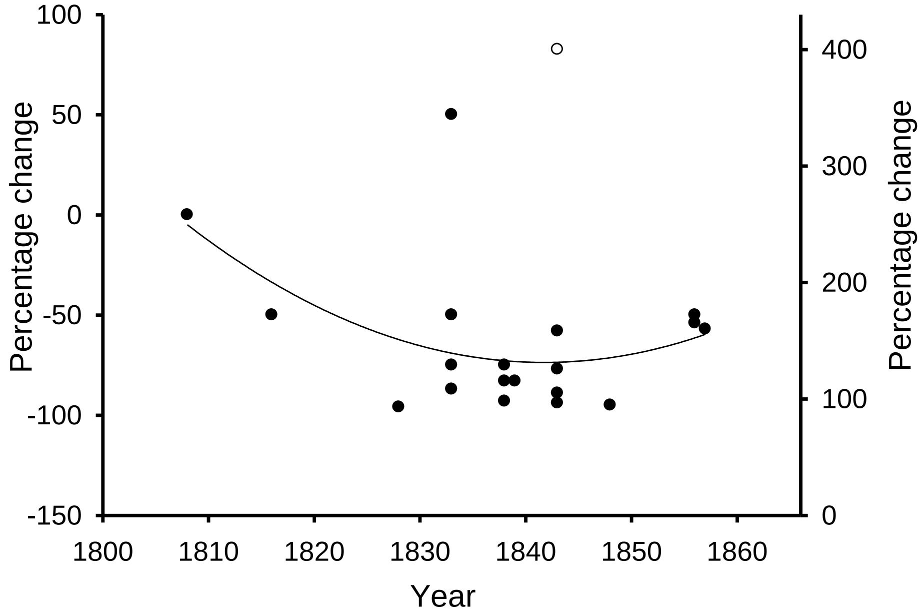

Figure 3. Witness perceptions of changes in fish stocks from northeast England. The year represents when each witness first perceived a difference in fish stocks, and the percentage change perceived from this period up to the time of the 1866 Royal Commission. Closed circles show the percentage change for all witnesses apart from one fisher whose perceptions of change were dramatically different to other witnesses. He is shown as an open circle using the scaling on the right axis and is not included in the analysis (n = 20) (R^2 = 0.22).

15 witnesses provided quantitative statements of changes in catch rates on the south coast. Of these, 7 were trawl fishers. Perceptions of change for the south coast showed high variation throughout the time series. This variation is likely due to fishers operating in different areas (e.g. bay versus offshore) and using

different gears (Report of the Commissioners 1866). Four fishers who had been fishing for 40 years or more stated that there had been a decline in whitefish, whilst in more recent years an increase in whitefish was perceived. Seven fishers, some of whom had been fishing for over 40 years stated they had seen no change during that time.

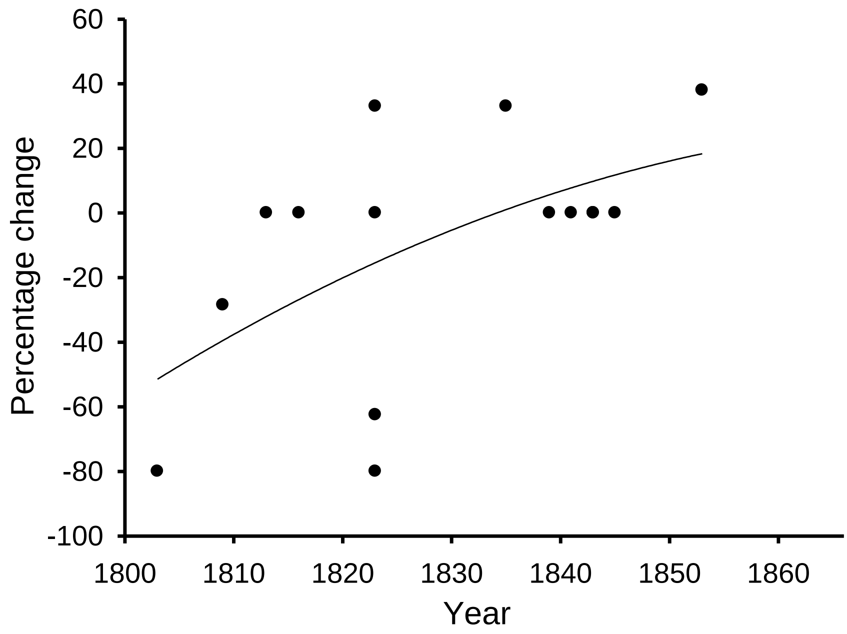

Figure 4. Witness perceptions of changes in fish stocks from south England. The year represents when each witness first perceived a difference in fish stocks, and the percentage change they perceived during this period up to the time of the 1866 Royal Commission (n = 15) (R^2 = 0.32).

In 1885 three regions were compared, the east of Scotland (Figure 5), the northeast of England (Figure 6), and southwest England (Figure 7). The majority of fishers interviewed in the southwest of England stated that there had been no change in fish stocks. However, the sparcity of interviews that generated quantitative data (n = 7) and the fact that interviews were only conducted at Brixham (mostly amongst trawl fishers), means that these results are unlikely to be very representative of southwest fishers.

By the 1880s, sail trawling was well established in the northeast of England, with trawl centres such as Grimsby and Hull having experienced rapid growth (Report of the Commissioners 1885). However, the introduction of steam trawls in the 1880s created new challenges for line and net fishers as these vessels did not rely on the winds and tides, hence were less predictable than sail trawlers (Roberts 2007). During the 1885 enquiry a shift in attitude towards sail trawlers is already noticeable. Whilst many fishers still viewed sail trawling as a problem, most understood that the trawl was here to stay and believed that the problems caused by sail trawlers were much less than those from the inshore steam trawlers. As H. MacDonald, a fisher from Golspie in the northeast of Scotland commented in 1883,

"I say the sailing trawler does not do so much injury as the steam trawler, although we found a difference even when the sailing trawlers commenced. We never had the same quantity of fish".

There were also trawl owners who believed that trawling was reducing fish populations by damaging inshore nursery grounds and who called for restrictions on this type of fishing, despite having positive attitudes about offshore trawling. Many of these people had long experience of trawl fishing and had seen the changes that had occurred within the industry, as well as the exhaustion of particular fishing grounds (A.W. Ansell, trawl owner at Hull; W.L. Robins, trawl owner at Hull). A.W. Ansell, a trawl owner from Hull stated,

"The round fish have increased. The catch is increasing because we go farther away to get it [...]. We go farther away because the yield of the fishing nearer home is not sufficient to pay us like the yield we get farther off."

Within Scotland (Figure 5), a similar pattern appeared to northeast England during the 1866 enquiry, in that the majority of fishers had perceived declines in fish stocks during their careers (Figure 3), although no trend was found for Scottish perceptions of change. Witnesses in Scotland consisted of line fishers and local fish merchants. Most trawlers fishing off the coast were English vessels who did not generally land their catch at the local ports. Therefore reports are likely to reflect the experiences of fishers who concentrated on areas relatively close inshore and who lost some of their best grounds to trawlers.

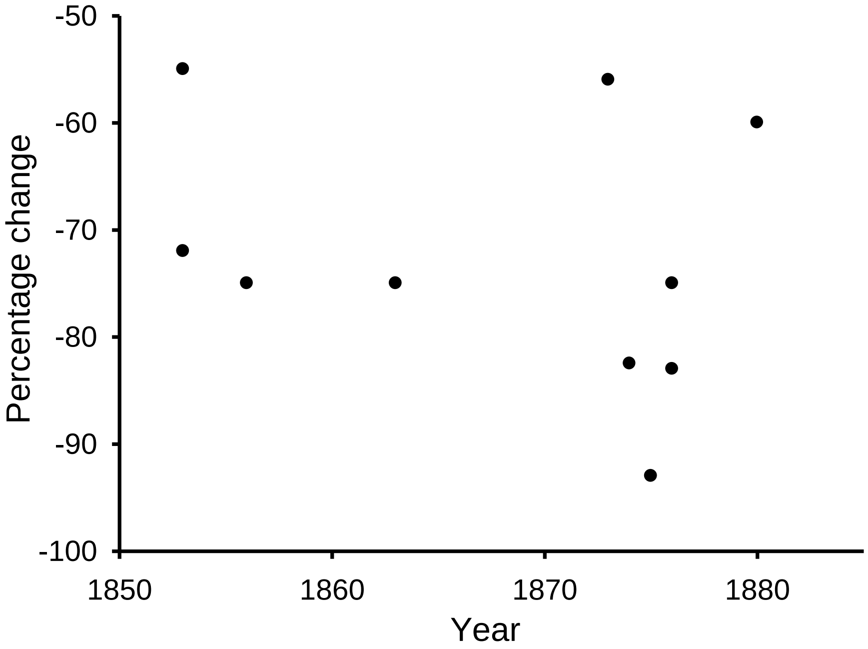

Figure 5. Witness perceptions of changes in fish stocks from east Scotland. The year represents when each witness first perceived a difference in fish stocks, and the percentage change they perceived during this period up to the time of the 1885 Royal Commission. (n = 10).

Within the northeast of England (Figure 6), it appeared that the majority of fishers perceived declines in whitefish. These opinions were provided by line fishers and trawl fishers and owners. The positive change perceived was by a fish merchant who had seen his sales increase in recent years. One trawl fisher stated that in inshore grounds fishing had declined. This is consistent with the views expressed by a number of trawl owners with long experience who stated during the 1885 enquiry that flatfish in particular were in decline throughout the North Sea.

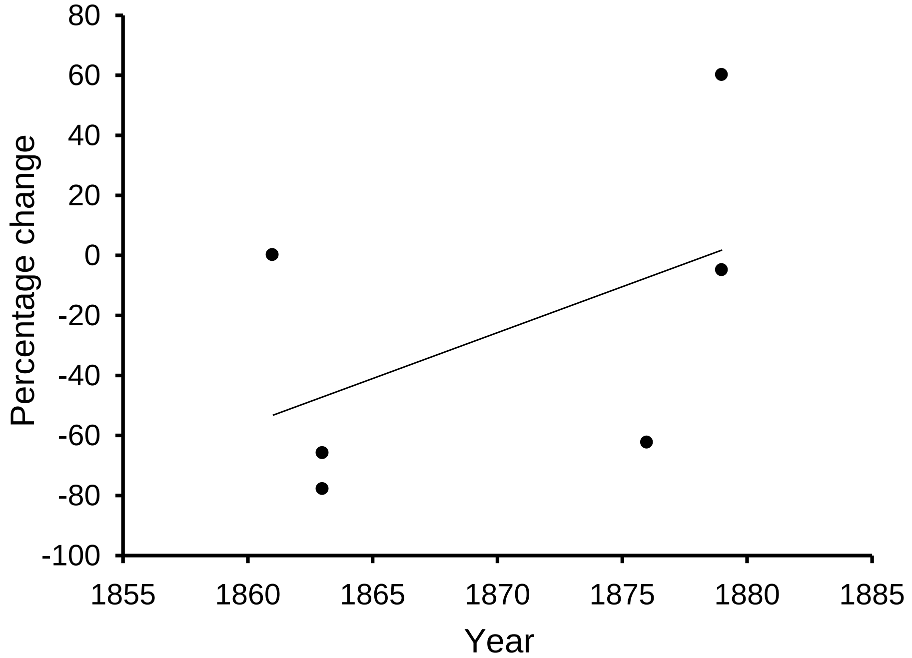

Figure 6. Witness perceptions of changes in fish stocks from northeast England. The year represents when each witness first perceived a difference in fish stocks, and the percentage change they perceived during this period up to the time of the 1885 Royal Commission. (n = 6) (R^2 = 0.25).

By the 1880s fish supplies into Britain were increasing, shown by increases in fish transported by rail, but only because of increases in effort further offshore. In Brixham whilst a recent scarcity of fish had been recognised by some fishers it was believed that this was short-term and due to bad weather rather than declines in fish (S. Pine, trawl fisher from Brixham; J. Stevens, trawl fisher from Brixham).

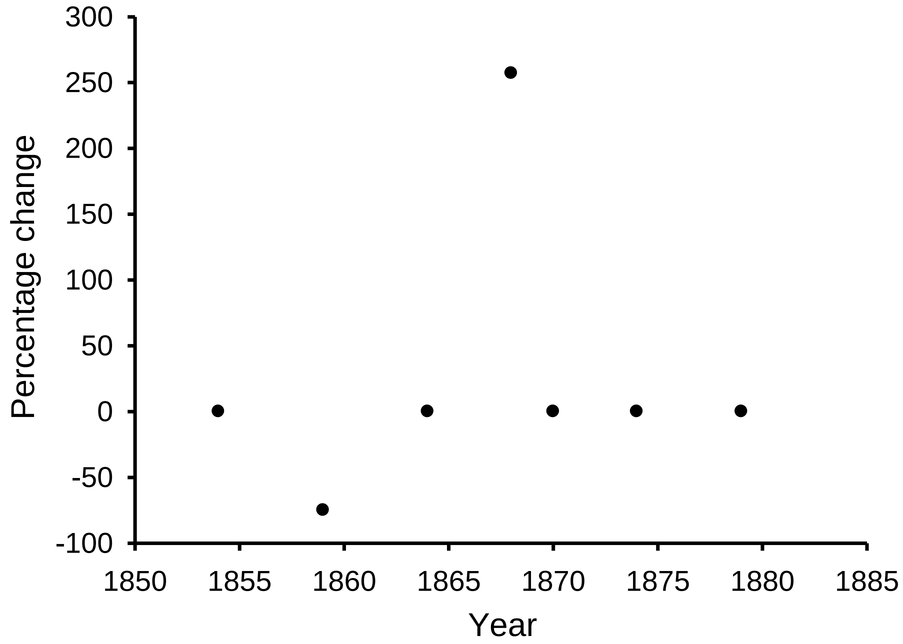

Figure 7. Witness perceptions of changes in fish stocks from southwest England. The year represents when each witness first perceived a difference in fish stocks, and the percentage change they perceived during this period up to the time of the 1885 Royal Commission (n = 7).

From the preceding figures, greater declines were perceived in the northeast of England and east Scotland than the south of England. Whilst there was likely a very real decline in inshore areas as habitats were altered and large and small fish taken (see following sections), some of the perceived declines may also be attributed to loss in fishing opportunities as line fishers lost their best grounds to trawlers. In addition, some declines in the northeast of England began before trawling became established (Figures 1 and 3), showing that intensive net and line fisheries also had effects upon inshore stocks.

Whilst many inshore fishers perceived declines in fish caught over the course of their working lives, the only source of official statistics, the quantity of fish conveyed by railway, showed a direct contrast to the statements they made to the Commissioners. Figure 8 shows the quantity of fish (finfish and shellfish) transported from principal ports around England by three rail companies of the time. Whilst rail company records had only been kept for a short period by the time of the 1866 enquiry, it was clear even then that fish quantities transported inland were increasing. This rise in transported fish increased at a greater rate during the late 19th century (Figure 8).

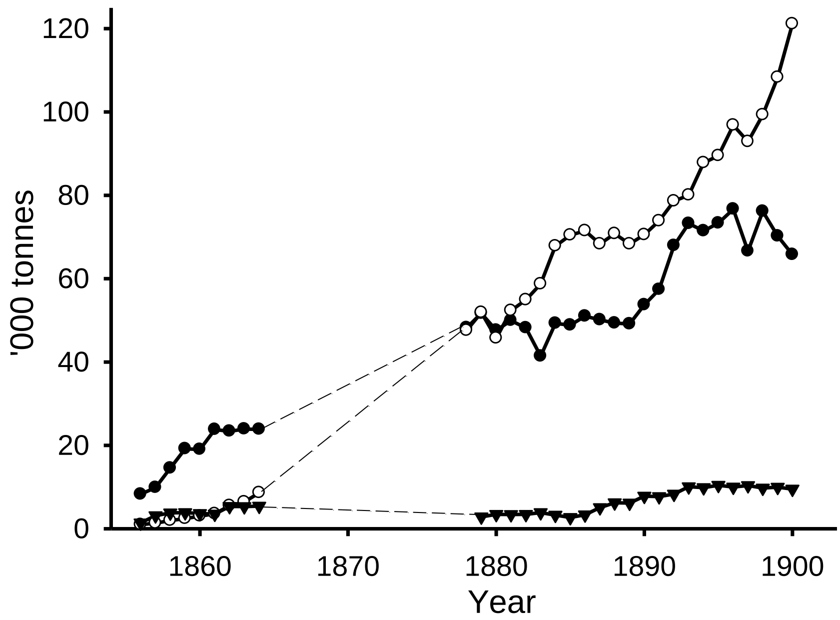

Figure 8. Fish (i.e. finfish and shellfish) transported from coastal ports by three 19th century rail companies. Closed circles show the North-Eastern rail company (transported from Northumberland, Durham, Yorkshire and Lincolnshire ports), open circles show the Manchester, Sheffield and Lincolnshire rail company (transported from Grimsby and Hull), closed triangles show the Great Northern rail company (transported from Boston). Dashed lines indicate missing data. Sources: 1866 and 1885 Royal Commissions and Sea Fisheries of United Kingdom statistical tables (various years).

2.4.2 Summary

The increase in fish transported by rail made it hard for the Commissioners to accept line and net fishers' testimonies of decline. Declines were also masked by improving technology and exploitation of new fishing grounds, as discussed in the following section. This ‘masking’ of decline was demonstrated by Garstang (1900) who showed that landings of fish in the last decade of the 19th century had only risen because the power of the fishing fleet increased. Garstang (1900) demonstrated this on a national scale for the years 1889-1898. However similar patterns could be seen for individual trawlers throughout the 19th century. Figure 9 shows average landings of fish per year for typical sail trawlers fishing in the North Sea. Landings peaked during the 1860s but declined throughout the latter half of the century. Whilst these data are only a snapshot of what occurred in the northeast England trawl industry they reflect the concerns about declining catches of many trawl owners apparent during the 1885 enquiry. After this period, steam trawlers came into general use, resulting in new fishing opportunities and increased landings once again.

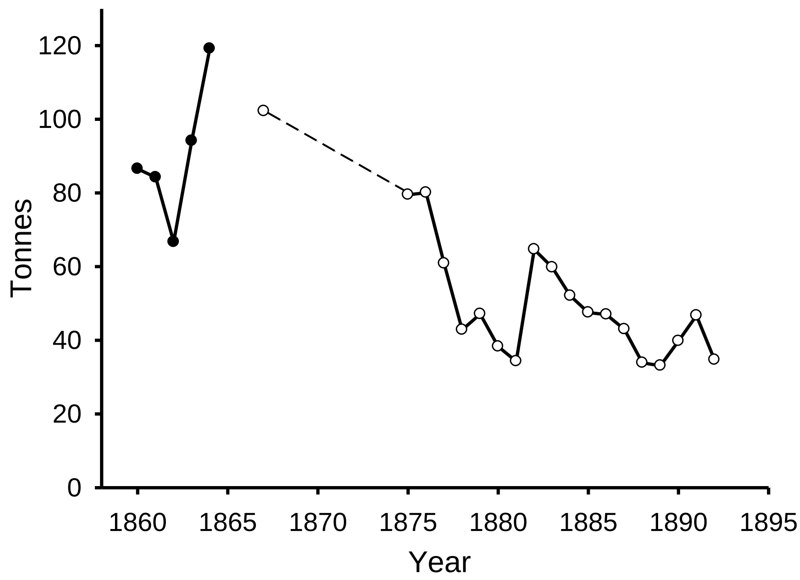

Figure 9. Average landings of fish per year by a Grimsby sail trawler. Closed circles show landings statistics provided by H. Knott, a trawl owner from Grimsby for an average sail trawler fishing in the North Sea. Open circles show the average catch per vessel from four sail trawlers fishing in the North Sea, data provided by G.L. Alward, a trawl owner from Grimsby (Source: 1866 enquiry and Garstang 1900). Dashed line indicates years when data were not available.

2.5 HOW DID PEOPLE ADAPT TO CHANGES IN DEMAND FOR AND AVAILABILITY OF FISH?

Here I examine witness statements for recollections of practices aimed at sustaining or increasing the supply of fish. They include increases in distances travelled to fishing grounds, and alteration and improvement of fishing gear.

2.5.1 Fishing effort

Fishers attempted to adapt to changes in demand for and availability of fish in a number of different ways. Increasing competition for the best fishing grounds as numbers of trawlers increased, as well as depletion of fish stocks in nearshore waters meant that many fishers needed to increase their effort in order to maintain catches (Garstang 1900). The arrival of railways also meant that many coastal ports had a fast and reliable link to inland markets (Robinson 1996). Throughout Britain the number of fishing boats began to increase as fishing opportunities improved. The 1866 enquiry provides records from fishing stations around the country (Figure 10). Whilst there was much variation, a general trend can be seen showing that fishers who remembered further back in time perceived a greater increase in the number of boats. However, the introduction of the railways meant that whilst some ports greatly increased their trade and hence the number of boats, some ports that were too far away from fast transport networks began to stagnate and numbers of boats declined (Robinson 1996).

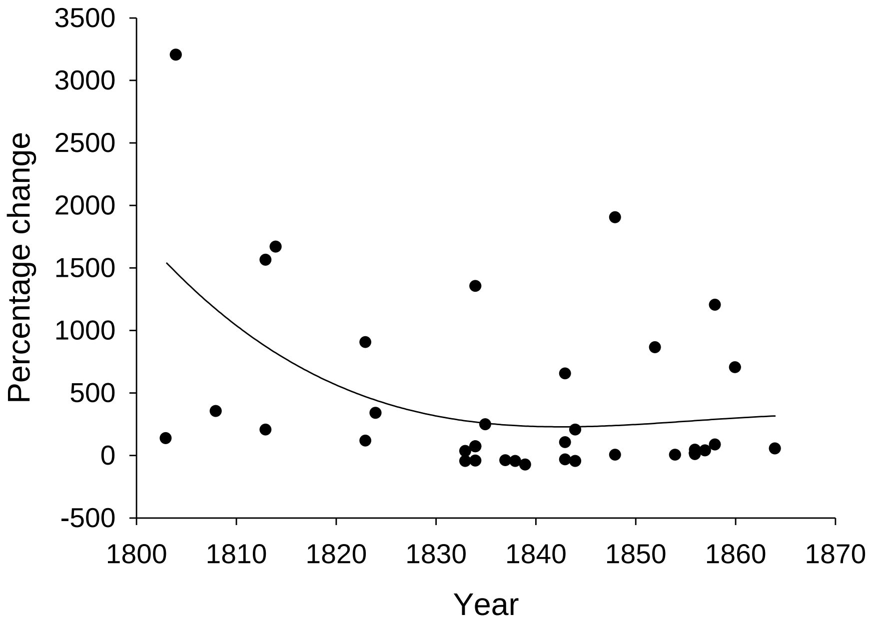

Figure 10. Perceived increase in number of boats around the UK taken from the 1866 Royal Commission. The year represents when each witness first perceived a difference and the percentage change they perceived during this period up to the time of the Royal Commission (n = 38) (R^2 = 0.22).

Other ways to increase fishing effort involved improvements to fishing gear, for example increases in the number of lines and hooks in a boat, the tonnage of vessels and the distance travelled from shore. Whilst there were only 6 quantitative statements showing distance from shore travelled that could be used, these showed that distances travelled for fish by liners and trawlers had increased over time (Figure 11).

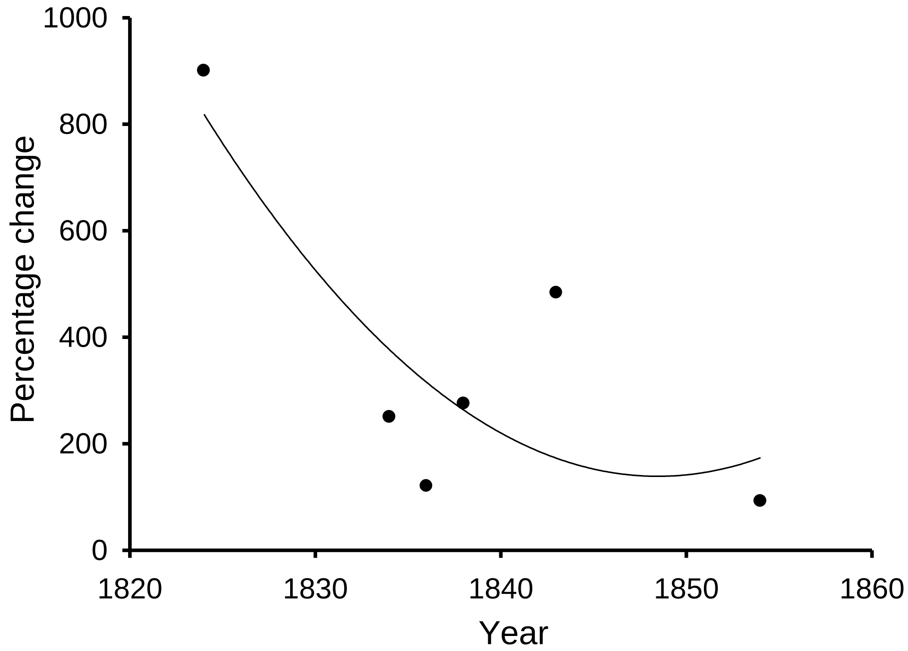

Figure 11. Perceived increase in distance fished from shore around the UK taken from the 1866 Royal Commission. The year represents when each witness first perceived a difference and the percentage change they perceived during this period up to the time of the Royal Commission (n = 6) (R^2 = 0.64).

Some fishers described the changes they had made to their gear over the years to compensate for declines in fish stocks or to meet increased demand. Quantitative statements were few and for a wide range of gear types, but provide evidence that gear was increasing in size and efficiency quickly.

R. Nicholson, a line and net fisher for 50 years from Cullercoats stated that cobles now set *"lengths of 20 nets"*, yet used to set no more than *"6 lengths"* 30 years previously. A similar pattern occurred with hook and line fishing. J. Patterson from North Sunderland stated that 21 years before, lines would have *"400-500 hooks"*, but that fishers now used *"800-1000 hooks per line"*. Oyster fishers had also improved their catching ability. J. Bell from Wexford stated that 40 years prior to the 1866 enquiry oyster dredgers only used *"one dredge per boat"*, but that now they used *"6-8 dredges"*. Trawls also got larger as boats increased in size; H. Salisbury, a trawlerman from Brixham, increased his trawl beam length from 33 feet to 43 feet within 20 years. In Hull, W.I. Markcrow, a trawl vessel owner stated that trawl beam lengths had increased and head irons had become heavier within the last 20 years.

During the 1885 enquiry, the most mentioned change in fishing effort was the distance that vessels had to travel from port. Again, this varied substantially, with some small line boats still fishing in coastal bays and estuaries, whilst larger trawlers travelled to the opposite side of the North Sea. Despite the small number of cases (n = 9), all witnesses perceived an increase in the distance they had to travel to fish (Figure 12). J.L. Potter, a trawl owner at Hull, spoke of the trend,

"When I first went to sea the nearest fishing grounds to the mouth of the river Humber were distant from between 30 and 40 miles in an E.N.E. direction. Since that time they have gradually moved into a more northerly direction, and the nearest fishing grounds of any note are now distant from the Humber 170 miles."

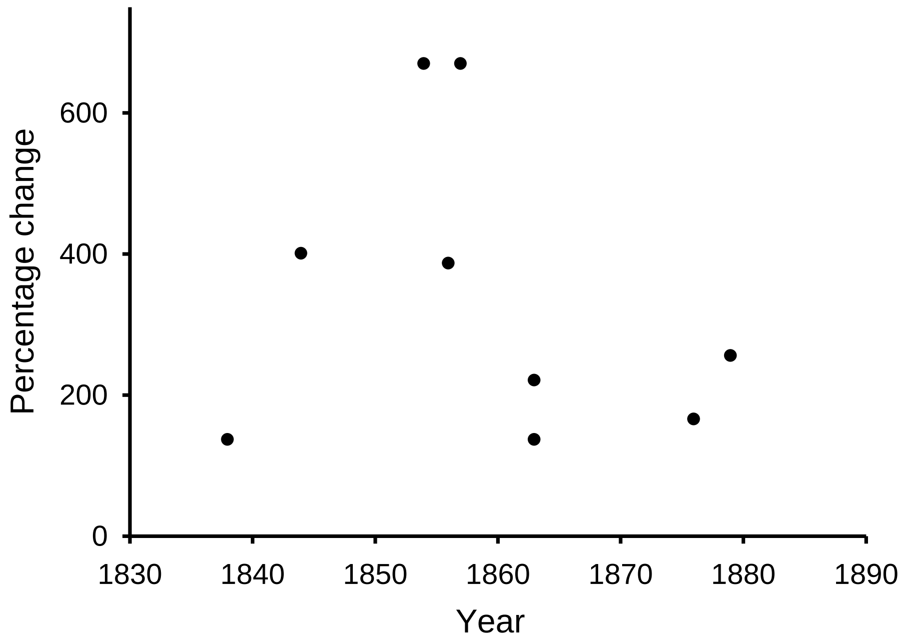

Figure 12. Perceived increase in distance fished from shore around the UK taken from the 1885 Royal Commission. The year represents when each witness first perceived a difference and the percentage change they perceived during this period up to the time of the Royal Commission (n = 9).

2.5.2 Changes to the price of fish

Increases in the value of a commodity may indicate an increase in demand, a reduction in supply or a mix of the two (Jones 2008). The influx of trawlers increased the national supply of fish as they spread further offshore, but little of this was destined for coastal communities. Fish prices on the coast rose because the national railway network sent supplies to inland markets (Robinson 1996), whilst small-scale fishers were hit by declining inshore stocks. These effects helped fuel further outcries against trawling.

Figure 13 shows averaged witnesses perceptions of price increases around the UK (n = 12) for whitefish and flatfish in coastal communities. For example, J. Page, a fisher and fish salesman from Hastings described how a basket of plaice had increased from 2 shillings 17 years prior to the enquiry (equivalent to £8.70

today[1]) to over 4 shillings in 1866 (equivalent to £18 today) due to a rise in demand from the railways. In general, witnesses who recollected earlier times spoke of greater increases in the price of whitefish and flatfish (Figure 13).

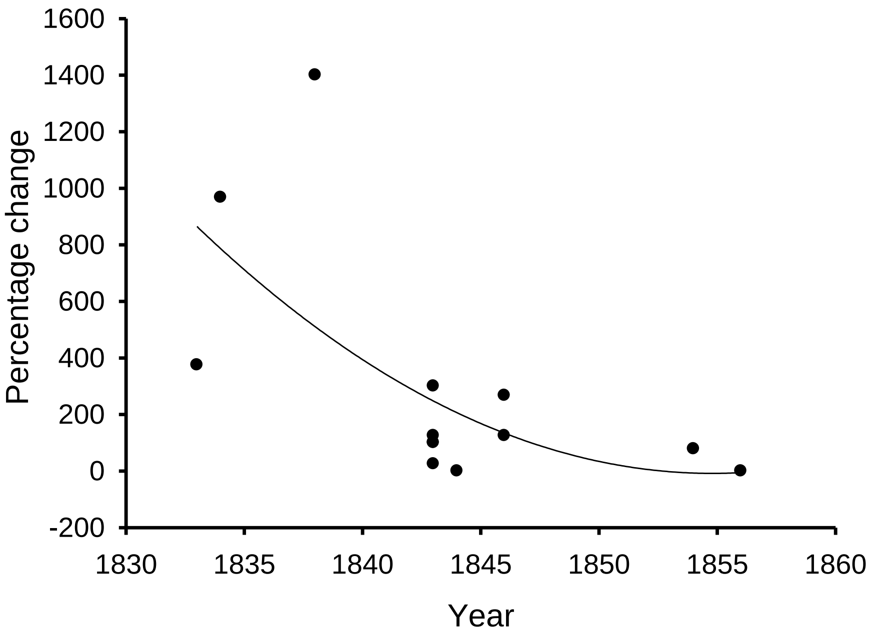

Figure 13. Perceived increase in price of whitefish and flatfish according to witnesses from coastal areas around Britain taken from the 1866 Royal Commission. The year represents when each witness first perceived a difference and the percentage change they perceived during this period up to the time of the Royal Commission (n = 13) (R^2 = 0.41).

The perceived increases in Figure 13 can be compared to price rises recorded in official record books provided to the Royal Commission during the 1866 enquiry. These were recorded for an inland town, Manchester, and a coastal port, Newcastle-upon-Tyne.

[1] Historical inflation rates taken from http://safalra.com/other/historical-uk-inflation-price-conversion/

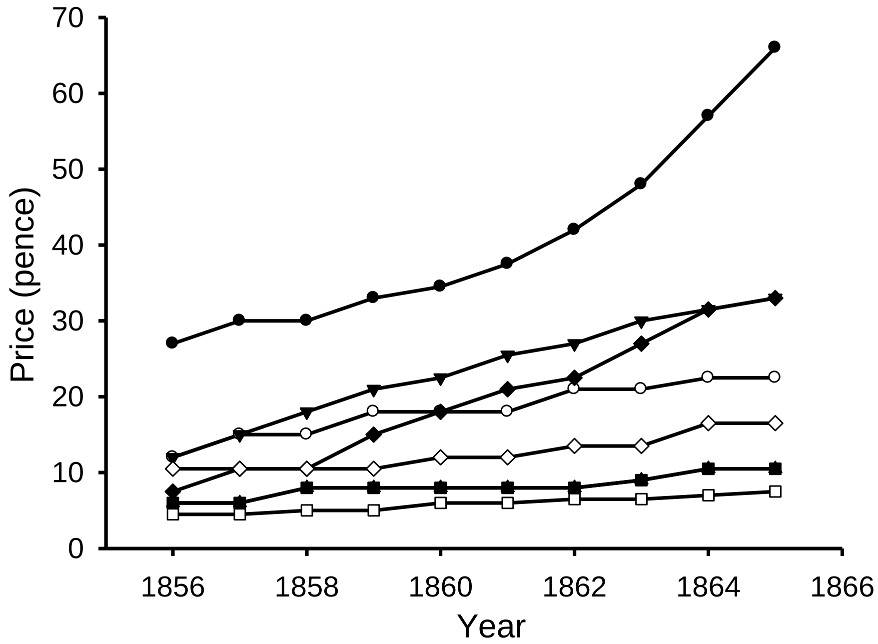

Figure 14. Retail prices of fish in Newcastle-upon-Tyne obtained from Market Inspectors records (1866 enquiry). Fish such as cod and haddock were sold separately whilst other species were sold by weight or per pair. Turbot per stone (closed circles), soles per pair (open circles), cod each (closed triangles), codlings each (closed squares), haddock each (open squares), skate each (closed diamonds), whiting per stone (open diamonds).

Figure 14 shows the median sale value for different species of fish at Newcastle-upon-Tyne fish market for a period of 10 years. Within this time, prime species such as turbot had increased by 144%, skate had increased by 340% and haddock by 67%. These species had previously been seen as trash fish, yet the rise in price indicates that demand increased during this period. If witnesses' statements are quantified as percentage change per year, the average price rise for whitefish from 1856-1865 was 148%, similar to the official figures.

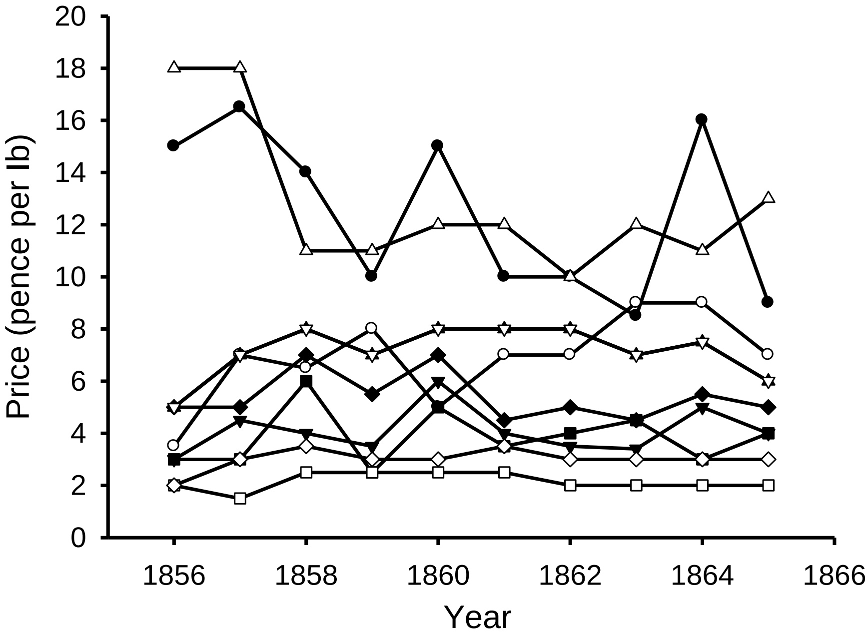

Figure 15. Retail prices of fish in Manchester obtained from Market Inspectors records (1866 enquiry). Fish were sold per pound of weight (lb) regardless of species. Turbot (closed circles), soles (open circles), cod (closed triangles), sparlings (smelts, open triangles), haddock (closed squares), plaice (open squares), brill (closed diamonds), ray (open diamonds), halibut (stars).

At inland markets the price of fish remained more stable over the same time period, albeit more expensive than at coastal markets (Figure 15). However, the different methods of selling fish between the coast and inland areas (i.e. whole, per pair or per pound) makes it difficult to compare prices for most species. Table 2 shows comparative values for turbot, a prime fish species, at Newcastle and Manchester fish markets (pence per lb). In 1856, there were large differences between the prices, but during the next decade prices rose at the coast and gradually dropped inland (although fluctuations were greater).

Table 2. Price of turbot (pence per lb) at Newcastle-upon-Tyne and Manchester fish markets (median values taken from 1866 enquiry).

	1856	1857	1858	1859	1860	1861	1862	1863	1864	1865
Newcastle-upon-Tyne	1.9	2.1	2.1	2.4	2.5	2.7	3.0	3.4	4.1	4.7
Manchester	15	16.5	14	10	15	10	10	8.5	16	9

A longer term record of prices paid for oysters also shows a gradual increase between 1825 and 1864, particularly in the years leading up to the enquiry (Figure 16). During this period there had been a lack of good spatting seasons (seasons where high amounts of oyster larvae fell and settled upon the beds) and the quantity of oysters upon public and private beds had declined. Overfishing was also likely to be a factor, although the Commissioners were unwilling to ascribe fishery problems to overexploitation (Report of the Commissioners 1885).

J.H. Nichols, foreman of the Whitstable Oyster Company, stated that the prices of oysters had particularly increased in the last 5-6 years (1858-1864) as supplies had dwindled. However, the lack of oysters upon private beds had additional ramifications for public oyster fisheries, as W.H. Williamson, an oyster merchant from Falmouth pointed out. He stated that oysters from Falmouth had increased in price from *"2 shillings to 18 shillings"* between 1852 and 1864 (equivalent to £10 and £86 respectively). This had led to most oysters being fished before they could reproduce as they were transported to areas of declining yield where they were fattened for market.

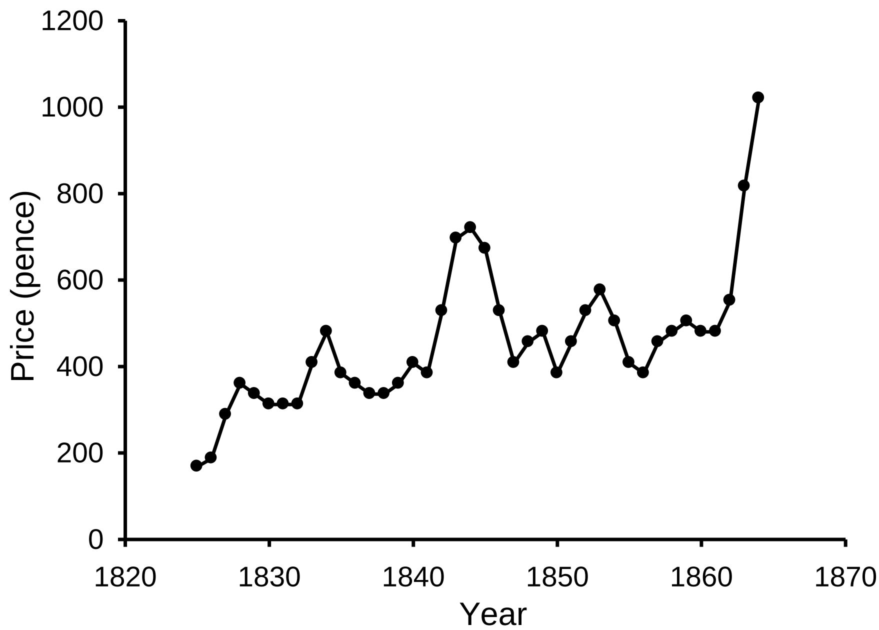

Figure 16. Average yearly prices per bushel for Whitstable oysters after correction for inflation (RPI) (http://safalra.com/other/historical-uk-inflation-price-conversion/) (1866 enquiry).

By the time of the 1885 enquiry, railway networks were well established all over the UK and the use of the trawls and ice enabled fish to be caught and transported in bulk. Figure 17 shows that prices continued to increase in coastal areas until closer to the 1885 enquiry. It was this increase in price that enabled many line fishers to maintain some income after their catches had reduced as they lost grounds to trawlers and as inshore stocks declined (J. Dickson, line fisher from Cockenzie, T. Eason, line fisher from North Berwick).

A.W. Ansell, a smack-owner from Hull, was able to show from his record books that flatfish and soles had greatly diminished in the traditional fishing grounds of the North Sea between 1855 and 1883, and that smacks had to travel further for roundfish. He also stated that from 1845-55 soles could be brought from between 8d to 1s.6d per stone (equivalent to £3.00-£7.50). By the time of the 1885 enquiry they reached from 14s to 23s per stone (equivalent to £67-£110). Bait was also more expensive as intertidal populations of shellfish were overexploited or succumbed to pollution, creating another problem for line fishermen (J. Ouston, line fisher from Scarborough).

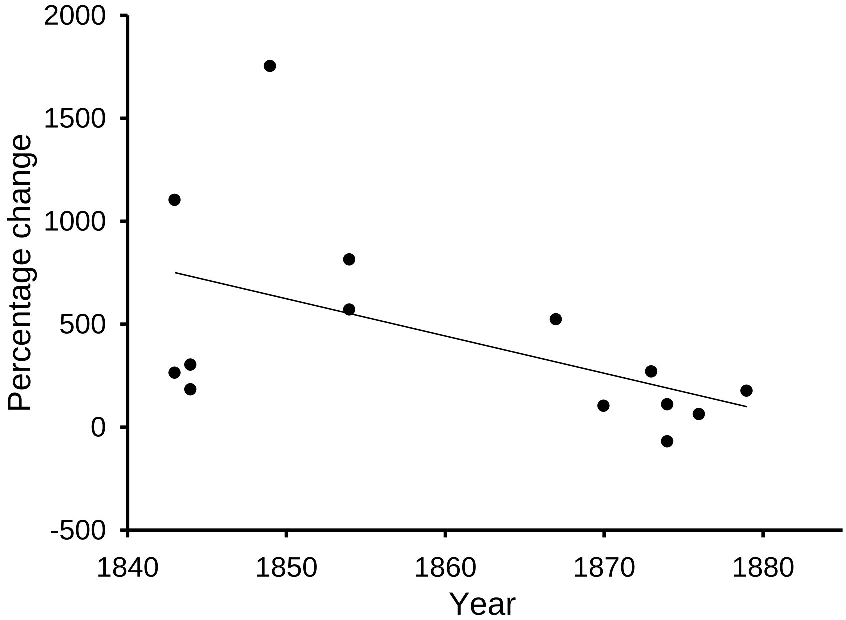

Figure 17. Perceived increase in average price for fish (coastal areas) according to witnesses from coastal areas around Britain taken from the 1866 Royal Commission. The year represents when each witness first perceived a difference and the percentage change they perceived during this period up to the time of the Royal Commission (n = 14) (R^2 = 0.27).

2.5.3 Summary

Throughout the 19th century fish became available to a greater number of people as transport improved. Although inland prices were always higher than coastal ones due to transport costs, prices on the coast where fish was often an important part of people's diet continued to rise as demand from inland markets soared. Increasing prices and high demand at least allowed line fishers to keep a competitive edge against trawlers by providing high value prime fish which the trawlers could not do.

Official records provided by G.L. Alward, a trawl owner from Grimsby (Garstang 1900) from the years 1875-1892 are presented in Figure 18 and provide another source of evidence of rises in the price of trawled fish. Over this period, average prices per tonne of fish rose by 39.5% after inflation, despite a decline in the amount of prime fish in the overall catch. These prices come from the average landings of the four sail trawlers detailed in Figure 9 and show that prices increased as catches declined. This decline in landings would be arrested by the introduction of steam trawls, which allowed fishers to exploit new grounds further afield.

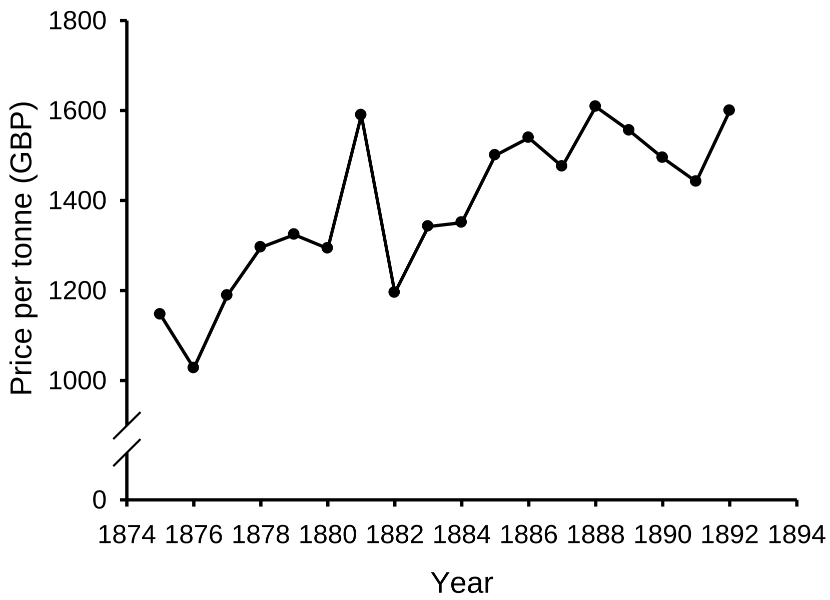

Figure 18. Average price per tonne of four sail trawlers landing fish into Grimsby from the North Sea. Prices were converted to equivalent 2010 prices using the RPI inflation measure (http://safalra.com/other/historical-uk-inflation-price-conversion/). Data from G.L. Alward (source: Garstang 1900).

2.6 WHAT WERE THE TRIGGERS FOR THE TRAWLING CONTROVERSY?

Early texts have much to say about the effects of trawling, with some commentators outspoken in their denunciation of the method as early as 1843 (Bellamy 1843). In this section I investigate people's feelings towards trawling based upon their occupation and location and explore the different triggers for concern.

During the 1866 enquiry, I compare perceptions of trawling between two contrasting fishing communities: the northeast and the southwest coast of England. As mentioned earlier, in the northeast trawling was relatively new and had been met with hostility by line and net fishers, but on the south coast was a well-established fishing method from a number of ports. The enquiry in the northeast elicited a wide range of responses; line and net fishers were often very negative about trawling, and in response trawl fishers tended to be defensive of their trade. Few people had little to say on the subject of trawling;

"If this trawling is not done away with there will be no haddocks at all. With regard to haddock-fishing, trawling destroys the spawn [...]. Now, when these trawls go over the ground, if there was a shilling lying on the ground they would take it from the bottom. The consequence is that they take all the spawn away, and there is nothing left at all to breed from." R. Nicholson, line fisher from Cullercoats.

"These trawling boats [...] are the proper ruin of Cullercoats; they are just taking all the fish off the coast, and if something is not done with them it will come to starvation among the fishermen." W. Scott, a fisher from Cullercoats who also trawled in shallow water for soles part time.

Figure 19 shows that in the northeast there were two contrasting views about trawling based upon people's occupations (trawler, other-fisher or non-fisher) (n = 104).

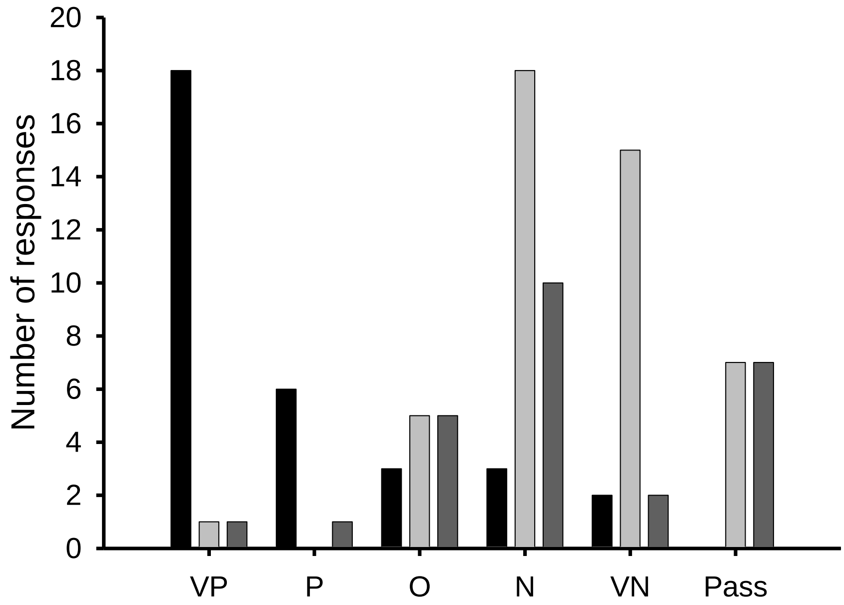

Figure 19. Perception of trawling from witnesses interviewed in the northeast of England (1866 enquiry) (n = 104). Reponses were classified according to the Likert scale (VP = very positive, P = positive, O = neutral, N = negative, VN = very negative, Pass = trawling not mentioned). Black bars = trawlers, light grey bars = other fisher, dark grey bars = non-fishers.

Opinions on the south coast were different (Figure 20, n = 100). J. Salter, a smack owner from Brixham in the south of England, believed that trawling could damage fisheries within the bays but that other modes of fishing were also responsible for declines,

"There is a great decrease in flatfish and soles. [...] My conviction is that it is owing to fishing in the shallow waters in the bays within the headlands, and also using the drag seines."

J. Couch, a resident of Polperro (southwest England) who had an interest in the fisheries, summed up the local importance of trawlers in maintaining supplies of fish, *"I think that the trawling has now become far too wide an interest to be interfered with unnecessarily. They catch an abundance of fish which no one else would catch; they therefore form a very valuable interest, and one which ought to be supported. The trawl boats likewise form an excellent school for the training of sailors. Under these circumstances anything that I could say as to imposing restrictions upon their fishing must be taken with the utmost reserve. At the same time I think that if they are prevented from trawling by night it would be satisfactory. [...] They ought not to be allowed to come close in-shore."*

Although the 1863 Commission interviewed fewer trawlers in the south (n = 15), those that were consulted were not defensive about their occupation as few people appeared to completely oppose trawling. Rather trawl fishers were more negative about seine nets in the estuaries or trawling close inshore in fish nursery grounds. Many pot or line fishers were negative about the effects of trawling upon some fisheries, but in being so did not show the same vehemence that a number of northeast fishermen did. However, the triggers for negative perceptions were similar on both coastlines (Figure 21). The major reasons stated were destruction of small fish and spawn or wasteful destruction of adult fish. Damage to the seabed or associated habitats were rarely mentioned, but the loss of pots, lines and nets by trawling was of much concern.

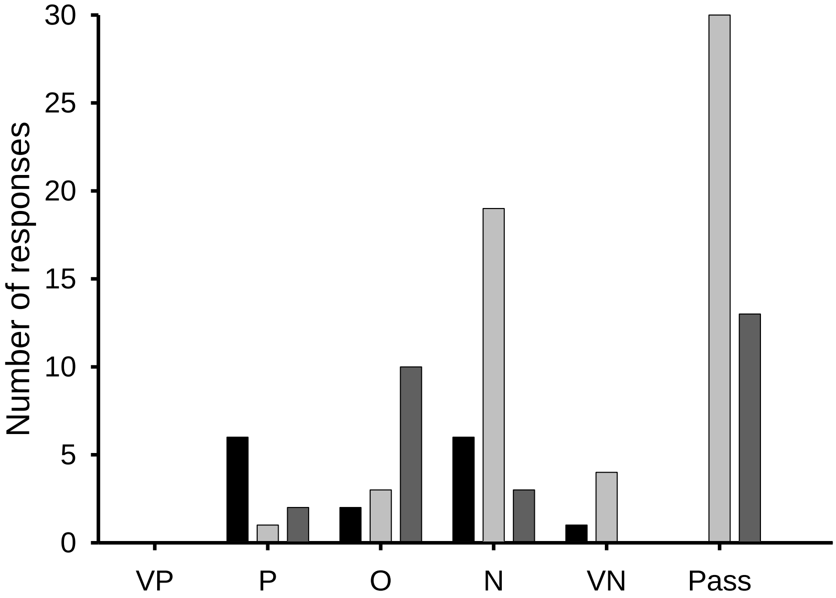

Figure 20. Perception of trawling from witnesses interviewed in the southwest of England (1866 enquiry) (n = 100). Reponses were classified according to the Likert scale (VP = very positive, P = positive, O = neutral, N = negative, VN = very negative, Pass = trawling not mentioned). Black bars = trawlers, light grey bars = other fisher, dark grey bars = non-fishers.

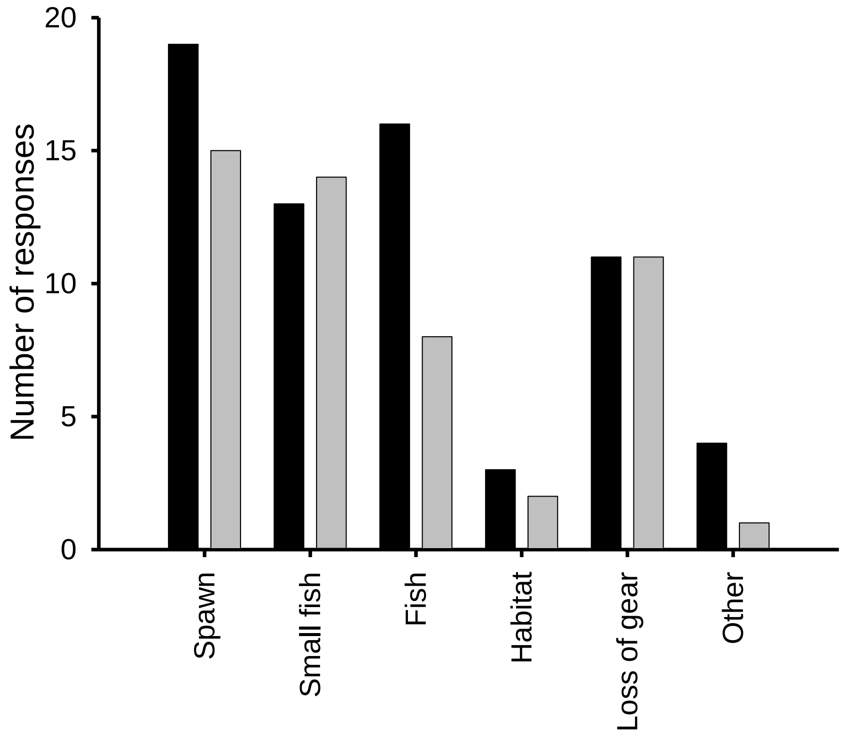

Figure 21. Triggers for negative perceptions of trawling in the northeast (black bars) and southwest (grey bars) of England (1866 enquiry) (n = 117).

By the 1880s, sail and small steam trawlers had reached the east coast of Scotland (Figure 22, n = 127). This led to a similar outcry to the one 20 years earlier on the northeast coast of England. Few trawlermen were interviewed in the 1885 enquiry (n = 17), but the majority of other fishers had a negative view of trawling.

"Of course I would recommend the abolition of the trawling altogether. My idea is that their system of trawling is a system of extermination [for the fish]." W. Thomson, line fisher from Buckhaven.

"We fishermen have got good ground to complain that our industry will be almost entirely destroyed unless the trawling system be put a stop to, or if that be unattainable let the trawlers go off to the deep sea." R. Smith, line and net fisher from Dunbar.

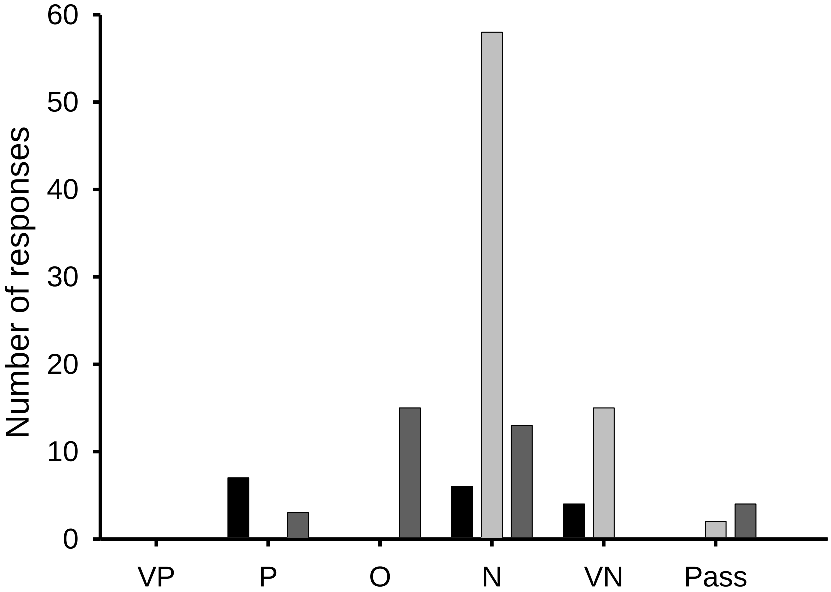

Figure 22. Perceptions of trawling in Scotland (1885 enquiry) (n = 127). Reponses were classified according to the Likert scale (VP = very positive, P = positive, O = neutral, N = negative, VN = very negative, Pass = trawling not mentioned). Black bars = trawlers, light grey bars = other fisher, dark grey bars = non-fishers.

From the northeast coast of England, more trawlers than other fishers were interviewed and therefore views on trawling tended to be more positive (Figure 23). During this enquiry it was noticeable that non-trawl fishers, whilst being very negative about sail and steam trawling, appeared to admit that trawling would never be erased. So instead of calling for it to be stopped completely the majority requested that a limit be put on trawling inshore. This same request also came from a number of trawl owners who were aware of falling catches in traditional fishing grounds, particularly of flat fish, and who believed a limit should be put on trawling along the shores to protect breeding grounds within the 3 mile limit of territorial seas.

"This decrease I attribute to trawling as carried on within these territorial waters and within the rivers and bays. I am of opinion that trawling of all kinds

within those limits should be put a stop to entirely. I am also of opinion that the practise of steam trawling within the territorial limits has contributed to the deficiency of the supply of fish [...]. I think that the best legislative remedy would be the prevention of such trawling by an Act of Parliament stopping all trawling within a limit of three miles. I should, were it not for the difficulties in the way, prefer a limit of 10 miles". W.L. Robins, trawl owner from Hull.

"...where scientific men determine that there are breeding grounds, or nurseries as we might term them, I think it might be judicious to limit the trawling operations." J. Alward, trawl owner from Grimsby.

This shows a distinct shift in attitude since the previous enquiry, particularly among trawl owners. Some line fishers were still adamant that little fishing would exist in future years should trawlers continue to fish, but the majority in the fishing industry were of the opinion that trawling was here to stay. However, the realisation that trawling could affect fish stocks and their habitats was increasingly accepted, including by some who had long-term vested interests in trawling.

"Some years ago our vessels caught an immense number of dogfish, enough to fill a trawl in one haul; when caught they contained herring, showing what food they got; few dogfish are caught now, our vessels having destroyed so many." A.W. Ansell, trawl owner from Hull.

"I am directly opposed to trawling within the territorial waters, and I am convinced that if such trawling were prohibited in a very short time the supply of fish would increase, and that a plentiful supply could be caught nearer home." P. Bates, trawl owner from Hull.

"The southern part of the North Sea is fished out in my opinion." M. Peaker, trawl owner from Hull.

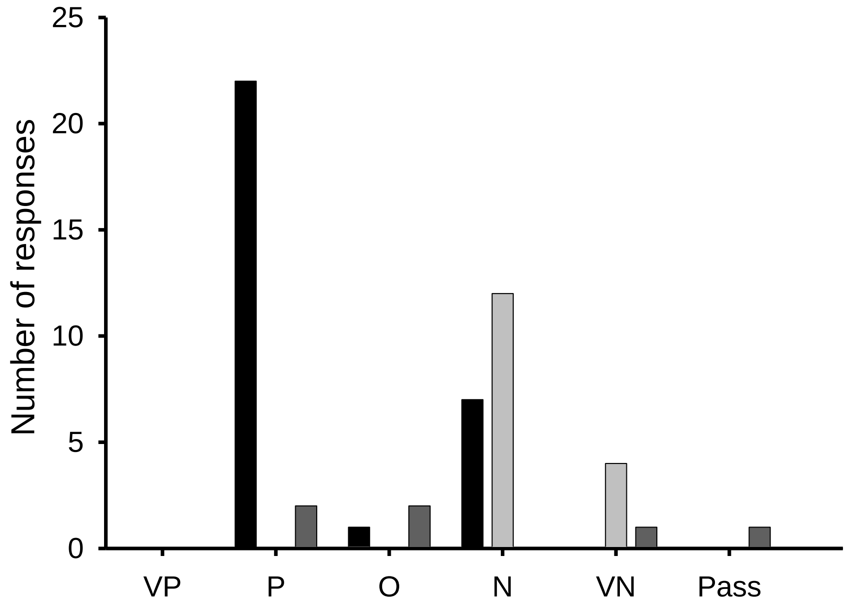

Figure 23. Perceptions of trawling in the northeast of England (1885 enquiry) (n = 52). Reponses were classified according to the Likert scale (VP = very positive, P = positive, O = neutral, N = negative, VN = very negative, Pass = trawling not mentioned). Black bars = trawlers, light grey bars = other fisher, dark grey bars = non-fishers.

Figure 24 shows that the reasons for witnesses’ negativity in east Scotland and Northeast England during the 1885 enquiry did not differ from the previous enquiry. Despite scientific advances that provided evidence that the spawn of many demersal fish species floated on the surface of the sea, many fishers were unaware of this and continued to insist that spawn was damaged by trawlers. Destruction of small fish was a common trigger for complaint, and damage to seabed habitats or food beds was acknowledged by more witnesses (n = 75).

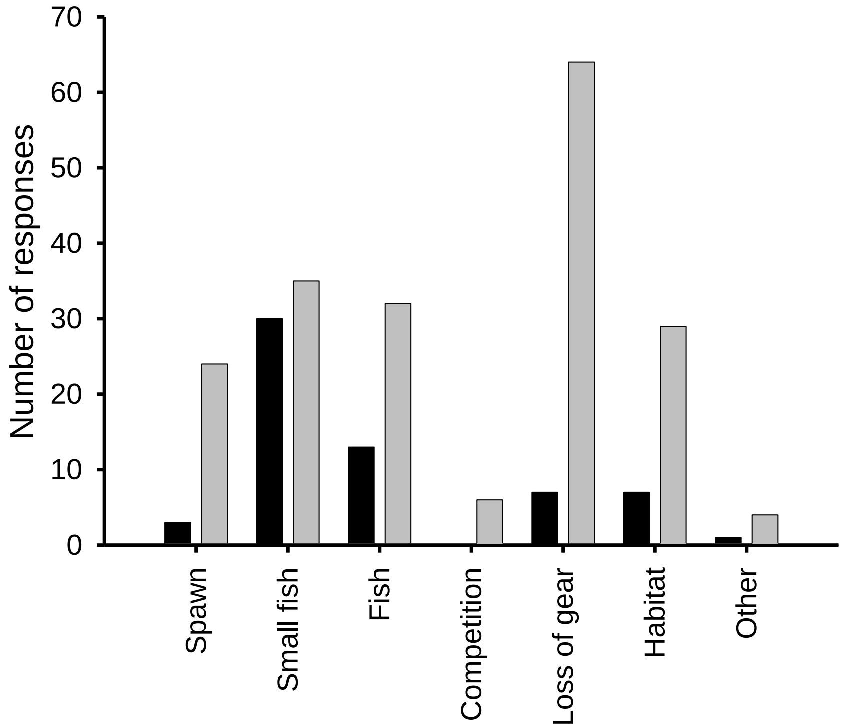

Figure 24. Triggers for negative perceptions of trawling in the northeast of England (black bars) and east of Scotland (grey bars) (1885 enquiry) (n = 75).

2.6.1 Summary

Trawling created great controversy when it first appeared and this did not die away as people became used to the presence of trawlers. During the 1866 enquiry, all fishers believed that fish spawn attached to the seabed. In addition, many of the seabed life forms were like nothing upon land, hence most fishers called all forms of life upon the seabed 'spawn'. Although trawlers may not have been destructive to fish spawn as fishers believed, the 'spawn' that some witnesses claimed to see on trawl nets when they were hauled showed that this technology was having an impact upon habitats.

2.7 WHAT WERE THE FIRST SIGNS OF FISHING IMPACT ON HABITATS?

It is generally agreed that impacts from trawling escalated greatly after the introduction of steam power (Roberts 2007). However, sail trawlers were not entirely benign and had almost certainly affected habitats in similar ways to steam trawlers. During the 1866 enquiry, trawling in the northeast of England was relatively recent, with the impact of the trawl being felt upon many seabed habitats for the first time. Whilst it is difficult to quantify the effects of trawling upon habitats, qualitative statements exist which serve to build up a picture of the vast changes trawl gear had made upon pristine habitat. In this section I catalogue statements that describe effects of trawling upon seabed habitats.

During the 1866 enquiry, some fishers, particularly trawlers defended the action of the trawl by comparing it to farming,

"…the oftener the smacks and the trawls go there the more fish they get. And for this reason; we compare the fish in the sea with the birds in the air, the farmer in the field with the fisherman in the sea. The farmer in the field ploughs the ground, and the birds in the air follow after to pick up the worms, and we can say safely too that wherever we go with our trawls we plough the ground at the bottom of the sea." W. Bartlett, trawl fisher from Hartlepool.

"I think that the ground being disturbed by the trawling vessels has given us leagues of ground to fish on where we had only miles before." J. Hill, line fisher and ex-trawler from Hull.

Others believed that food turned up by trawlers such as worms provided feeding for commercial fish, thereby improving the fishery,

"I think it [trawling] has increased it [quantity of fish], because the foot-rope is constantly stirring up the bottom and supplying the fish by that means with food.

The fish will be behind picking up the food as we stir it up." J. Clements, trawl fisher from Sunderland.

"...I think trawl-fishing does us good. […] The trawl as it goes over the ground disturbs it, and things come up so that the cods can follow and obtain good food." B. Bulpit, line fisher and ex-trawler from Grimsby.

However, many fishers interviewed had a negative perception of the trawl, and did not see its action as 'ploughing' the ground. Most fishers believed that trawlers did most damage by destroying eggs and spawn of the fish,

"This ground-rope weighing with the pair of irons to keep it down 250 lbs is dragged over the ground; it goes over the ground at the rate of a tide, and for 20 miles it will scour the ground wherever it goes, and that, in my opinion, is where the destruction is caused. It destroys all the eggs." T. Hodder, trawl fisher from Brixham.

"The trawls are like so many harrows going over the ground tearing up everything; they do twice the harm that any other mode of fishing does; they tear up the ground and do not allow the spawn to be upon it; they harrow it all up." D. MacMillan, net fisher from Campbeltown.

"All I have seen brought up has been a sort of white dirt in the bay that we call "skulch". In Wales, in Carmarthen Bay, we could hardly haul up our trawls for a kind of blubber stuff that they have there. I have seen that brought up, and also a flimsy sort of thing that we shake away, but I have never seen any of what you call real spawn." R. Stibbs, trawl owner from Plymouth.

Other witnesses believed that the destruction reached further than eggs and spawn, and some statements noted the importance of seabed habitat for feeding and aggregation of fish, *"It is generally thought that young fish in large multitudes are upon the ground when the trawls are principally in action. They are accustomed to go in towards the land from long distances to places where there are a considerable number of flexible corallines to be found. In such places as that the fish I refer to seek to deposit their spawn. It is, therefore, not simply the young fish which are destroyed, but that which attracts the fish to the spawning ground is also destroyed."* J. Couch, resident of Polperro.

"I believe that the trawlers destroy the food of the fish. I consider the bottom of the sea as a sort of forest, full of crustacea of different sorts which supply food for the fish. There are two sorts of crustacea, one the stalk-eyed and the other the sessile-eyed, and they are to be found among the coralline sponges. The fish have been in the habit of coming in to the shore to feed upon these beds, which were almost like a forest of well-cultivated ground. The trawlers, however, have almost entirely destroyed these grounds, and as the fish can no longer find food when they come in they have ceased to frequent the shore." W. Laughrin, fisher from Polperro.

"They [trawlers] take away the shells too and the wood and other things to which spawn might adhere, and the consequence is that all the beds have been spoilt, and will remain so for a few years to come." A. Welch, fish curer from Anstruther.

"They break the coral beds where the cod and herring go to spawn. They break it all up and tear it away." R. Quirk, net/line fisher from Peel.

"The net drawn along the bottom of the sea is pretty heavy in itself, but in order to save it, they attach aprons to it, and make it twice as heavy again. The sand being volatile, these nets harrow into it, and they tear up the spawn, and crush it so much that it never can come to maturity. They crush the spat and spawn of the crustaceous fish, such as shrimps, crayfish, and whelks; very large whelks, horse-cockles, and all kinds of shell-fish of that description are destroyed by

them. I may say that beds over which the trawl-nets are used are alive with animalcule, which is the reason why the fish resort there. [...] I think that the whole of these spawning grounds have been destroyed, and that by degrees the fish are becoming extinct on the coast." W. Brabazon, amateur fisher and ex-trawler from Howth.

Some of the statements made show the extent of destruction of the trawl even before the introduction of steam,

"...I have been towing astern of a trawler when the nets have been pulled up, and I have observed the spawn come up in the nets. I have seen the nets almost full of spawn, some of it a dark red colour, some of it a pale red, some of it blue, and part of it a salmony-coloured red. [...] They told me that their trawl net went over and destroyed the spawn; of course, there must be millions of fish destroyed. [...] I think it is quite as possible for an aerial machine to be passed over Great Britain, and to drag all over the land without doing injury, as for these trawlers to continue their fishing on the northeast coast without destroying the fish." R. Blair, sea pilot from Cullercoats.

"We call [them] "teats" or "thumbs". It is a kind of weed that grows at the bottom of the sea, but I believe it is of a living nature. It would be about the size of your fist [...]. It is full of holes. It is full of nothing but water. We catch many tons of that during the year." H. Roberts, trawl fisher from Sunderland.

"I have caught immense quantities of spawn like candles. [...] there is another kind of spawn like feathers." S. Mitchell, master pilot acquainted with trawling from Dunmore.

"In regard to spawn, [...] I have been taking spawn of different kinds out of my nets often [...]. Some of it had a red cast and some a white cast and some a yellowish cast [...]. Some were the length of my arm, [...] and sometimes you would see the fish alive in it." W. Hearn, trawler from Dunmore.

The descriptions of the life brought up during this time (when many areas on the northeast coast of England were being trawled for the first time), provides a vivid illustration of the initial damage caused.

Fishers' beliefs that fish spawn adhered to the seabed was still strong during the 1885 enquiry, as scientific advances had not filtered through to the majority of the fishing community. This did not help their standing with the Royal Commission of 1885, who were aware of recent scientific investigations that concluded that most fish spawn floated upon the sea surface. However most fishers refused to believe that the substances found upon the seabed could be anything other than spawn.

By 1885, small steam trawlers had appeared in some areas of the coast, but sail trawlers still dominated. However, as described earlier, in Scotland any kind of trawling was relatively new, so similar sentiments to those uttered 20 years before in the northeast of England were prevalent,

"They trawl along the bottom and tear everything that is before them." J. MacDonald, line fisher from Golspie.

"I believe there is not a portion of the ground but what the trawl destroys. […] I have dragged 50 miles off Aberdeen. I have got fast there, and brought up coral about 2.5 feet in circumference, lumps of soft coral, and I am prepared to say that whatever is in the way of the beam trawler will not escape." G. Cormack, ex trawler from Torry.

"In two years, if trawling goes on, there will not be a fisherman in Scotland.[…] They must go to poverty, owing to that great ponderous thing going through the sea, killing more than it catches, like a scavenger on the streets sweeping everything before it." G. Caie, line/net fisher from Cove.

"I do not think it would be a great hardship to put them [trawlers] three miles off. […] Then I would give them every freedom there, and not stop them at night that they catch most fish. It is very essential to keep certain ground for spawning undisturbed for the propagation of fish. I cannot but believe that these heavy beam trawlers scraping over the ground injure the fish before they come to maturity. If you sow a field with corn and harrow it every day, the corn will not thrive, and I cannot see, if these heavy beam trawls scrape over the ground every day, that the fish can thrive either." G. Davidson, steam trawl owner, ex-line fisher from Aberdeen.

"…in three weeks time we had that spot of ground raken and torn up and in such a condition that we had every fish off it. I believe it was as bare as the council chamber. I believe there was nothing escaped. I have seen as high as three and four cartloads of ground in the trawl. [...] Horse bait, and stones, and shells, and clams." J.W. Driver, ex-trawler from Newhaven.

"The crust is all gone. [...] The ground that the scallops live amongst. It is just a ground made up of broken shells, and all the like of these sorts of things; and underneath that is mud." W. Hunnam, line fisher from Cockenzie.

"…the ground abounded with small shell fish, particularly the cray fish, which is the chief food of large fish. […] Now the ground is cleaned of this sort of shellfish by trawling, and now we have no large fish, because their food is all taken away. […] I say the more undisturbed the ground is, the more plentiful the fish will be." J. Murray, line/net fisher from North Berwick.

"…the destruction of the ground, that is, by the destruction of the herbage of the sea; the zoophytes and the plants at the bottom of the sea." J.J. Hills, Secretary of the Sunderland Sea Fishery Protection Committee.

Despite the trawl being a regular feature throughout much of the northeast of England by 1885, some fishers still remembered times before the trawl, *"[50 years ago] we used to go to the back of west rock, that is abreast of Filey, very often, and at that time we could not trawl more than an hour and a half or two hours in consequence of the shells, what we call the clam shells, some dead ones and others alive. Those dead shells had at that time white and brown thusks in them, and all among these shells the soles inhabited; and we by this small beam net, which was not more than 17 feet, and in a coble could get 40 and 50 pair of soles in a tide. We were compelled to haul in, because the net being so light, these shells used to cut the net. We were therefore compelled to haul in by the time we had been trawling an hour and a half or so; if not the net would have torn with these shells. Well now, you could take the same coble, the same net, the same everything, and trawl over the same ground and where there are no shells, and I would think we would not get five pair of soles in a tide. [...] They have trawled it [the shell fish] away and trawled it up."* W. Appleby, line fisher and ex-trawler from Scarborough.

Others replied that the trawl caused more damage than to just take up small fish,

"If you tear a man's house down, there is no place for him to live in." D. Cole, line/net fisher from Staithes.

"Well, I believe the places where there was rough ground were the places that the fish went to dwell on. Where it is all torn up, there cannot be any food for the fish to resort to." J. Owston, line/net fisher from Scarborough.

However there was also enthusiastic support from those who depended upon trawling,

"There is nothing [brought up in a trawl] that is not marketable, except perhaps those sea anemones of which we sometimes bring up a quantity." W. Brantingham, trawl owner from Sunderland.

"As the crow follows the plough for the worm, so the stirring of the ground brought the fish, and made our fishing ground really prolific, a beautiful provision of nature." J. Bartlett, chairman of the local fishery board, Brixham.

Whilst the strongest criticisms against trawling were uttered by witnesses from areas where the trawl was relatively new, the following quotes by Bellamy (1843) (a Victorian author on natural history) show that even on the south coast where trawling was well established, some people were of the opinion that it could cause significant damage,

"... the employment of the Trawl, however, during a long series of years, must assuredly act with the greatest prejudice towards these races [of fish]. Dragged along with force over considerable areas of marine bottom, it tears away promiscuously hosts of the inferior beings there resident, besides bringing destruction on multitudes of smaller fishes, the whole of which, be it observed, are the appointed diet of those edible species sought after as human food. It also disturbs and drags forth the masses of deposited ova of various species. An interference with the economical arrangement of Creation, of such magnitude, and of such long duration, will hereafter bring its fruits in a perceptible diminution of those articles of consumption for which we at present seem to have so great necessity." (Bellamy 1843)

"We are far too prone to regard the sea in the light of a wilderness of produce, a sort of chaos, where multitudes of creatures exist confusedly, and without ordained purpose or relation to others; such a conclusion is palpably erroneous, and, is at variance with all analogy in nature. How unjust in every sense, then, is the reckless destruction of countless young fishes, heaps of ova, and immense multitudes of inferior grades of animals, the residents of its beds!" (Bellamy 1843)

2.7.1 Summary

Recent research on the ability of habitats to recover from trawling activity has taken place. For example, Hall-Spencer and Moore (2000) showed that unfished maerl beds that were subsequently trawled failed to recover after four years of monitoring, whilst Collie et al. (2000) found that fauna in more stable sediments are more adversely affected by trawling and dredging that those in unstable sediments. However, gaps in our knowledge remain on the long-term effects of trawling and dredging upon habitats. The quotes in the previous section show that during the 19th century the extent of trawling impacts upon seabed was widespread in inshore areas, affecting shell and coral habitats, as well as more muddy areas. These impacts were severe and appear to have taken place within a short period of time.

2.8 DISCUSSION

The Royal Commissions of 1866 and 1885 took place at times of great change in the fishing industry. The 1860s saw the opening up of coastal towns to inland markets via the national rail network. The 1880s heralded the arrival of the steam trawler and the beginning of industrial fishing. Prior to this time few records or statistical tables exist to enable us to piece together the changes that took place as trawling expanded around the British Isles. The Royal Commissions of Enquiry contain invaluable information on fisheries during this period.

The 1866 enquiry concluded that fish supplies were increasing throughout the British Isles and that trawling should be encouraged. Whilst some rules and regulations did exist prior to the enquiry these were outdated, inadequate and largely unknown or ignored by fishers (Royal Commission 1866). By the 1860s, the trawl fishing industry was experiencing unprecedented growth. The whole of the North Sea had not yet been explored and opportunities seemed endless. The Commissioners attributed declines described in witness statements to exaggeration or a glorified view of the past. Whilst this may have been true for some witnesses, it does appear that negative views of trawling were not taken seriously by the Commissioners. However, by the time of the 1885 enquiry a number of trawl owners, some of whom had kept their own detailed records of landings, as well as line and net fishers were convinced that inshore fisheries were in decline as a result of overexploitation. The stories of decline could be ignored no longer, and the Commissioners of 1885 were more willing than their predecessors to accept that exhaustion of fishing grounds could occur,

"As regards actual exhaustion [of fishing grounds], continuous fishing with such an effective implement as the beam trawl, within a limited area, may sensibly diminish the quantity of fish. This is especially likely to happen in narrow waters, and we believe that in several instances it actually has happened."

However they were less sure of the injury done to habitats and invertebrates by the trawl. Because of a lack of direct evidence, they commissioned Professor McIntosh, an esteemed fisheries scientist of the time, to conduct trawling experiments off the east coast of Scotland (Royal Commission 1885). His results are recorded in the appendices of the Royal Commission (1885),

"The effect of the trawl on the bottom fauna of the [Firth of] Forth [...] appears to be as follows. – The sponges and hydroid zoophytes seem to suffer little. The ground rope sweeps through the coralline forests, picking off here and there a tuft of Hydrallmania *or other zoophyte attached to a yielding surface, or which is comparatively free (e.g., attached to a shell.). Generally, however, zoophytes grow rapidly, so that even though extensive injury were done to any submarine surface in this respect the loss would be rapidly repaired [...]. To sum up, therefore, a certain amount of damage is inflicted by the trawl on the invertebrate inhabitants of the fishing banks, but the nature of the fauna and their surroundings is such that this injury occurs rather in the net and on the deck of the vessel than on the sea bed. No evidence has been obtained that fishes will not frequent a bank that has been trawled over.*

Whilst McIntosh admitted that some damage to seabed inhabitants occurred, his conclusions probably underestimated the extent of the damage. His report describes an abundance of species such as echinoderms, starfish, anemones, hydroids, horse mussels and crustaceans brought up in the trawl, many of which were thrown back overboard. Yet he did not account for delayed mortality as a result of crushing in the net or being thrown back onto unsuitable ground. He also did not take into account animals left injured or killed in the path of the trawl but which were not brought up in the nets and hence were not recorded. In addition, McIntosh trawled in areas that were worked fishing grounds and as such would have been trawled over previously and sustained the greatest damage prior to the investigation.

Upon the testimony of witnesses and scientific evidence, the Commissioners of 1885 concluded,

"Without accurate statistical information extending over many years it is impossible to form any satisfactory conclusion [...]. We are, therefore, unable to come to the conclusion that trawling is the sole cause of the decrease of fish in inshore waters. In so far as it may contribute to that decrease, we think it can only be as part of a system of over-fishing, and not because of any wasteful destruction of spawn, fish-food, or immature fish."

In addition they championed the need for scientific research into the effect of trawling,

"It has been frequently urged upon us by witnesses that trawling should be prohibited within territorial waters. But we do not consider that we should be justified in making such a sweeping recommendation [...]. In recommending, however, that experiments should be made to test the effect of trawling, it is obvious, as we have already pointed out, that, if they are to be successfully carried on, power must be given to the authorities superintending them to

prohibit trawling or any form of fishing in certain places for such time as may be necessary."

Despite these more promising conclusions, the Commissioners still failed to appreciate the extent of habitat alteration that could be achieved by trawling or the importance of protecting species other than food-fish. However, a direct result of this Commission was that national fisheries statistics began to be collected.

2.8.1 Conclusion

Fisheries regulations implemented since the time of these Commission reports have continued to be single-species orientated and have rarely taken conservation of non-commercial species or habitats into account (Roberts 2007). This research shows that destruction of seabed habitats and declines of inshore fish populations took place long before collection of fisheries statistics commenced and even longer before regular scientific monitoring began. Had the complaints of inshore fishers been acknowledged more fully during the 1866 Royal Commission, perhaps more appropriate management and restriction of trawling activities may have occurred. However, by the 1860s trawling was highly profitable, and the warning signs recorded in these testimonies were overlooked by the Commissioners.

From the analyses of these Commissions of Enquiry, it seems clear that Thomas Huxley and his fellow Commissioners would have reached different conclusions on the potential for overfishing had they looked further than the subjective views of fishers and seen the wider picture these testimonies reveal. Had they taken steps to manage fisheries with caution and as part of a wider, integrated ecosystem, the history of fishing may have been rather different.

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Chapter 3: The effects of 118 years of industrial fishing on UK bottom trawl fisheries

3.1 PREFACE

After the Royal Commission of Enquiry of 1885 sea fisheries statistics began to be collected at a national level, along with numbers and types of vessels a few years later. From the mid 19th century the sail trawler had dominated demersal fish catches, but by the 1880s the steam engine had been adopted by a number of trawlers and was to change the face of fishing.

The increasing adoption of steam power by fishing boats during the 1880s meant that vessels were able to fish for longer periods of time and further offshore where higher abundances of fish could be found (Robinson 2000). Areas that had previously been off limits to sail trawlers because of their distance from shore or greater depth were opened up for exploitation because of the increased power of steam vessels.

To comprehend what changes industrial fishing has caused we must reach back in time using available statistics and anecdotal evidence to build up a picture of change. Throughout the UK, the documentation of landings data into ports has occurred since the 1880s, yet these important data sets have not been fully explored.

In this chapter, I create an index of fish availability of demersal fish populations at the onset of industrial trawling and describe how this availability has altered during the last 118 years of exploitation. I demonstrate that many fisheries were in decline long before regular scientific surveys began and that marine and fisheries managers must take historical datasets into account if they are to successfully improve biodiversity and long-term sustainability of the seas.

This paper is written in the style of the journal Nature Communications where it was published on 04/05/2010. The paper can be found at http://www.nature.com/ncomms/journal/v1/n2/full/ncomms1013.html

I declare that the work submitted is my own. Author contributions are detailed at the end of the manuscript.

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The effects of 118 years of industrial fishing on UK bottom trawl fisheries

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Abstract

In 2009 the European Commission estimated that 88% of monitored marine fish stocks were overfished, based on data that go back 20 to 40 years and depending on the species investigated. However, commercial sea fishing goes back centuries, calling into question the validity of management conclusions drawn from recent data. We compiled statistics of annual demersal fish landings from bottom trawl catches landing in England and Wales dating back to 1889, using previously neglected UK Government data. We then corrected the figures for increases in fishing power over time and a recent shift in the proportion of fish landed abroad to estimate the change in landings per unit of fishing power (LPUP), a measure of the commercial productivity of fisheries. LPUP fell by 94% –17-fold– over the last 118 years. This implies an extraordinary decline in the availability of bottom-living fish and a profound reorganisation of seabed ecosystems since the 19th century industrialisation of fishing.

Introduction

Most assessments of fish stocks do not take long-term historical data into account[1], yet commercial sea fishing has occurred for hundreds of years[2]. The first reference to bottom trawling anywhere in the world, the main method of catching bottom-living fish today, was in 1376[3]. Until the early 19th century, bottom trawlers were sail powered and fished close to ports. However, the development of railways from the 1830s onwards increased demand for fish from inland urban populations, and bottom trawling quickly became more widespread[4].

The development of steam trawlers in the 1880s marked the beginning of a rapid expansion of fishing effort that continued until the late 20th century[5]. Steam power enabled vessels to fish further offshore, for longer, with larger gear which could reach deeper[5]. In the UK, steam trawlers competed for fish with line fishers and trawling became highly controversial, leading to a government inquiry in 1885 to examine claims of falling fish stocks and habitat damage[6]. The enquiry failed to reach any firm conclusions because of the absence of fishery statistics. It recommended that catch data should be collected, and from 1889 fishery statistics were gathered for all the major ports of England and Wales. These data provide invaluable, but until now neglected, information on fish landings and fleet composition that enable us to reconstruct the changing fortunes of the industry since the late 19th century.

Previous studies have estimated long-term changes in fish stocks in the North Atlantic. Christensen et al.[7] used trophic balanced models to estimate past biomass of predatory fishes. Their data suggested that predatory fish had declined by 90% since 1900. Myers and Worm[8] used different datasets to arrive at a similar conclusion, that global predatory fish biomass today is only about 10% of pre-industrial levels. Another approach by Jennings and Blanchard[9] used macroecological theory to predict the abundance and size-structure of unexploited fish communities in the North Atlantic and North Sea. Their study suggested that the current biomass of large fishes in the North Sea weighing 4-16kg and 16-66kg, respectively, is 97.4% and 99.2% lower than it would be if no fishing had occurred. Rosenberg et al.[10] used historical fishing records to model past cod biomass on Canada's Scotian Shelf and estimated that the cod population had been reduced by 96% since 1852 as a result of intensive fishing. Rose[11] modelled past Newfoundland cod biomass back to 1505 using a combination of reconstructed landings, cod biology and climate records. His model demonstrated that whilst stocks had declined and rebounded in the past as a result of changing climatic conditions, intensive fishing led to collapses in the late 20th century. Rose estimated that, by 1992, only one-third of one per cent of the original Newfoundland cod population remained[11].

UK Government data enable us to trace the extent and pattern of decline, in unprecedented detail, for an entire, mixed species fishery covering a wide range of bottom-living species. The northeast Atlantic fishing grounds exploited by the UK fleet represent one of the most productive and intensively exploited in the world, and to our knowledge, the data represent the longest continuous national scale fisheries statistics. These empirical data offer the opportunity to explore the validity and generality of inferences from theoretical, modelling, and single species studies. They reveal the effects of the bottom trawl fishery on populations, and the way in which the fleet adapted to declines over the last 118 years by making technological advances and shifting to different fishing grounds. We show how the crash in north-east Atlantic bottom fisheries pre-dates the Common Fisheries Policy, the usual scapegoat for fisheries mismanagement and decline in Europe.

Results

Data collection. We compiled data on demersal (i.e. bottom-living species such as cod, haddock and plaice) fish landings into England and Wales and the UK overall (excluding shellfish) from 1889-2007. Figure 1a shows a rapid rise in total landings from the late 19th century to the mid-20th century corresponding to growth of the fleet, technological advance and expansion to new grounds. The increase was punctuated by abrupt falls during the two world wars when fishing became too dangerous and vessels were put to other uses[2]. After World War II, landings went into long-term decline, despite heavy investment in the fleet.

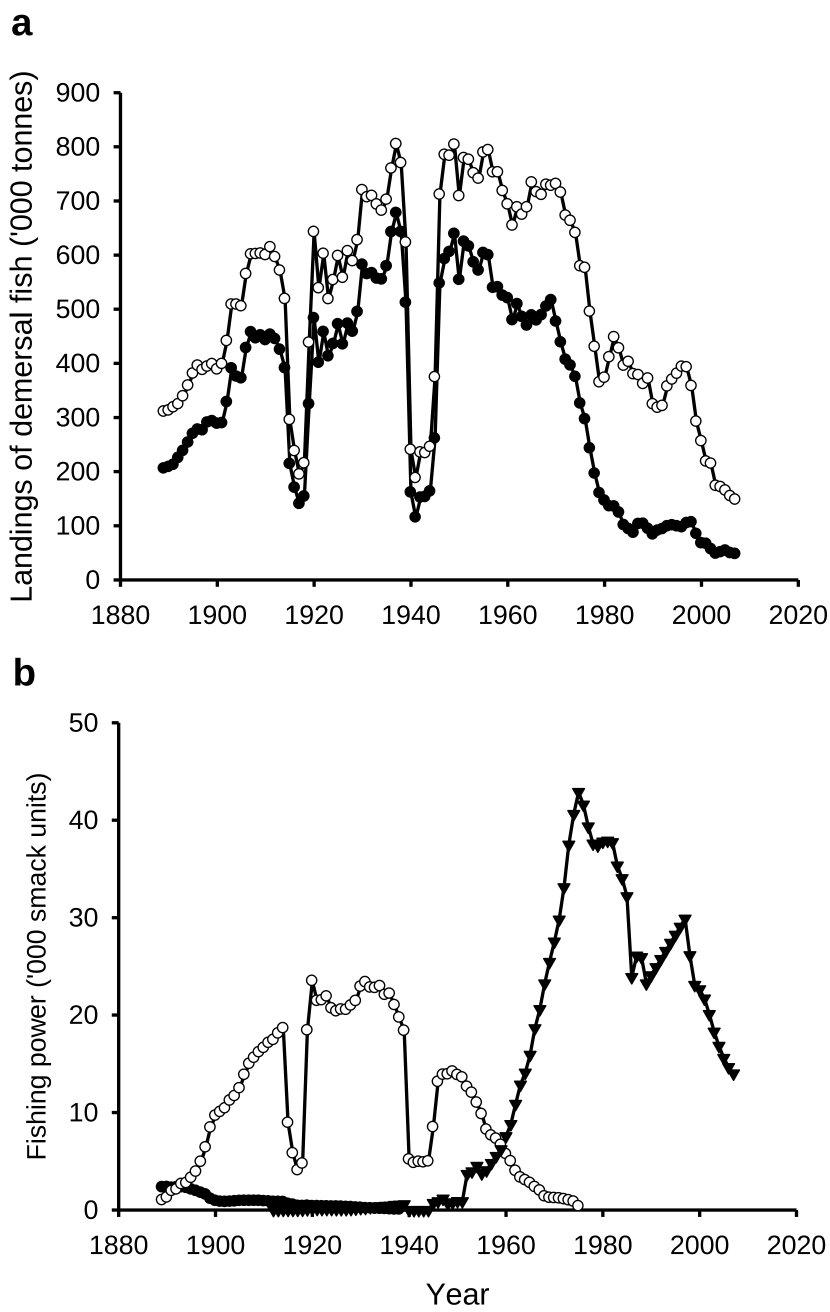

Figure 1a: Total landings of bottom-living fish species. Landings into England and Wales (closed circles) and UK (open circles) by British vessels from 1889 to 2007.

Figure 1b: Estimated total fishing power of large British trawlers registered to England and Wales from 1889 to 2007. Closed circles indicate sail trawlers, open circles steam trawlers and closed triangles motor trawlers.

Changes in fishing power. There have clearly been vast changes to landings within British fisheries since records began in 1889, but how much are declines due to overexploitation? Landings are a product of fish availability, fishing effort and regulations on catches. Improvements in technology and migration to new fishing grounds can keep landings high even as stocks decline. By contrast, reduced fishing effort may lead to a fall in landings that does not reflect a decline in wild fish populations. To determine underlying trends in fish availability, we indexed landings against the changing fishing power of the fleet. ‘Fishing power’ is a measure of how fishers increase their catching power over time, for example by improvements in gear, or ability to detect fish (e.g. larger boats and engines, tougher, lighter nets and electronic fish finding gear). This technological creep, as it is called, has to be factored out if one is to produce a reliable, long-term index of change in productivity of the fishery.

To estimate change in fishing power, we extracted data on numbers of large British trawler vessels registered to English and Welsh ports from 1889 to 2007 (data were not available for the UK overall until 1965). ‘Large’ vessels are those recorded as first class vessels in the statistical tables. During 1935 inshore fishing by smaller vessels accounted for only one percent of white fish landings in England and Wales, and in 1955, 97% of the demersal catch was landed by first class (large) vessels. By 1982 the majority of the demersal catch (78%) was still being taken by these vessels[12]. We combined these data with estimates of increases in fishing power of individual vessels since the 1880s[13] to provide a measure of change in the overall fishing power of the English and Welsh registered-fleet. Fishing power is expressed in ‘smack units’, equivalent to the catching power of one sailing trawler in the late 1880s[14].

Figure 1b shows the changing composition of the fleet over time. The sail trawling fleet began with around 2.5 times the overall fishing power of steam trawlers in 1889, but the latter had eclipsed the sail fleet by the beginning of the 20th century. Steam power peaked in the inter-war period, but declined after World War II as diesel engines were adopted. Comparison of Figures 1a and 1b shows that total fishing power continued to climb after World War II and peaked in 1972, well after landings began to fall.

Landings per unit of fishing power. In Figure 2a we divide landings by fishing power to provide a measure of the productivity of fishing from 1889 to 2007.

While not a direct measure of stock size, this index of ‘landings per unit of fishing power’ (LPUP) (closed circles) offers insight into the availability of commercially valuable fish to the fleet. The picture is complicated slightly from the mid-1970s when landings limits for some species began to be introduced. In 1983 the European Common Fisheries Policy was formally enacted introducing a system for setting total allowable catches among member states[15]. However, by this time, Figure 2a shows, most of the decline in fisheries had already played out.

Since the onset of the Common Fisheries Policy, a growing proportion of catches by the English and Welsh fleets has been landed into mainland Europe (6% in 1988 rising to 34% in 2007). We corrected Figure 2a for this shift using data from UK Sea Fisheries Statistical Tables, so the curve better reflects fish availability. Comparable fishery statistics for Scotland were only available for 1924 onwards. However, they show a nearly identical pattern to those of the English and Welsh fleets over the same period (Figure 2b).

From 1924 until 1982, government statistics also report landings per 100 hours of fishing by large trawlers (the time trawls were in the water). Figure 2a (open circles) shows that this more direct measure of landings per unit effort closely matches the trend in landings per unit power and suggests that the latter is a reliable indicator of fish availability. In addition, more comprehensive data on changes to fishing power during the late 19th century were collected by Garstang, which closely match our results for the early part of the time-series. As early as 1900, Garstang demonstrated that although landings of fish into England and Wales had increased in the preceding decade, this was because of technological advances and growth in fleet size (Figure 1b). When the latter were accounted for, he showed that landings per unit of fishing power fell by around 39% in the last 10 years of the 19th century. Garstang was able to collect more comprehensive data by collaborating directly with smack owners of the time and by including liner vessels in his analysis[14].

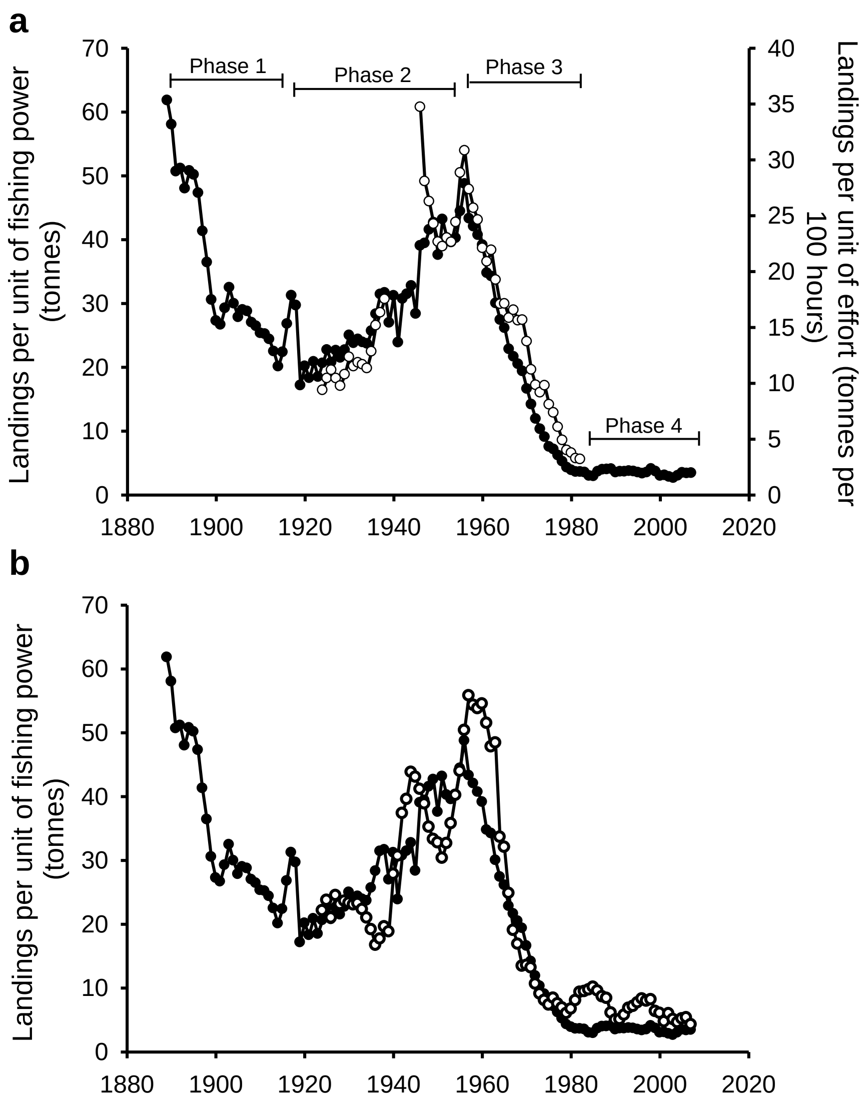

Figure 2a: Landings of bottom-living fish per unit of fishing power of large British trawlers. Closed circles show landings per unit of fishing power into England and Wales, open circles, landings per unit of fishing effort of large British trawlers (corrected for fishing power) into England and Wales. Figure 2b: Landings of bottom-living fish per unit of fishing power of large British trawlers from England, Wales and Scotland. Closed circles show landings per unit of fishing power into England and Wales, open circles show landings per unit of fishing power into Scotland.

Phases in the fisheries. Figure 2a reveals four phases in the fisheries of England and Wales. Phase 1, from 1889 to the onset of World War I corresponds to the rapid industrialisation and intensification of fishing in home waters. During this period, the fleet was converted from sail to steam power. Landings increased but new technology, more boats and expanded grounds masked a steep decline in fish stocks[14]. Phase 2 covers the interwar years of 1919 to 1939 and saw a second wave of expansion as fishing vessels sought new grounds in the Arctic and West Africa[2]. The exploitation of these unexploited grounds brought an increase in LPUP that lasted until the late 1950s. Phase 3 covers the precipitous collapse in catches between 1956 and 1982 as distant water stocks became fully exploited[2]. Toward the end of this period, there was a sharp contraction in distant water fishing opportunities as Iceland and other nations declared first 50, then 200 nautical mile Exclusive Economic Zones. However, the timing of these moves (late 1960s to late 1970s) indicate that they were a response to declines in fish stocks[5] rather than a cause of the collapse in fish landings experienced by the English and Welsh fleets. Phase 4 began in 1983 with the formal creation of the Common Fisheries Policy. Comparison of Figures 1a and 1b shows that landings into England and Wales were only maintained throughout the 1960s because of an increase in fishing power. A sharp decline in LPUP began in 1957, a decade before the collapse in landings began.

Changes in stock biomass. Regulation of landings under the Common Fisheries Policy from 1983 makes it difficult to discern trends in underlying fish stocks from LPUP data. However, direct estimates of spawning stock biomass (SSB) are available after 1982 for seven principal demersal species that together made up over half of total landings, and show that during the period to 2007, combined stocks around the UK declined by 42.6% (Figure 2c)[16] while LPUP for the same period declined by only 5.0% (Figure 2a). If landings per unit of power had tracked stocks rather than quotas, the measure would have declined by 96.7% since 1889 – a 30-fold decline – rather than 94%. We contend that EU management of fisheries has held up landings in the face of stock decline over this period. Under the Common Fisheries Policy, politicians have, since 1984, routinely set quotas 25-35% higher than levels advised as safe by scientists, thereby propping up landings even as spawning stocks fell[2].

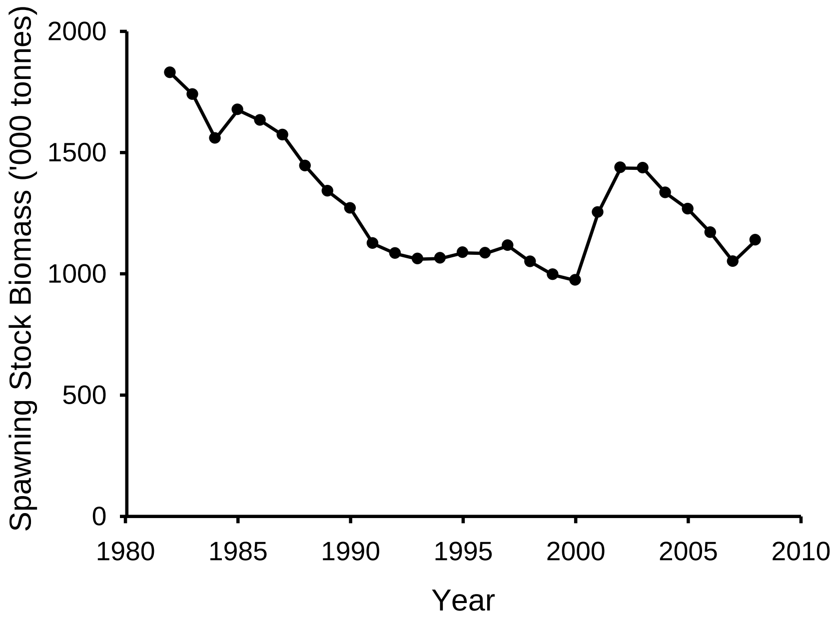

Figure 2c: Spawning stock biomass. Summed spawning stock biomass of species in waters around the UK, where assessments are available (species included were cod, haddock, plaice, sole, whiting, saithe and hake). Spawning stock estimates were taken from ICES sub-areas appropriate to these species and in proximity to the UK, including IIIa (Skagerrak), IV (North Sea), VIa (West of Scotland), VIb (Rockall), VIIa (Irish Sea), VIId-e (English Channel) VIIf-k (Celtic Sea). The hake stock from subareas VIIIa,b was also included.

Other gears used to target bottom-fisheries. Throughout the 118-year time series, trawl vessels were responsible for the majority of demersal landings. In 1935 large trawlers landed 96% of the demersal fish caught by large British fishing vessels using demersal gear, and in 1955 landed 91%. Throughout the 1950s, the Danish seine increased in importance as a demersal gear, but by 1982 large trawlers still landed 74% of the total demersal catch by large vessels[12]. Landings per unit of fishing power were calculated for other vessels (liners and Danish seines) during the years for which disaggregated landings were available (1903-1982) by calculating the average landings per vessel per year, and comparing these to the average landings of a trawl vessel per year to provide a relative unit of fishing power (Figure 3). Landings per unit of fishing power by trawlers alone have previously been shown in Figure 2. However, we found that there was very little difference in overall landings per unit of fishing power during the period 1903-1982 (using trawlers alone, landings per unit of fishing power = 88.9% decline, including all gears, landings per unit of fishing power = 91.0% decline). Since the onset of the Common Fisheries Policy, trawlers have continued to dominate landings.

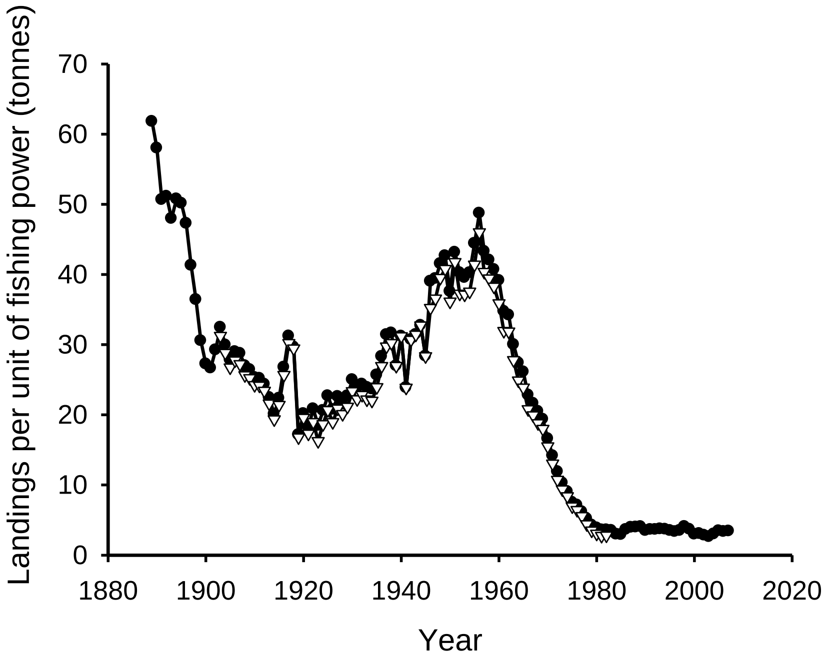

Figure 3: Landings of bottom-living fish per unit of fishing power of all British bottom-gear vessels. Landings per unit of fishing power of large British trawler vessels (closed circles) landing into England and Wales, compared to landings per unit of fishing power of all large bottom-gear vessels (trawlers, liners, Danish seines) (open triangles). There is a close correspondence between patterns of change in landings per unit of fishing effort between the bottom trawl data and the all fishing methods data set.

Data on individual species. Table 1 shows change in catch rates for individual species, with some losses estimated at greater than 99%. Haddock, for example, have declined over 100 times, and halibut by 500 times since records began. These declines are much greater than those suggested by the shorter time series of data used to underpin fisheries management in Europe.

Table 1: Single species landings per unit of fishing power by the English and Welsh trawl fleet.

Species	Early averaged LPUP (t) (SD)	Early LPUP timescale	Latest averaged LPUP (t) (SD)	Latest LPUP timescale	Percent decline
Cod	4.27 (0.350)	1889-1893	0.58 (0.074)	2003-2007	**86.6**
Brill	0.20 (0.010)	1890-1894	0.03 (0.005)	2003-2007	**85.7**
Plaice	8.18 (0.344)	1889-1893	0.23 (0.024)	2003-2007	**97.2**
Skates and rays	1.34 (0.092)	1902-1906	0.22 (0.008)	2003-2007	**83.4**
Turbot	0.21 (0.040)	1903-1907	0.03 (0.003)	2003-2007	**84.8**
Wolffish	0.19 (0.026)	1903-1907	0.01 (0.002)	2001-2005	**95.8**
Conger eel	0.20 (0.021)	1902-1906	0.02 (0.003)	2002-2006	**89.2**
Haddock	20.72 (1.335)	1889-1893	0.19 (0.041)	2003-2007	**99.1**
Hake	1.63 (0.392)	1891-1895	0.07 (0.014)	2003-2007	**95.2**
Halibut	1.03 (0.154)	1890-1894	0.00 (0.000)	2002-2006	**99.8**
Ling	1.17 (0.146)	1889-1893	0.05 (0.009)	2003-2007	**95.7**

Landings per unit of fishing power (LPUP) were averaged for the first and latest five years of the fishery (timescales shown). Landings per unit of fishing power are based upon landings by British vessels (UK vessels after 1990) into England and Wales. Later landings per unit of fishing power were corrected to take account of vessels landing their catch into other countries. SD = standard deviation.

Discussion

Landings per unit power figures suggest that the availability of bottom-living fish to the fleet fell by 94% from 1889 to 2007. This implies a massive loss of biomass of commercially fished bottom-living fish from seas exploited by the UK fleet. The loss is particularly serious as it encompasses an entire component of the marine ecosystem rather than a single species.

The collapse in fisheries productivity is brought into sharp relief by the landings data. In 1889, a largely sail powered fleet landed twice as many fish into the UK than does the present-day fleet of technologically sophisticated vessels. One hundred years ago, in 1910, the fleet landed four times more fish into the UK than it does today. Peak catches came in 1938, when landings were 5.4 times greater than today. The trawl fishery first expanded in southern England in the early 19th century and then spread northward[3]. The decline in landings for English and Welsh fleets is even more stark (Figure 1a) with a decrease of 4.3 times since 1889, 9.3 since 1910 and a peak in 1937 of 14.2 times greater landings than today.

The year 1889 does not represent the onset of fisheries intensification in England and Wales; it simply picks it up from the point when catch statistics become available. As early as 1863, complaints about the declining condition of demersal fish stocks (mainly nearshore) led to a Royal Commission of Enquiry into fisheries.

One complication with using LPUP data as an index of fish availability to the fleet is the problem of discarding, i.e. fish caught but not landed. Whilst the Common Fisheries Policy has been extensively criticised for requirements to discard over-quota species, the issue of discarding commercial and bycatch species has been a concern since trawling began[17-19].

Because of a lack of quantitative information, we were unable to incorporate discard estimates into the dataset. However, because most of the collapse pre-dates the Common Fisheries Policy, any subsequent increases in discarding would have little effect on the overall picture. For example, if an arbitrary increase in discard rate of 50% is included within landings since 1983 to account for regulatory discards, the overall decline of LPUP into England and Wales since 1889 would still be greater than 91%.

Historical data are increasingly recognised as vital to our understanding of long-term human impacts and necessary to provide a baseline measure by which to judge the condition of ecosystems[20-22]. Whilst our data on landings per unit of fishing power do not provide a direct estimate of fish stock decline, they clearly illustrate how the rewards of fishing have fallen since the 1880s. For every unit of fishing power expended today, bottom trawlers land little more than one seventeenth of the catches in the late 19th century. Our results lend strong empirical support to previous inferences on levels of fish population decline from theoretical research[9], single species studies[10,11], and mixtures of model and data[7].

It is clear that seabed ecosystems have undergone a profound reorganisation since the industrialisation of fishing and that commercial stocks of most bottom-living species, which once comprised an important component of marine ecosystems, collapsed long ago. The Common Fisheries Policy was not responsible for this collapse, although under its auspices most stocks have continued to decline. Our findings emphasise the need for urgent action to eliminate overexploitation of European fisheries and rebuild fish stocks to much higher levels of abundance than prevail today.

Methods

Landings data. Data on fish landings and vessel numbers for England and Wales were taken from annual Sea Fisheries Statistics published by the Department for Environment, Food and Rural Affairs, at http://www.mfa.gov.uk/statistics/ukseafish-archive.htm [Marine and Fisheries Agency, 2009]. Data for Scotland were collated from annual Scottish Sea Fisheries Statistical Tables, at http://www.scotland.gov.uk/Topics/Statistics/Browse/Agriculture-Fisheries/PubFisheries [The Scottish Government, 2009].

The data describe landings of bottom-living fish (excluding shellfish) into England and Wales by British-registered vessels from 1889-1989. After 1990 landings are by UK-registered vessels due to changes to the format of the statistical tables. Early landings data were provided in UK hundredweights and have been converted to metric tonnes.

Calculating fishing power. We calculated the fishing power of trawl vessels throughout the 20th century using the 'smack unit' as the baseline unit of fishing power (the fishing power of a typical 1880s sail trawler, or sailing smack as they were then called)[14]. From 1889-1898 fishing power estimates for trawler vessels were taken directly from Garstang's research[14]. From 1889-2007, we used estimates by Engelhard[13] of changes in fishing power for a typical North Sea trawler fishing for cod, as throughout the 20th century, cod and other roundfish formed the majority of demersal landings (for example, data from the Sea Fisheries Statistical Tables shows that during the period 1906-2006, cod landings by British and foreign vessels into England and Wales averaged over 40% of total demersal landings, whilst haddock landings averaged 14%). Otter trawl estimates were used after the introduction of otter trawls in 1895, as the major trawling centres around the UK quickly adopted this gear due to its greater efficiency, making it the most important gear for the capture of bottom-fish[23]. Where Engelhard provided a range of fishing power estimates for a given year, median values were used. His study provided a number of estimates of fishing power at different points throughout the 20th century. We interpolated between these points to provide annual estimates of fishing power. To calculate the overall fishing power of the fleet, fishing power estimates were multiplied by the registered numbers of first class trawlers every year (data from Sea Fisheries Statistical Tables). For periods where numbers of registered vessels are not available (1990-1996), known data from 1989 and 1997 were interpolated to estimate vessel numbers. First class (large) vessels were those registered as at least 15 tons gross weight (1889-1954). From 1955 this was altered to vessels of 40 feet or greater registered length (12.2 metres) until 1990 when the format was altered again to report vessels as less than or greater than 10 metres registered length. From this point first-class vessels are classed as those over 10 metres registered length.

Calculating landings per unit of fishing power. This measure was calculated by dividing annual landings of demersal fish by the fishing power of the trawler fleet. Fishing power of other bottom-gears was not included (see description of workings above). Restricting our calculations to data obtained from trawlers alone has resulted in a more conservative estimate of change. For example, if estimates of fishing power of other demersal gears are included within the calculations throughout the entire time-series, overall declines in landings per unit of fishing power are estimated at 95% from 1889-2007, rather than 94% using trawlers alone.

Prior to 1988 we assumed that landings by vessels registered to England and Wales were landed into England and Wales rather than other countries. This is backed up by sources which indicate that throughout most of the 20th century the amount of bottom-living species landed into other countries was insignificant, and that English and Welsh boats largely served the home market[14,19]. However, the introduction of the Common Fisheries Policy in 1983 altered markets and a significant amount of fish caught by UK vessels began to be landed into other countries. The percentage of landings abroad by UK vessels was used as a proxy to correct for this, as landings abroad by English and Welsh vessels alone were not available. We added the weight of fish landed abroad to those landed into England and Wales, before dividing by fishing power.

Scottish landing statistics. Landings of demersal fish by British vessels into Scotland were also collated from 1924-2007, alongside numbers of first class steam, motor and sail trawlers registered to Scottish ports. The same fishing power data trend was used to calculate fishing power of the fleet as for England and Wales. During 1990-1997 data were not available on numbers of first class Scottish-registered trawlers (over 10 metres length), therefore data for these years were interpolated from known data for 1989 and 1998. Landings into other countries were also corrected for using the same UK data as for England and Wales.

Calculating fishing effort data. Landings per unit of fishing effort were included in the Sea Fisheries Statistical Tables from 1924-1982 providing landings per 100 hours of fishing by first class British trawlers landing into England and Wales. The total hours fished and total demersal landings by sail, steam and motor trawlers were gathered from each year to provide landings per 100 hours that fishing was in progress. The proportion of landings caught by sail, steam and motor trawlers were weighted according to their different relative levels of fishing power each year, allowing us to correct for improvements in fishing power over time.

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Author contributions. Data analysis of demersal fish landings and trawl fishing power estimates were performed by RHT and SB. RHT provided fishing power estimates of liner and seine vessels and wrote the paper. CMR aided in data analysis and drafts of the paper. All authors discussed and commented on the manuscript.

Competing financial interests statement. The authors declare they have no competing financial interests.

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Chapter 4: Historical reconstruction of the nature of seabed habitats in the UK

4.1 ABSTRACT

Bottom trawling and dredging activities affect not only targeted species, but also their associated habitats. This chapter investigates three areas around the United Kingdom to determine how their benthic environments have changed over timescales of decades to more than a century. Sites studied were the Firth of Forth (south-east Scotland) and Swansea Bay and Caldey Island (south Wales). All once contained celebrated oyster fisheries which declined either before, or shortly after, the turn of the 20th century. Quantitative underwater surveys were conducted to determine the current state of seabed habitats. No live oysters were found at any of the sites surveyed and few dead shells were present. Sediment cores were taken from the Firth of Forth and Caldey Island sites (cores from Swansea Bay were unable to be used due to issues when extracting the sediment) and shell remains throughout the cores were quantified and identified. Nine of the Firth of Forth cores were then dated using radiometric analyses in an attempt to establish a timeline for the changes. At four of the nine sites in the Forth, mollusc species richness and shell biomass declined during the 19th century, with possible recovery observed from the mid-20th century onwards. These findings indicate that the impact of fishing and other activities were not just limited to target species. My research suggests that benthic habitats in the Firth of Forth and in parts of Swansea Bay have been fundamentally altered, making future re-establishment of oyster beds unlikely.

4.2 INTRODUCTION

Humans have fundamentally altered the nature of marine habitats through activities such as bottom trawling, pollution and land reclamation (Jackson et al., 2001). However, estimating the full extent of change in marine environments over long periods of time holds many challenges due to a lack of baseline information. For example, scientific surveys of an area often took place long after fishing began hence pre-fishing records of benthic habitats are rarely available (Robinson and Frid 2008).

Shellfish habitats such as oyster beds (*Ostrea edulis*) and horse mussel reefs (*Modiolus modiolus*) promote benthic diversity by providing hard substrate (Hiscock et al., 2005), but many throughout the UK were severely degraded before 1900 (Airoldi and Beck 2007; Royal Commission 1885). A number of studies have described loss of shellfish habitats over time. Kirby (2004) explored the timing of shellfish reef degradation along the North American coast using a number of different factors as a proxy for early signs of degradation. These were; the earliest known regulation of oyster fisheries, the beginning of importation of oysters to maintain existing beds, time series of oyster landings and earliest evidence for bottom dredging. Using these factors Kirby found that exploitation began closest to major population centres and expanded further afield as stocks declined, showing sequential exploitation of a resource.

Edgar and Samson (2004) described changes to molluscan assemblages in Tasmania over a period of 120 years. They dated sediment cores from a number of estuarine environments and quantified shellfish remains found throughout the cores. They found that shell abundance declined over time, particularly that of scallops and oysters which had been commercially fished. Mollusc species richness also declined. Declines observed coincided with the commencement of a scallop dredging fishery; however until this research mollusc declines in the region (with the exception of target species) had gone unnoticed.

Robinson and Frid (2008) determined changes to North Sea benthos as a result of fishing by comparing lists of species from the postglacial period (100-5000 years before present) against contemporary species lists for the North Sea, as well as comparisons of surveys of specific areas over time. From the postglacial records they found that 5% (13 taxa) of pre-fished species had been extirpated at the North Sea level, in particular species whose life histories rendered them vulnerable to fishing effort. Robinson and Frid also made quantitative comparisons of five ICES rectangles that had been surveyed during the 1920s and post-1985. They found that shifts in benthic community composition had occurred in three of the five rectangles, particularly increases in opportunistic species. They state that these results are likely to underestimate the full extent of change because data were collected after industrial fishing began, hence habitats were likely already altered from their pre-fished state.

Berghahn and Ruth (2005) argue that oyster stocks in the Wadden Sea, previously thought to have disappeared due to overexploitation, declined as a result of coastal engineering projects which altered the hydrodynamics of the area rather than directed fisheries for oysters. They also state that Wadden Sea oyster stocks may have been dependent on inputs of larvae from the large North Sea oyster beds. These declined throughout the 19th century as a result of trawling thus reducing larval input to the Wadden Sea.

An analysis by Beck et al. (2011) estimated that 85% of global oyster reefs have been lost, and that in many bays where they continue to exist oyster reefs are functionally extinct because of low abundance and density of oysters. The authors state that these values are conservative and that real loss of reefs could be higher. In addition many areas that have undergone losses of 90% or more of their original reef habitat are still being fished for oysters, so degradation continues. Unlike the plight of coral reefs and predatory fish, widespread declines of shellfish reefs have largely escaped public attention despite their importance to biodiversity (Beck et al., 2011). Conversely, an in-depth inventory of four historical oyster beds in Georgia, US found that previous surveys had overestimated the extent of habitat loss and that these reefs had probably improved since the late 19th century (Power et al., 2010).

In the UK, studies have been made on the state of current oyster beds and the potential to restock oysters. For example Laing et al. (2005) concluded that recovery of beds was likely to be slow (25 years or more) even for established populations and that this would be impeded by competition from invasive species and disease. Cooke (2003) has described dive surveys upon remaining native wild oyster beds in south Wales. Low abundances were found in Milford Haven, however none were found in Swansea Bay, an area which once supported an important local oyster fishery (Wright 1932). Scientists from the Millport Marine Biological Station surveyed extant oyster populations on the west coast of Scotland. Whilst some sites still contained oysters, numbers were low and they concluded it likely that a number of smaller populations had become extinct (UMBS 2007).

Shelmerdine and Leslie (2009) used historical records to identify past oyster beds around the Shetland Isles and to assess the suitability of areas for restocking native oysters. They found that declines of oysters were probably due to overfishing during the 1890s and severe winter weather during 1914. Oysters used to be found throughout the Shetland Isles, however intertidal and subtidal surveys were unable to locate any live specimens. Many subtidal sites now contain unsuitable substrate for the attachment of oysters, instead consisting of very soft, unstable sediments (Shelmerdine and Leslie 2009). They hypothesize that these sites have been subjected to a regime shift as oyster numbers declined.

4.2.1 Aims of research

In this chapter I examine four sites around the United Kingdom to determine past and present conditions of seabed habitats, and how conditions have changed over timescales of decades to over a century. I focus upon places with confirmed past presence of oyster fisheries and other shellfish beds, as previous existence and subsequent loss indicates likely declines in biodiversity (Hiscock et al., 2005).

I use historical records and field research to compare past descriptions of the seabed and species present with the present day. I also take sediment core samples from each site, because as sediments build up mollusc shells are often preserved which can provide information of past species richness and abundance (Edgar and Samson 2004). I quantify past mollusc abundance and species richness within sections of the cores. I then date sections of the core to specific periods of time in order to determine whether shellfish other than targeted species were affected by fishing activities and if so, when these changes occurred.

4.3 METHODS

4.3.1 Historical records

I conducted a literature search using the internet, local museums, university libraries and public archives to find information on historical shellfish fisheries. I also consulted Admiralty charts dating from the 1830s onwards at the National Maritime Museum in Greenwich to search for past locations of oyster or other shellfish beds. From these, I identified four areas around the UK as being potential field sites for oyster beds. These were the Firth of Forth (south-east Scotland), Cleethorpes (north-east England), Swansea Bay and Caldey Island (south Wales).

I recorded the locations of possible field sites onto current Admiralty charts by comparing the position of the marked bed on historical charts in relation to at least two obvious landmarks present on both charts (e.g. a named rock or a headland). I also used two historical surveys to establish possible field sites in addition to those obtained from Admiralty charts; Fulton's survey of the Firth of Forth (1896) and Wright's survey of Swansea Bay (1932). Together, these sources provided more potential areas than could realistically be explored in the time allowed, hence I selected sites for analysis on the basis of their practical suitability for diving. Sites that were unsuitable due to factors such as depth, strong currents, high shipping traffic or distance from a launch site were removed from consideration. I also discounted sites which were likely to have been substantially altered by navigational dredging. Final decisions from the choice of study sites were made on the day of diving following the assessment of site conditions.

4.3.2 Location of field sites: Swansea and Caldey Island

I surveyed 5 sites in Swansea Bay in June and August 2010 (Figure 1). Swansea has a mean spring tidal range of 8.5 m and a mean neap range of 4.1 m. Currents can be up to 1.5 knots. I chose sites using marked sites from Wright's 1932 survey. Table 1 shows the GPS coordinates and depths for sites surveyed at

Swansea and also Caldey Island, where I surveyed 6 sites in August 2010 (Figure 2). Caldey Island has a mean spring tidal range of 7.5 m and a mean neap range of 3.3 m. Currents can be up to 2.6 knots. I chose Caldey Island sites using an Admiralty chart from 1830 that shows the location of oyster beds (Figure 3).

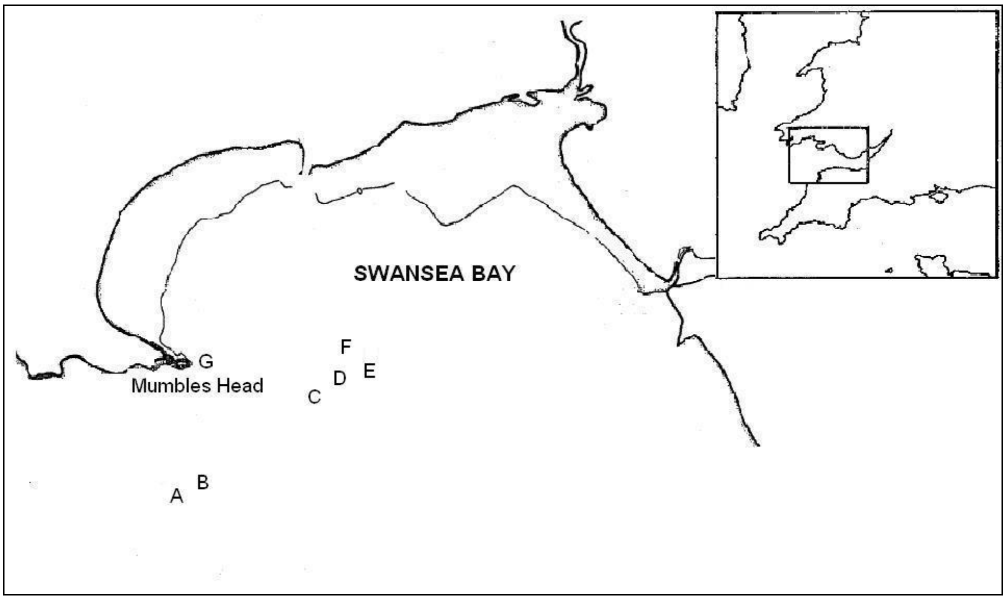

Figure 1. Field sites around Swansea Bay.

Table 1. Positions of sites, bearings and average depths at chart datum for Swansea and Caldey Island.

Site	Date surveyed	GPS coordinates		Bearing (deg)	Core length (m)	Depth (m)
		Latitude	Longitude			
Swansea Bay						
A	06/06/10	51°31'610N	3°59'910W	38°	-	15
B	-	51°32'060N	3°59'510W	No survey undertaken		
C	04/06/10	51°33'970N	3°55'720W	27°	0.69	12
D	-	51°34'250N	3°55'625W	No survey undertaken		
E	02/08/10	51°34'360N	3°55'340W	75°	0.47	8
F	04/06/10	51°34'470N	3°55'760W	66°	-	7
G	02/08/10	51°34'180N	3°58'290W	106°	-	5
Caldey Island						
1	-	51°38'930N	4°41'635W	No survey undertaken		
2	03/08/10	51°38'995N	4°41'480W	80°	0.58	4
3	03/08/10	51°39'030N	4°41'640W	80°	0.83	7
4	06/08/10	51°39'215N	4°41'470W	80°	-	6
5	04/08/10	51°39'150N	4°41'180W	80°	-	7
6	04/08/10	51°39'365N	4°41'330W	80°	0.43	6.5
7	-	51°38'950N	4°41'285W	No survey undertaken		
8	05/08/10	51°38'740N	4°41'290W	80°	0.80	4

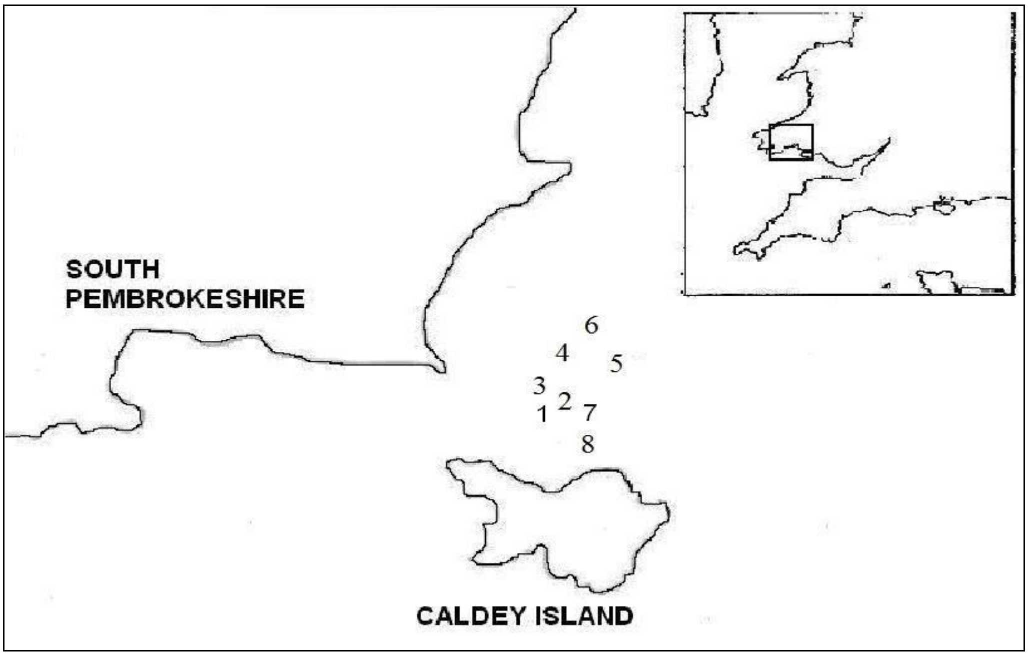

Figure 2. Field sites at Caldey Island.

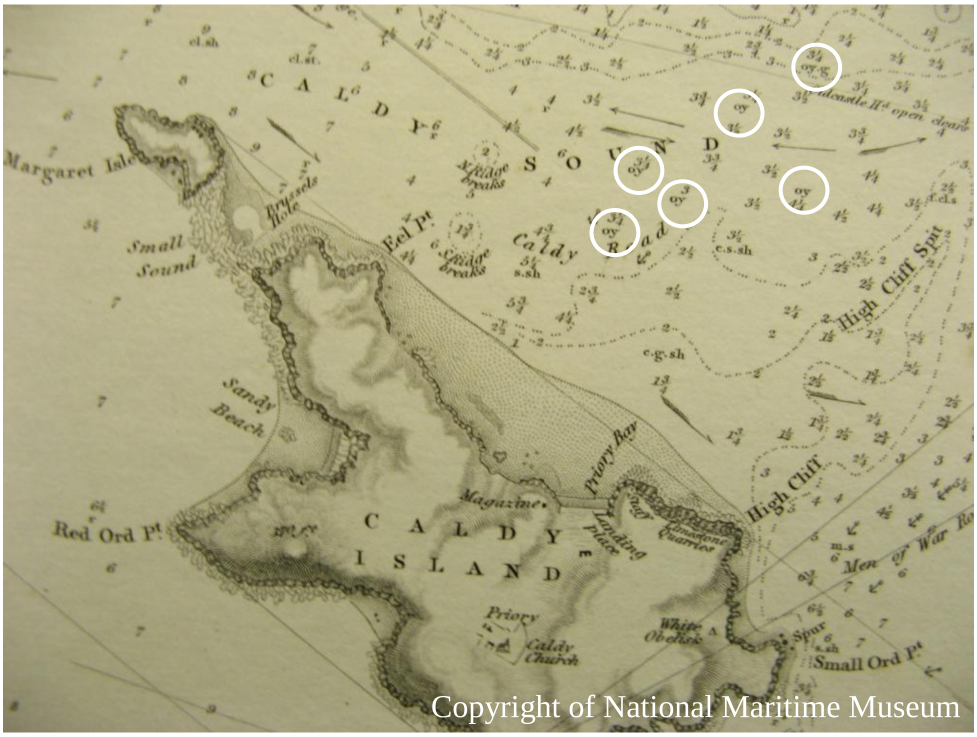

Figure 3. Section of Admiralty chart of Caldey Island surveyed in 1830 showing location of oysters (marked ‘oy’). Depth in fathoms. Source: National Maritime Museum.

4.3.3 Location of field sites: Firth of Forth

The Firth of Forth has a mean spring tidal range of 5.0 m and a mean neap tidal range of 2.5 m (Webb and Metcalfe, 1987), with currents up to 1.5 knots. I surveyed 11 sites in the Firth of Forth between April and October 2010, with sites chosen using marked sites from historical Admiralty charts and Fulton's surveys (1896). Figure 4 shows the location of each site and Table 2 provides additional details such as coordinates and depth of seabed at chart datum. Figure 5 shows an example of an Admiralty chart from which I derived the location of two of the final sites.

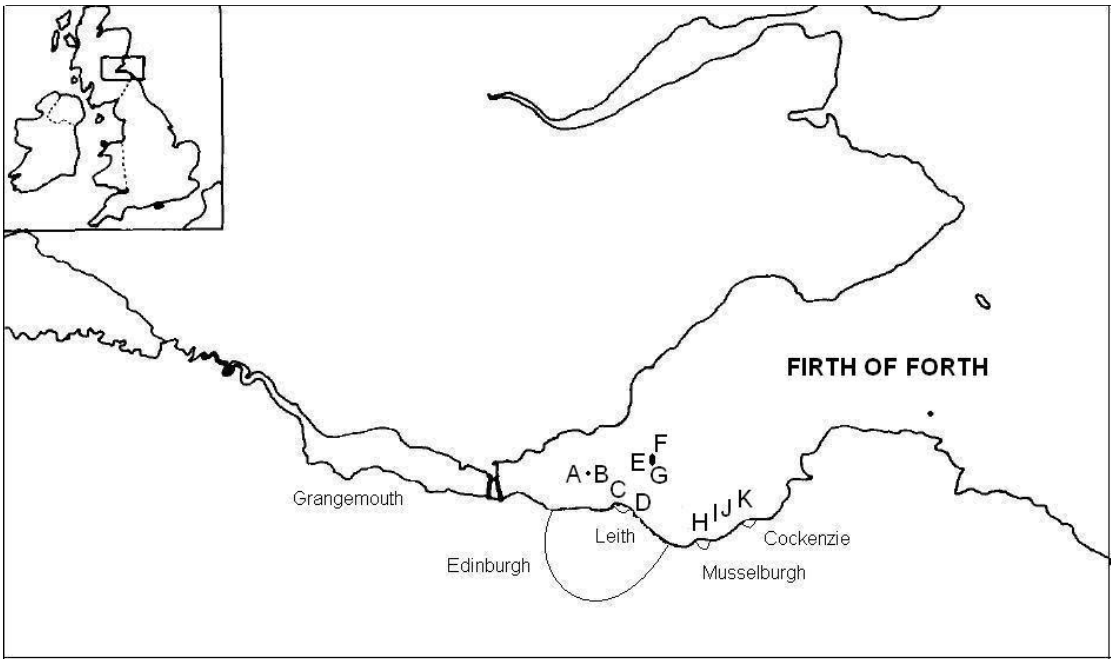

Figure 4. Field sites in the Firth of Forth. Sites A to I were taken from Fulton's surveys in 1895 (Fulton 1896). Sites J to K were taken from the 1852-56 Admiralty chart for the Firth of Forth (see Figure 5).

Table 2. Positions of sites, bearings and chart datum depths for the Firth of Forth.

Site	Date surveyed	GPS coordinates		Bearing (deg)	Core length (m)	Depth (m)
		Latitude	Longitude			
A	03/10/10	56^{o}00’680N	3^{o}15’620W	262^{o}	-	4.5
B	03/10/10	56^{o}00’655N	3^{o}16’860W	91^{o}	0.80	2.5
C	23/05/10	56^{o}00’480N	3^{o}14’140W	83.5^{o}	0.92	5
D	02/10/10	55^{o}59’635N	3^{o}10’030W	260^{o}	0.58	2.5
E	02/10/10	56^{o}01’520N	3^{o}08’510W	255^{o}	0.36	7.5
F	22/05/10	56^{o}02’290N	3^{o}07’780W	102^{o}	0.64	13
G	22/05/10	56^{o}00’950N	3^{o}07’660W	158^{o}	0.90	7
H	25/04/10	55^{o}58’050N	3^{o}00’640W	58.5^{o}	0.97	6
I	25/04/10	55^{o}57’660N	3^{o}01’080W	143^{o}	0.88	6
J	24/04/10	55^{o}58’860N	2^{o}58’030W	58.5^{o}	1.00	7
K	24/04/10	55^{o}59’160N	2^{o}57’290W	58.5^{o}	1.05	7

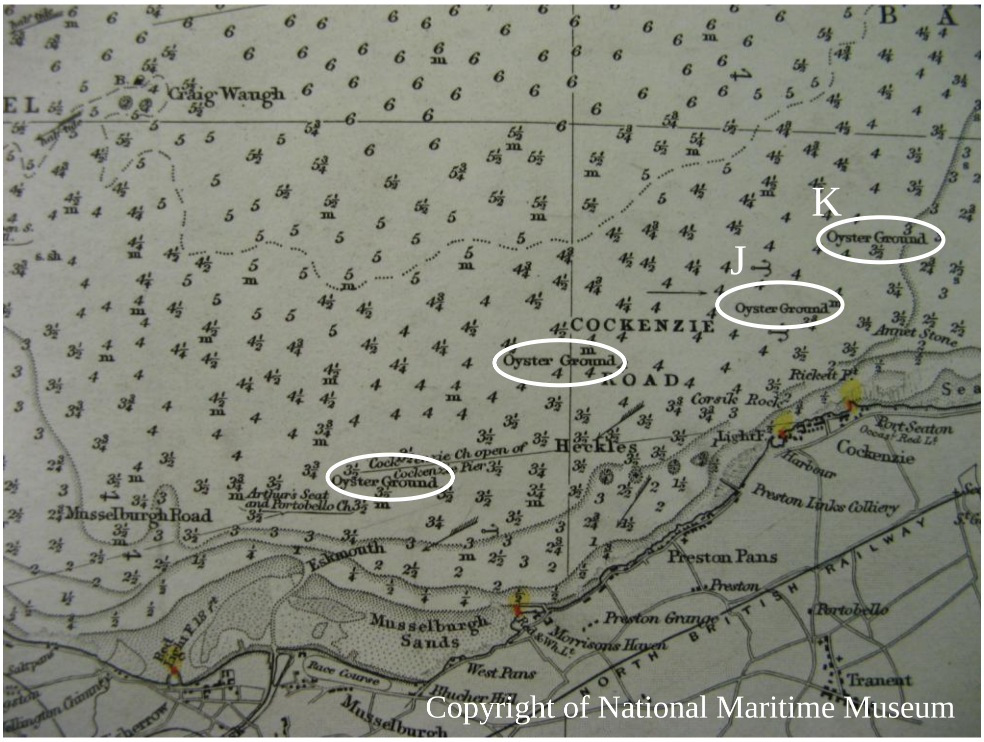

Figure 5. Section of Admiralty chart for the Firth of Forth surveyed in 1852-56 showing location of oyster grounds and field sites J and K. Depth measured in fathoms. Source: National Maritime Museum.

4.3.4 Location of field sites: Cleethorpes

At Cleethorpes an on-site assessment revealed the area to be unsuitable for field data collection due to the compacted sandy bed and zero visibility conditions.

4.3.5 Field methods (coring techniques adapted from Edgar and Samson 2004)

Fieldwork took place between April and October 2010. A team of four divers including myself performed two dives at each site, the first to conduct quadrat and video analysis of the benthic habitat, the second to take a sediment sample for shell community analysis. Once at the dive site, a weighted shot line was deployed for the duration of the dives. I and my buddy descended the shot line first and laid a 50 metre transect tape. The direction of the transect either followed the direction of dredge surveys conducted by Fulton (1896) and Wright (1932), or what was most practicable and safe for divers based upon current strength and direction. Once the tape was laid I took a video transect along one side of the tape to be analysed in the laboratory. I then randomly selected ten $1m^2$ quadrats on either side of the tape along the same 50 metre transect for in-situ analysis (random numbers had been decided prior to the field trip using a random number generator in Microsoft Excel). I filmed transects using a digital compact camera (Canon Finepix) and underwater housing, with a V8 video light on either side. At some sites only one method was used as conditions were too poor to perform both.

On completion of the video transect and quadrat dive a second pair of divers were deployed in the same spot to take a sediment core, using a two metre, 10 cm diameter PVC tube with 'teeth' cut at one end. One diver stood the tube upright on the seabed using a long handled-clamp bolted together with wing-nuts. The second diver forced the tube into the sediment using a modified post-driver. Once driven into the sediment they placed a cap on top of the core to allow it to be pulled out of the seabed with minimal loss of sediment. As soon as the corer was pulled out a cap was placed on the bottom of the core and a rope deployed allowing up-right recovery to the boat. The corer was kept upright until it was taken onto land where we siphoned off the seawater and extruded the core. Once extruded the core was split longitudinally: one half to be used for dating analysis, the other for shell community analysis.

4.3.6 Laboratory analysis

I analysed quadrats in-situ and recorded the results for species richness and diversity assessments. I then analysed the video transects in the laboratory. The video was played back and paused, either at four second intervals, or when the camera had moved forward to an area of substratum that did not overlap the previous image if this took more time. I captured the frozen image from the paused video and converted it to a JPEG image that could be analysed as a stand alone photograph. I discarded images that were too grainy or distorted to be analysed, and analysed the remaining with 20 randomly spaced points using the program Coral Point Count with Excel extension (CPCe) (Kohler and Gill 2006). Under each selected point I identified the habitat type or species as far as possible to obtain estimates of percentage cover. Video analysis was used predominantly as a back-up for in-situ quadrat analysis or as an alternative if conditions were unsuitable for the use of quadrats.

I analysed one half of each sediment core in the Environment Department at York University to determine shell community composition at different depths in the sediment. The other half was sent to the National Oceanographic Centre at Southampton to be dated. For shell community analysis, I split each core into 5 cm-long sections. I used a 1 mm sieve to rinse away the sediment, leaving behind mollusc shells. Shells were separated into those that were identifiable and those that were too fragmented to be positively identified. I weighed all shells to determine overall shell biomass for each 5 cm section. I then separated the identifiable shells by species and weighed them to determine species richness for that section of core. I used Simpson’s Reciprocal Index of Diversity to compare community diversity and evenness over time.

At Southampton, nine cores from the Firth of Forth were first analysed using a non-destructive Itrax core scanner to provide metal element profiles. Cores were then split into 1 cm sections for the dating analysis. Nine cores from the Firth of

Forth were analysed for Caesium-137 (Cs-137) and seven of these were analysed for Lead-210 (Pb-210). Each method used 10-15 sediment samples at various depths from each core. Cores from other sites were unsuitable for this kind of analysis due to the nature of their sediments (Ian Croudace, Southampton Oceanography Centre, *pers. comm.*). Cs-137 was analysed using gamma-spectrometry, and Pb-210 counts were conducted using alpha spectrometry.

Cs-137 is an artificial radionuclide that was released in large quantities from 1954 onwards as a result of atmospheric nuclear weapons testing. Weapons testing, and therefore levels of Cs-137, peaked in 1963, thus providing two potential reference dates. Around the UK, an additional source of Cs-137 comes from the Sellafield Nuclear Reprocessing Facility in Cumbria (west coast of England). Cs-137 derived from Sellafield emissions peaked in Forth sediments in 1978 providing another potential reference date (Bell et al., 1997). Thus if I can identify both the depth at which Cs-137 first appears and two peaks in concentration within each core, I can begin to draw conclusions about the age of sediment, and therefore the age of mollusc-shell remains at these depths. Site H was not analysed due to its proximity to site I and limited funding.

Pb-210 is a naturally occurring radioactive element produced from the Uranium-238 decay series. Radon gas escapes to the atmosphere, where after a series of short-lived decays (over hours or days) falls from the atmosphere as Pb-210 (half-life 22.3 years). Once on land or in water, Pb-210 becomes permanently fixed to sediment particles where over time its activity declines until it reaches equilibrium with background levels of Radium-226 present in the sediment (www.flettresearch.ca/Webdoc4.htm). This usually occurs after 5-6 half lives (110-130 years) but can be as little as 3 half lives (66 years) (Appleby 2004). Thus to date sediment the Pb-210 activity in different layers is measured in relation to the activity of Pb-210 on the surface of the sediment, and it is assumed that every time the Pb-210 activity halves 22.3 years have passed (www.flettresearch.ca/Webdoc4.htm).

4.4 RESULTS FROM SWANSEA AND CALDEY ISLAND

4.4.1 Outcomes of historical source review

Natural beds of native oysters were once found along the coast of south Wales (see Figure 6). The most prosperous of these were around Swansea Bay and Mumbles Head (Wright 1932). From the 1840s these beds were fished by boats from further afield to restock beds in the Thames and around France (Shackley et al., 1980). The local fishery also increased and throughout the late 19th century many oyster beds in south Wales exhibited a decline as dredging intensified.

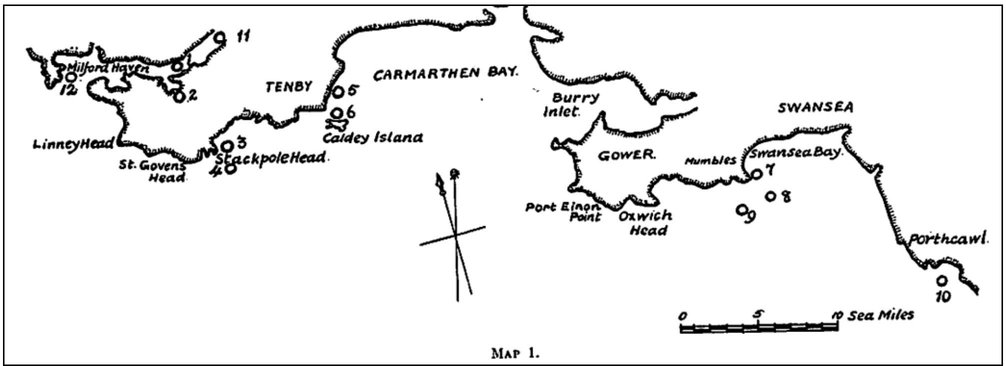

Figure 6. Locations of South Wales oyster beds. Sites surveyed included Caldey Island (6), Roads Haul, Mumbles Head (7), Green Grounds, Swansea Bay (8) and White Oyster Ledge (9). I surveyed sites at Mumbles Head (7), Swansea Bay (8), White Oyster Ledge (9) and Caldey Island (6). Source: Wright (1932).

Complaints of decline are recorded from the 1860s onwards (Royal Commission 1866; Wright 1932) and were attributed to a combination of over-dredging and long intervals between heavy spat-falls (Royal Commission 1866). Beds in Swansea Bay and off Mumbles Head started to recover during the early 20th century as exploitation declined but succumbed to disease during 1921-2 (Wright 1923). During 1922 and 1929 a series of dredging surveys took place to find out the condition of the oyster beds in South Wales (Wright 1932). Oyster beds were rarely shown on Admiralty charts of south Wales (with the exception of Caldey Island beds, Figure 3) and little knowledge of the location of old beds existed following the retirement of old fishers. However the known beds were surveyed by Wright (1932).

During the 1922 survey a few oysters were found on Caldey bed and the bottom was described as consisting of "*pebbles and larger fragments of stone, together with a good deal of old and decayed shell cultch*" (Wright 1932). On average 5.3 oysters were taken per dredge per haul. Off Mumbles Head and in Swansea Bay, an average of 30.2 oysters per dredge per haul was taken. In the inner Swansea Bay grounds the bottom consisted of rounded pebbles mixed with oyster shell, however in certain places very little shell was found. Clinkers and coal were also brought up that had been thrown from passing steam ships. The grounds were described as "*somewhat barren*" (Wright 1923). Table 3 shows the numbers of oysters recorded by Wright (1932) and descriptions of the sites I surveyed.

Table 3. Description by Wright (1932) of the sites I surveyed at Swansea.

Locality	Name of site in this survey	Name of site in Wright (1932)	Number of live oysters	Description of grounds
White oyster ledge	A	7*	8	Stony and clean. Few *Asterias* in most hauls and *Solaster*. Pests not abundant
White oyster ledge	B	4*	89	As above
Green grounds	C	9#	11	Clean
Green grounds	D	8#	14	Clean
Green grounds	E	7#	35	Clean
Green grounds	F	2#	4	Clean
Mumbles Head	G	10#	4	Muddy and foul

* Source: Track chart 5 (Wright 1932). # Source: Track chart 6 (Wright 1932).

In 1929 the Mumbles and Swansea Bay area along with other sites along the south Wales coast were once again surveyed by Wright. By this time the Swansea Bay beds had resumed to yield oysters (Wright 1932). However shortly after this the oyster fishery once again declined and has never since recovered (Davidson 1976). Figure 7 shows records of oyster landings from the Mumbles (Swansea Bay) fishery.

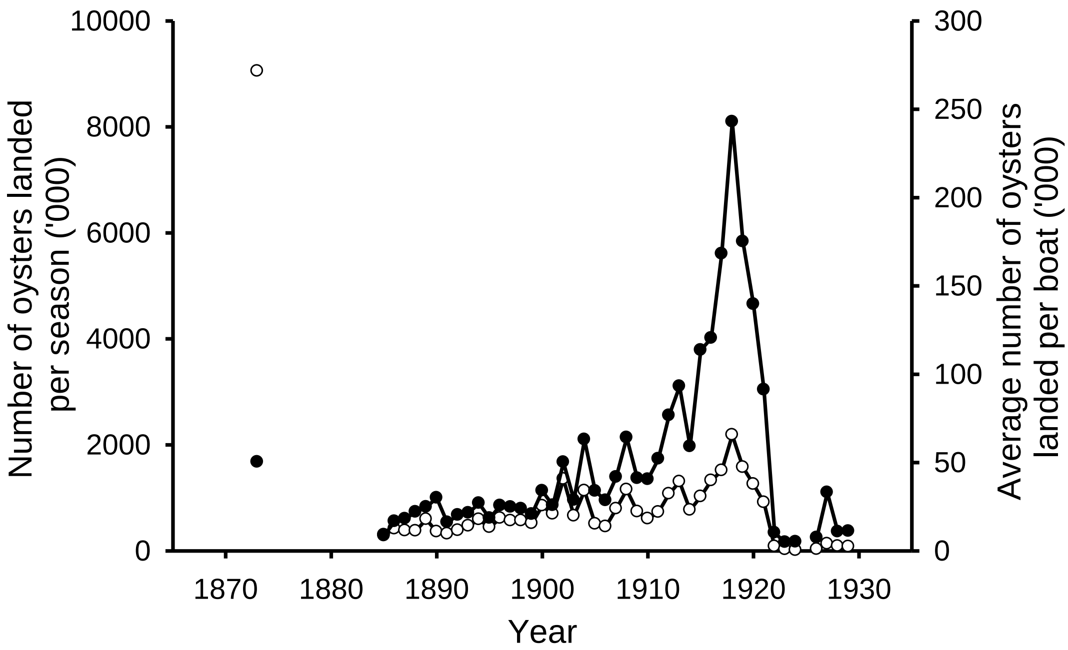

Figure 7. Number of oysters caught per season (open circles) and average number of oysters caught per boat (closed circles) at the Mumbles fishery. Source: Wright 1932.

4.4.2 Quadrat and video transect analysis

The following section shows results from in-situ quadrat and video transect analyses from sites at Swansea and Caldey Island. These provide a description of seabed habitats today which can be compared to the historical descriptions in the previous section. Site E was not compared as conditions did not allow the use of quadrats and the video footage acquired was too poor to be of use due to low visibility. Figure 8 shows the average percentage cover of the main habitat types at the Swansea sites. Sites C, F and G were composed mainly of fine sand and broken shell, whilst A was dominated by cobbles. Species present included bryozoa and hydroids (not identified to species) with small amounts of sea squirts (*Ascidiella aspersa)*, sponges (not identified to species) and anemones. Slipper limpets (*Crepidula fornicata*) were found at site G.

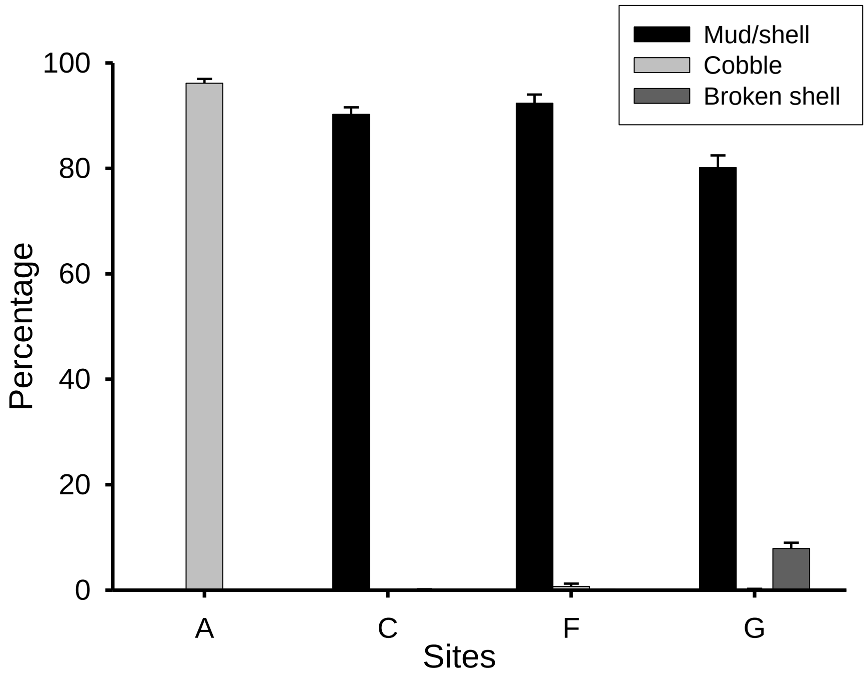

Figure 8. Average percentage cover of main habitat types present at Swansea sites with standard error bars.

Figure 9 shows differences in the total number of species identified by quadrat and video analysis. Low visibility conditions and small organisms made it difficult to accurately identify species by video analysis hence the difference in total numbers of species.

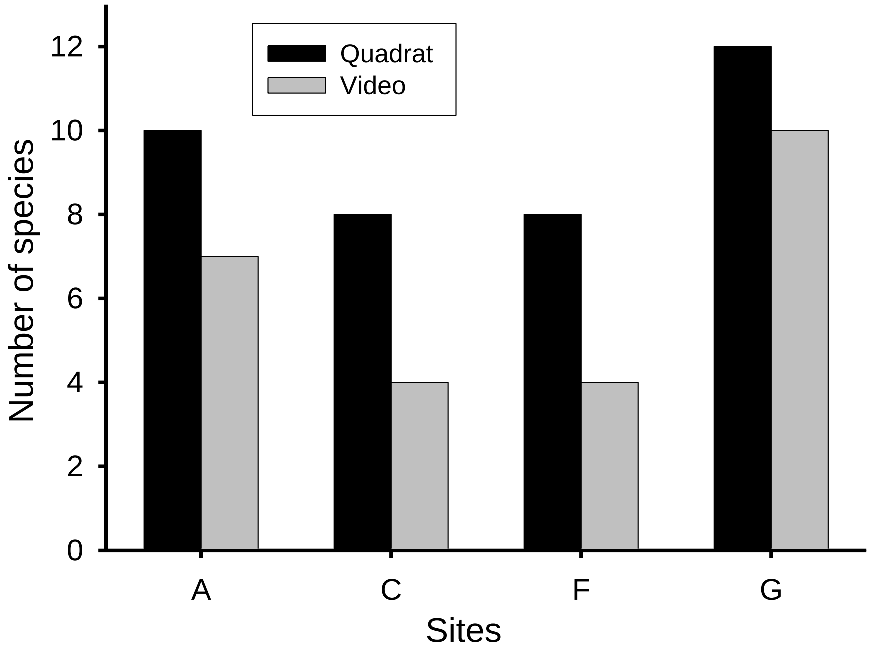

Figure 9. Comparisons of total number of species recorded by quadrat and video sampling at Swansea. Quadrat sampling covered 10 m^2 at each site; video sampling covered approximately 20 m^2.

Figure 10 shows the average percentage cover of the main habitat types at the Caldey Island sites. Sites 5, 6 and 8 were mainly composed of fine sand and shell or mud and shell. Sites 3 and 4 were made up of broken shells. As for Swansea, the number of species found using quadrats was greater than from video analysis (Figure 11).

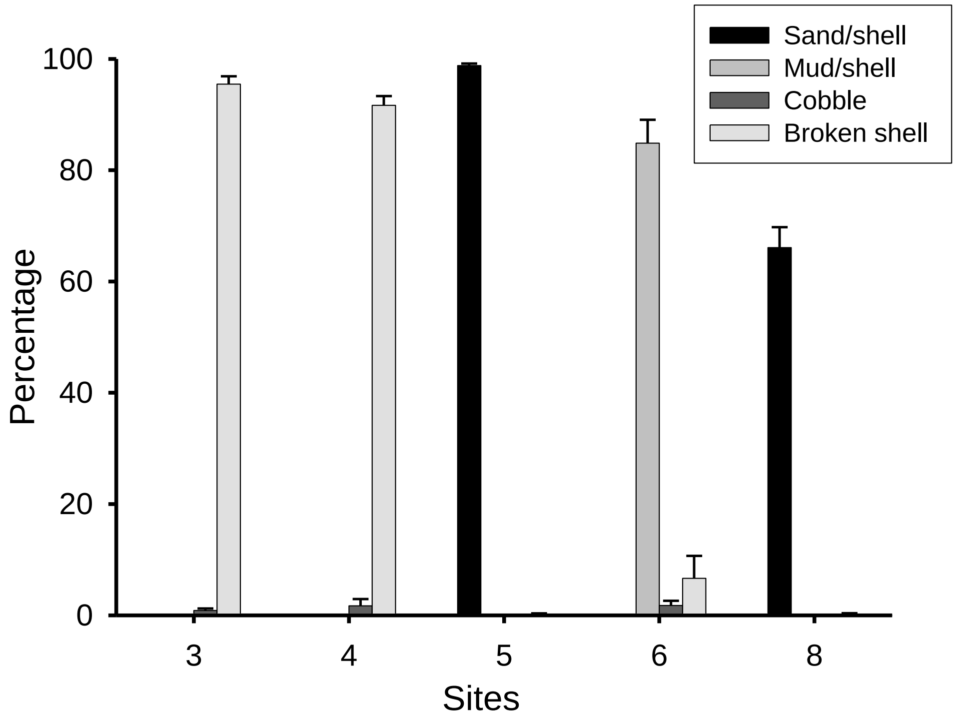

Figure 10. Average percentage cover of main habitat types present at Caldey Island sites with standard error bars.

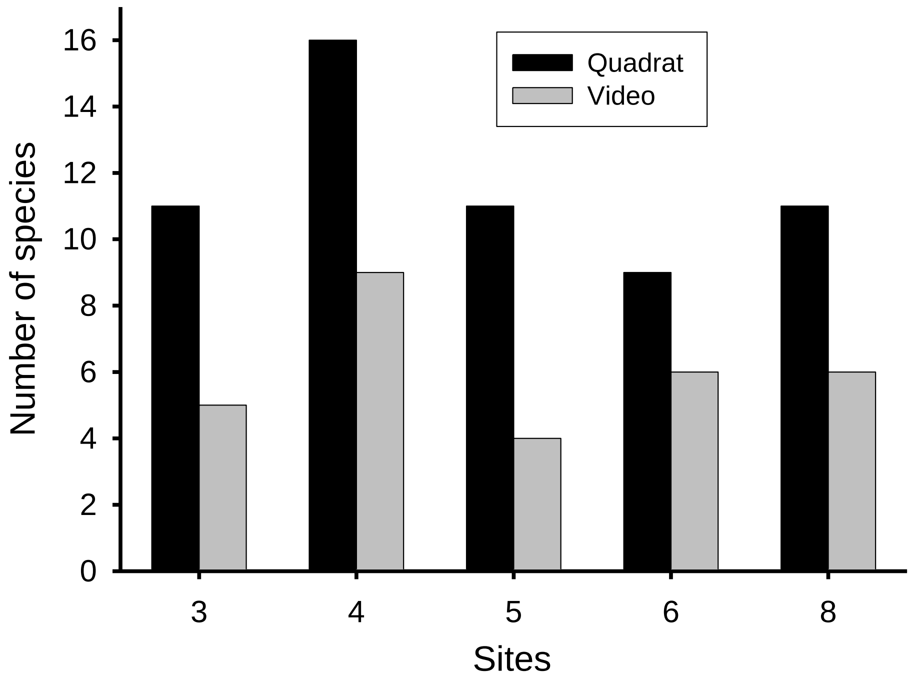

Figure 11. Comparisons of total number of species recorded by quadrat and video sampling at Caldey Island. Quadrat sampling covered 10 m^2 at each site; video sampling covered approximately 20 m^2.

4.4.3 Shell community analysis

Shell community analysis was only conducted on sediment cores taken at the Caldey Island sites. Due to the nature of the Swansea seabed viable cores for analysis were not obtained: sampling efforts yielded either short cores or cores whose integrity was destroyed upon extrusion. At Caldey Island cores were taken at sites 2, 3, 6, and 8. Cores were not taken from other Caldey sites due to tide and current constraints. It is assumed that the surface of the core (i.e. 0 cm) represents present day communities. I assume that shell-remains that occur deeper in the core are from earlier periods of time and that as they died sediment has accumulated on top of them, hence communities from earlier periods of time are based at deeper depths in the core. I demonstrate this on the following graphs by showing the direction of time elapsed. Cores were not dated at the National Oceanography Centre based on the advice that their sandy nature meant that Pb-210 and Cs-137 dating techniques were unlikely to be successful (Ian Croudace *pers. comm*.). Pb and Cs are preferentially adsorbed onto fine particulates such as silt and clay (Kirchner and Ehlers 1998) hence sandy materials usually have very low levels of activity making it difficult to analyse sandy sediments. Figure 12 shows the total weight of shells extracted from samples at Caldey Island. Overall weight of shells decline further back in time, as do the number of identified species (Figure 13).

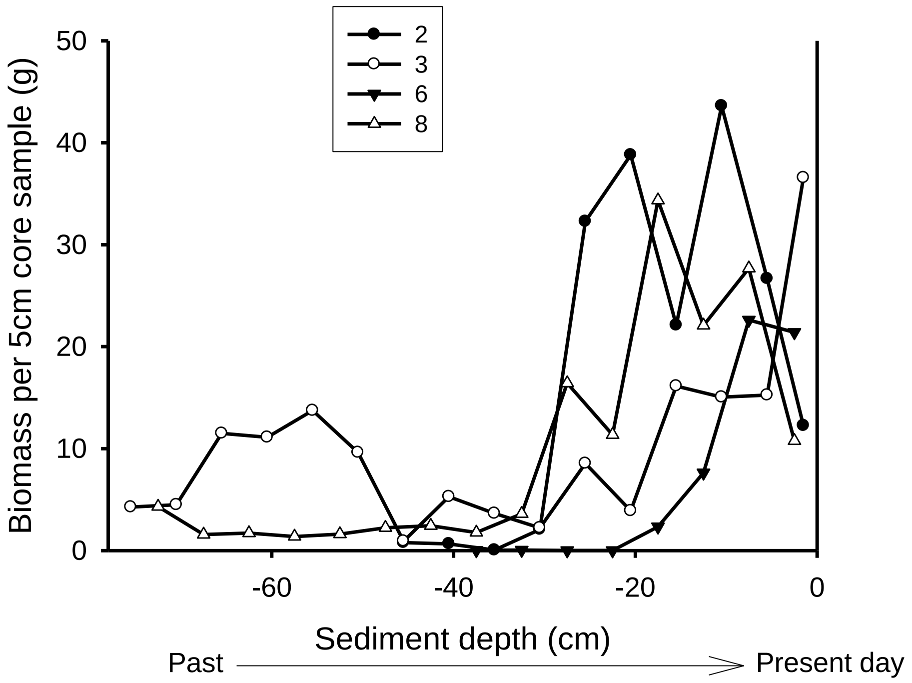

Figure 12. Changes to total shell biomass from sites at Caldey Island.

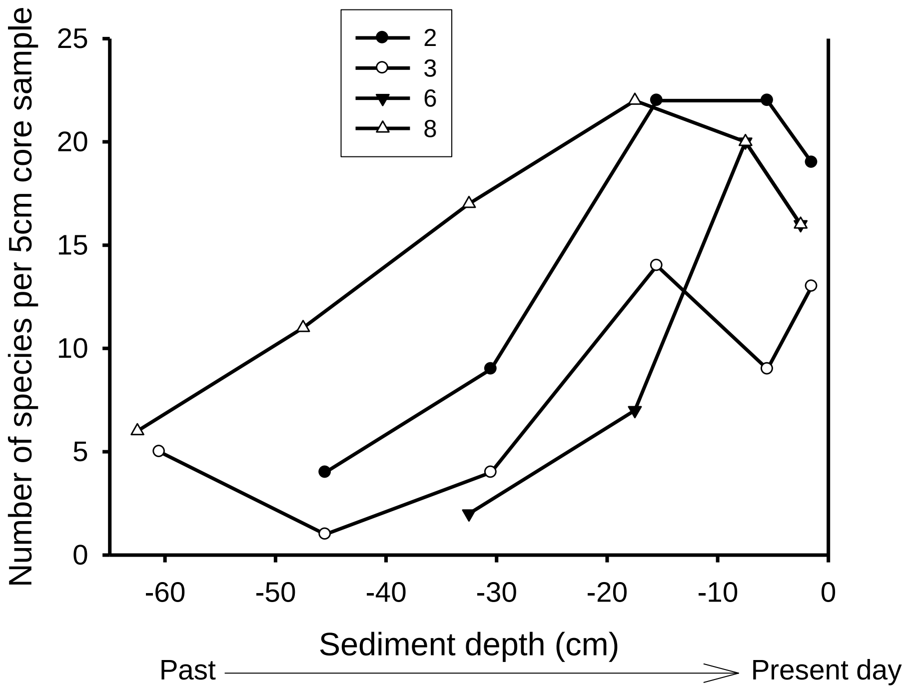

Figure 13. Changes to number of identified species from sites at Caldey Island.

Changes to community diversity throughout the core sections were also investigated using a species diversity index measure. Simpsons Reciprocal Index of Diversity was used for samples from each core as sample sizes are small and rely on relative abundance of species to determine a measure of diversity (Magurran 2004). No trends in community diversity or evenness were found for sites 3 or 8. At site 6, diversity increases with time (R^2 = 0.99), whilst evenness decreases with time (R^2 = 0.90) (Figures 14 and 15). At site 2, diversity again increases with time (R^2 = 0.82), whilst evenness decreases (R^2 = 0.82) (Figures 16 and 17).

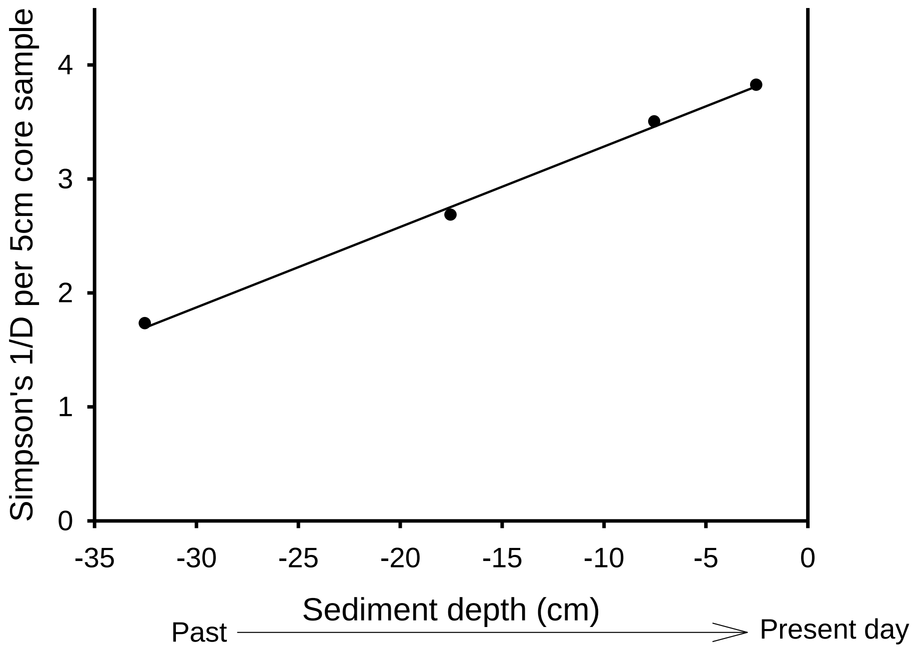

Figure 14. Caldey Island site 6, Simpson's Reciprocal Index of Diversity from samples at different depths using biomass of each species (R^2 = 0.99).

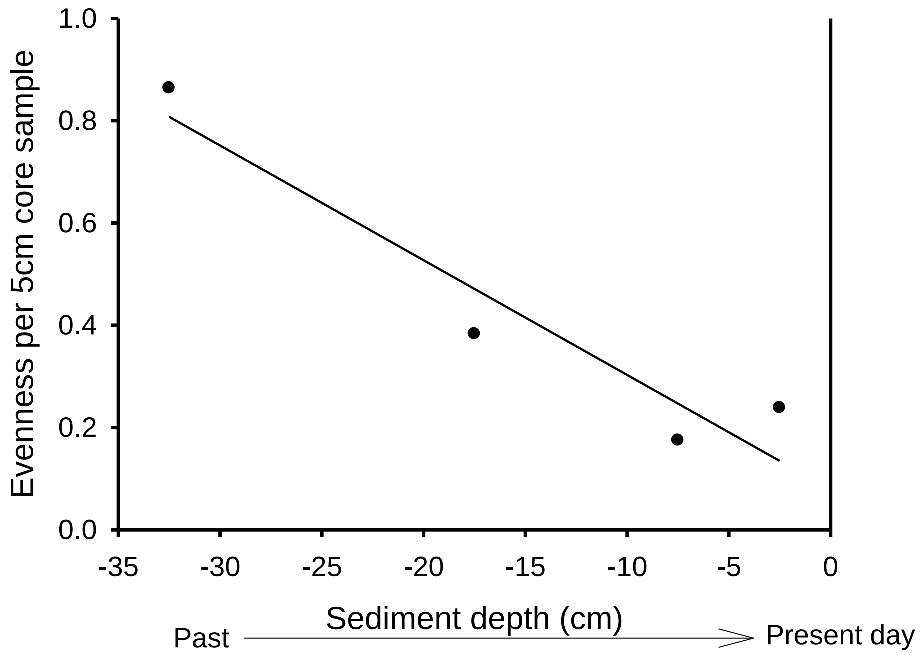

Figure 15. Caldey Island site 6, Simpson's evenness measure from samples at different depths using biomass of each species (R^2 = 0.91).

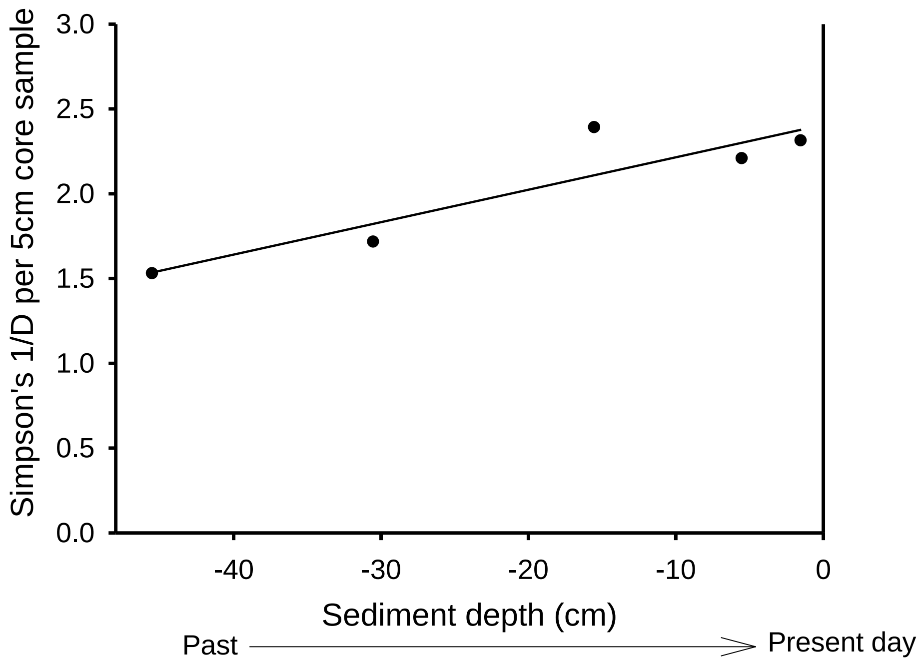

Figure 16. Caldey Island site 2, Simpson's Reciprocal Index of Diversity from samples at different depths using biomass of each species (R^2 = 0.83).

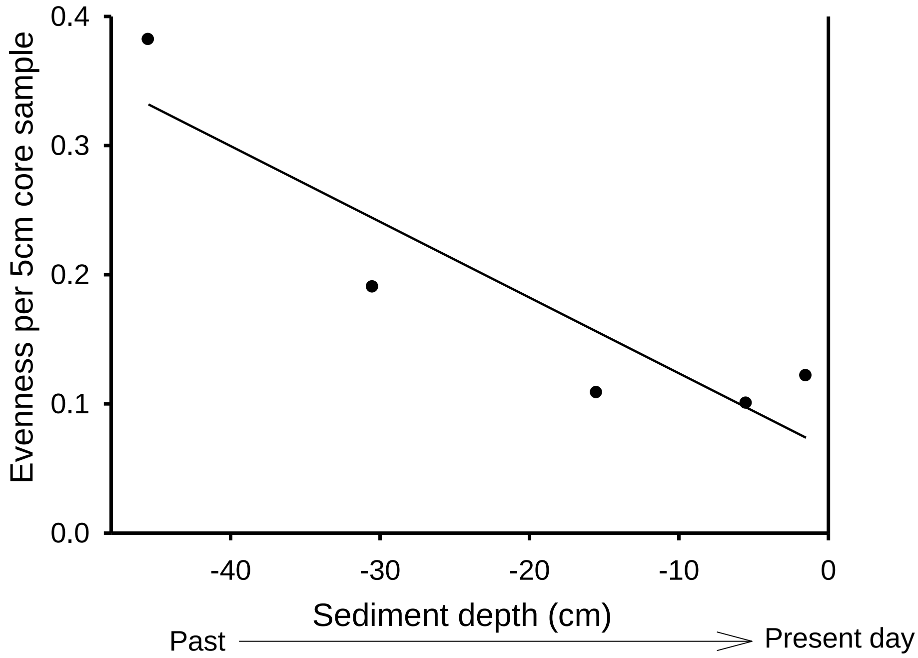

Figure 17. Caldey Island site 2, Simpson's evenness measure from samples at different depths using biomass of each species (R^2 = 0.82).

The four most dominant species at each site from the top, middle and bottom of each core were also recorded, as greater dominance by one species could indicate a more environmentally disturbed ecosystem (Magurran 2004). However, for all cores apart from site 3 (Figure 18) the biomass of shells was greatest at the top of the core towards the surface. This meant that it was difficult to compare species dominance patterns throughout the cores. At site 3 *Cerastoderma edule* was dominant at different levels, but otherwise there was little overlap of species. The main species found throughout the cores were the common cockle (*Cerastoderma edule*), blue mussel (*Mytilus edulis*) and the needle whelk (*Bittium reticulatum*).

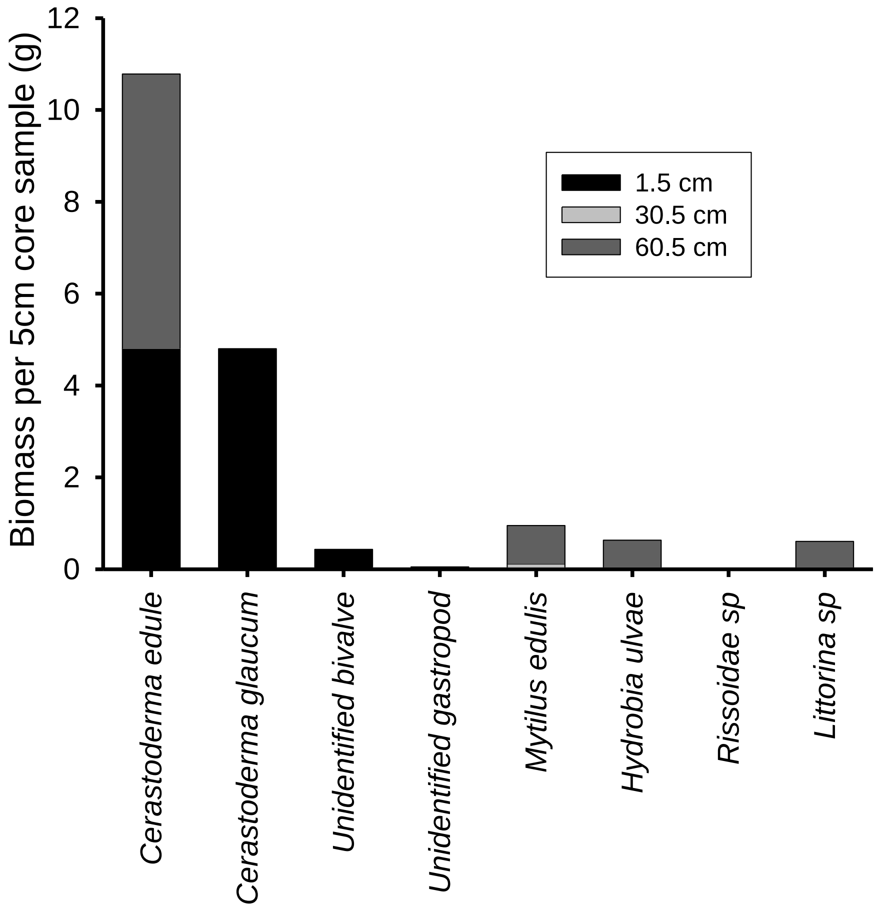

Figure 18. Four most dominant species by biomass at three different depths (equivalent to different points in time) at Caldey Island site 3.

4.5 RESULTS FROM THE FIRTH OF FORTH

4.5.1 Outcomes of historical source review

The Firth of Forth contained the most important oyster fishery in Scotland during the 1800s, with oyster beds that extended 20 miles along the Forth (Philpots 1891). At the beginning of the 19th century the oyster beds here were so productive that one boat could frequently drag up 6000 oysters in one day (Fishery Board for Scotland 1890). Boats from Prestonpans (on the south coast of the Firth of Forth) would ship 30-40,000 oysters to Newcastle 3 or 4 times during the season (Sinclair's Statistical Account of Scotland, taken from Fishery Board for Scotland 1890).

During the early 1800s exploitation of the Forth oyster beds increased as people took young oysters to restock overexploited beds in England and Holland. Local consumption of adult oysters also increased. From Newhaven alone an average of 19,900,000 oysters per year was estimated to have been exported during the period 1834-1836, whilst an estimated 1,700,000 oysters were sold in Edinburgh for local consumption (Fulton 1896). Information from local fishermen showed that from 1865-1870 the yield per boat amounted to 20-30,000 oysters per week (over 0.5 million oysters per week for all boats) during the season for boats from Prestonpans and Cockenzie (on the south coast of the Firth of Forth). Dr Fulton was a fisheries scientist with an interest in the Firth of Forth, in 1896 he stated,

"The oyster-beds at that time [...] were, in some places, six miles wide."

By 1889 Leith (on the south coast of the Firth of Forth) was the only port landing oysters commercially, with landings having dwindled to just 315 hundred oysters during the season (Fishery Board for Scotland 1890). By the 1890s there were no directed oyster fisheries in the Forth; the only ones caught having been obtained as bycatch during fishing for queen scallops (*Aequipecten opercularis*) and mussels (*Mytilus edulis*) (Fulton 1896). In 1895 the Fishery Board for Scotland commissioned Fulton to research the current state of the Forth oyster population and the possibilities for improving the fishery. To do this Fulton carried out 233 dredges in the Forth area during 1895. On average the dredge was dragged for 600 yards, (or 550 metres) and once brought up, the contents of the dredges were examined and numbers of live oysters, horse mussels, queen scallops and the number of shells were counted (Fulton 1896). Only 317 living oysters were found in the 233 dredges although old oyster shells were present in the majority of hauls. Nearly 35,000 live queen scallops and 8113 horse mussels were taken. I used the results from this survey to determine sites for analysis. Table 4 shows the contents of the dredges brought up by Fulton at sites which I surveyed.

Table 4. Description of sites and contents of dredges surveyed by Fulton (1896) in the Firth of Forth that were re-surveyed during this investigation.

Site	Name of site in Fulton (1896)	Dredge content description	Oysters		Clams		Horse mussels	
			Live	Dead (pair)	Live	Dead (pair)	Live	Dead
A	32	Hard. *Flustra* abundant, some stones	2	564	1	36	16	-
B	174	Some mud. *Solen*, *Mya*, and *Cyprina* shells	3	258	24	20	7	-
C	48	Clean	4	415	276	500	7	-
D	70	Clean. Much mussel seed	2	340	87	150	2	-
E	41	Shelly. *Laminaria*: *Carcinus* (1), *Alcyonium*: *Cribella* (1), *Ophioglypha*, *Ophiothrix*: *Hyas*: *Cyprina*: *Mya*	3	162	181	300	53	-
F	107	Clean. *S. endeca* (3)	4	73	569	267	5	-
G	153	Some mud. *Cribella* (1)	6	60	6	22	139	-
H	229	Slightly muddy	7	48	-	120	31	-
I	117	Clean. *Cribella* (1)	7	42	-	240	68	12
J	*	Slightly muddy	1	28	24	150	169	-
K	*	No description						

*Taken from 1852-6 Admiralty chart, site J is close to site 231 on Fulton's survey hence description of site 231 is given.

Fulton estimated that in 1895 in the Firth of Forth there was only one living oyster on every 660 square yards of bottom, or about 7.3 oysters to each acre. He calculated that between 250,000 and 500,000 oysters were present in the Firth of Forth in 1895, most likely closer to the lower estimate. As oysters declined queen scallops became more plentiful (Fullarton 1889) and fisheries were increasingly directed towards catching this species as bait for line fisheries (Scottish Mussel and Bait Beds Commission 1889).

In his report Fulton stated,

"*I am informed by fishermen that about twenty years ago, when oyster dredging, they generally took in a day's work some five or six hundred clams [queen scallops], which were thrown into a basket and taken ashore for bait; while now fifteen times that number may be taken by a boat in a day. As one of them said – 'It used to be a case of picking out clams when dredging for oysters; now it is picking out an occasional oyster when dredging for clams'.*"

He later concluded,

"*There can, indeed, be no doubt that the true cause of the exhaustion of the Forth oyster beds was the long course of improvident and reckless fishing to which they were subjected.*"

He attributed this to the trade in selling young oysters to English and Dutch private oyster fisheries, hence removing young oysters which would previously have been thrown back in the sea.

After Fulton's survey the oyster beds of the Firth of Forth continued to decline. By the 1920s the oyster fishery no longer existed (Millar 1961) and in 1957 another survey was undertaken to once again assess the state of the oyster beds (Millar 1961). 65 hauls were taken, yet no living oysters were found. Only one 'clock' (a pair of valves still attached by the ligament, indicating a recently dead oyster) was found, with dead shells found in 48 of the 65 hauls. In 1961 Miller summarised the difference between his and Fulton's results for five principal species, standardised to the mean number of species found per standard 10 minute haul in Table 5.

Table 5. Results from Millar (1961) showing differences between standardised hauls between 1895 and 1957 in the Firth of Forth. Results show number of each species.

Survey	*Asterias rubens*	*Solaster papposus*	*Chlamys opercularis*	*Buccinum undatum*	*Modiolus modiolus*
1895	19	1.1	150	6	35
1957	12	0.06	1.6	0.8	5.4
Ratio 1895/1957	**1.5**	**18.3**	**94**	**7.5**	**6.5**

Millar (1961) concluded that as well as reductions in numbers of oysters as a result of overfishing other species had also reduced in abundance, particularly the queen scallop. Fulton (1896) stated that in the 20 or 30 years preceding the 1895 survey, queen scallops had become much more abundant in the Firth of Forth and were popular as bait for line fisheries. By the time of the 1957 survey queen scallops had declined in abundance and oysters were not to be found. Horse mussels had also declined.

During the 1990s a study into the feasibility of restocking native oysters in the Firth of Forth was undertaken by Harding (1996) using Van Veen grabs. 34% of the sites examined contained remains of oyster shells and sites which used to support oyster beds largely consisted of semi-consolidated mud and fine sand. Harding (1996) states it to be unlikely that the underlying benthic substrate type will have changed significantly since oyster beds were present, but that the decline of oyster and scallop shells decreased the suitability of the substrate for their juveniles.

During the 1957 survey queen scallops had declined but were still frequent however, no trace of these beds occurred during the 1996 survey. This has been attributed to the build-up in solid sewage sediments and mine waste residues (Howard et al., 1987). No horse mussels were found during this study although Harding (1996) states that this may be due to sampling inefficiency. During the early 1970s the distribution of known populations of horse mussels in the southern area of the Forth was mapped and it was stated that horse mussels had taken over areas of the Firth that were once inhabited with oysters (Covill 1972).

In 1979 a population of adult horse mussels was found off Cramond Island and large numbers of juveniles were found in the vicinity of the Forth bridges (Elliott and Kingston 1987).

4.5.2 Industrial changes to the Firth of Forth

As the industrial revolution gained momentum coastal and inshore waters were increasingly affected by pollution from industry, centres of population and reclamation of land. In the Forth, levels of suspended solids were increased above background levels from the 1750s as areas such as Flanders Moss, a large area of raised peat bog in the Forth catchment, were drained and excavated for use as agricultural land (Scottish Natural Heritage 2009). This resulted in large quantities of material carried downstream and deposited in the Inner Firth as a thick black mud (Harding 1996). In addition, coal and ash solids were regularly deposited overboard by steam trawlers during the late 1800s, whilst suspended solids from coal mines posed a threat to benthic habitats by physical smothering (Harding 1996).

The main source of industrial pollution to the marine environment during the 19th century was from gas works, tanneries and dye works (Griffiths 1987). Today the Forth receives waste from sewage treatment works, petrochemical and oil refineries, coal-fired power stations, distilleries and yeast manufacturers. However on balance, it has been reported that pollutants to this part of the sea have been substantially reduced since the late 1980s (Graham et al., 2001).

4.5.3 Quadrat and video transect analysis

The following section shows results from my in-situ quadrat and video transect analyses from sites in the Firth of Forth. As for Caldey Island and Swansea these provide a description of seabed habitats today which can be compared to the historical descriptions in the previous section. Figure 19 shows the average percentage cover of habitats at each site using quadrats. Sites B, C, F, J and K were dominated by mud mixed with broken, unidentifiable shell. Sites A, E, H and I were dominated by mud that was not obviously mixed with shell. Site G was dominated by live and dead horse mussels mixed with pieces of coal. Site D was omitted from the analysis as no quadrat data were obtained and video footage was too poor to be of use due to low visibility.

Video analysis was carried out for each site with the exception of sites D and H as the video footage was unusable. At the other sites the quality of the resulting images meant it was often difficult to identify to organisms to species. Figure 20 shows the differences between the total number of species recorded using quadrats and video analysis. In general, more species were recorded using quadrats with the exception of site I. This is likely due to the difficulty of identifying many of the organisms when not on site and the poor visibility and low-light conditions experienced when videoing.

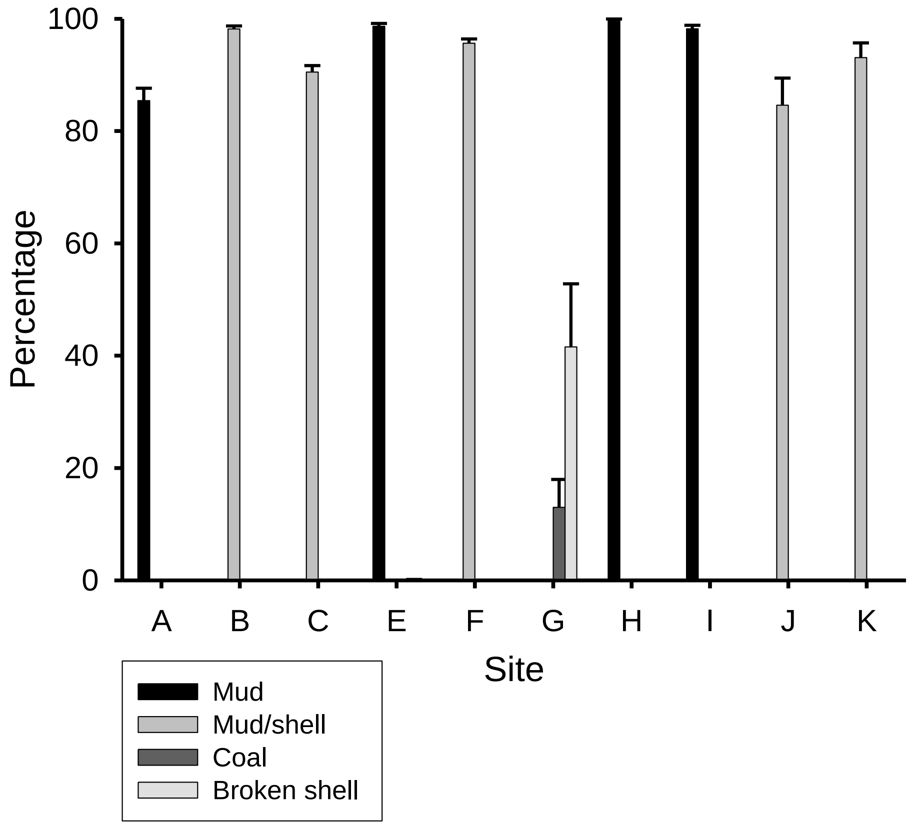

Figure 19. Average percentage cover of major substrate types at each site in the Firth of Forth using ten 1m^2 quadrats, with standard error.

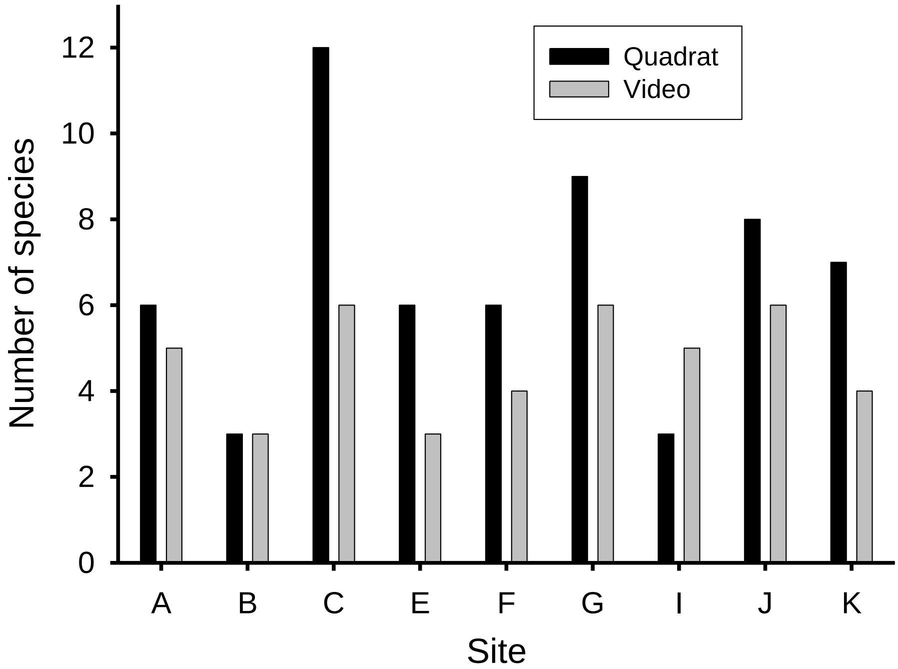

Figure 20. Differences between the total number of species recorded using quadrats and video analysis in the Firth of Forth. Quadrat sampling covered 10 m^2 at each site; video sampling covered approximately 20 m^2.

Figure 21 shows the average percentage cover of horse mussels (live and dead), bryozoa (not identified to species) and sea squirts (*Ascidiella aspersa*) at each site. These made up the majority of the live benthic cover. Other sessile species or shells present in small quantities included oyster shells (sites A, B and E), razor shell remains (*Ensis* sp.), blue mussel and queen shell remains, horn wrack (another species of bryozoan, *Flustra foliacea*), plumose anemones (*Metridium senile*), burrowing anemones (*Sagartiogeton laceratus*), phosphorescent seapens (*Pennatula phosphorea*, site H), soft coral (*Alcyonium digitatum*) and dahlia anemones (*Urticina felina*). Most of these were only found at a few sites and made up a very small percentage of the overall counts. Mobile species weren’t taken into account when calculating percentage cover but included sea mice (*Aphrodita aculeata*, site H), sand gobies (*Pomatoschistus minutus*), common starfish (*Asterias rubens*) and small crabs (e.g. *Macropodia* spp.).

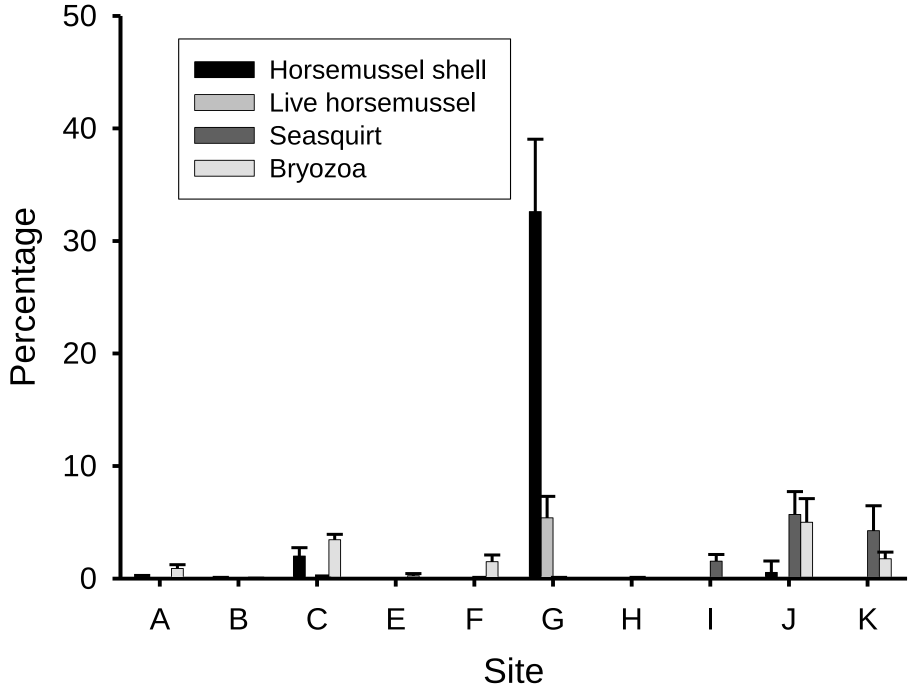

Figure 21. Percentage cover of species present at Forth sites with standard error.

Figure 22 shows the number of shells of live or dead queen scallops, horse mussels or oysters counted at each site within the ten quadrats. With the exception of sites A and G, most sites had low quantities of live or dead individuals. No live oysters and few live queen scallops were found. Only site G had live horse mussels present.

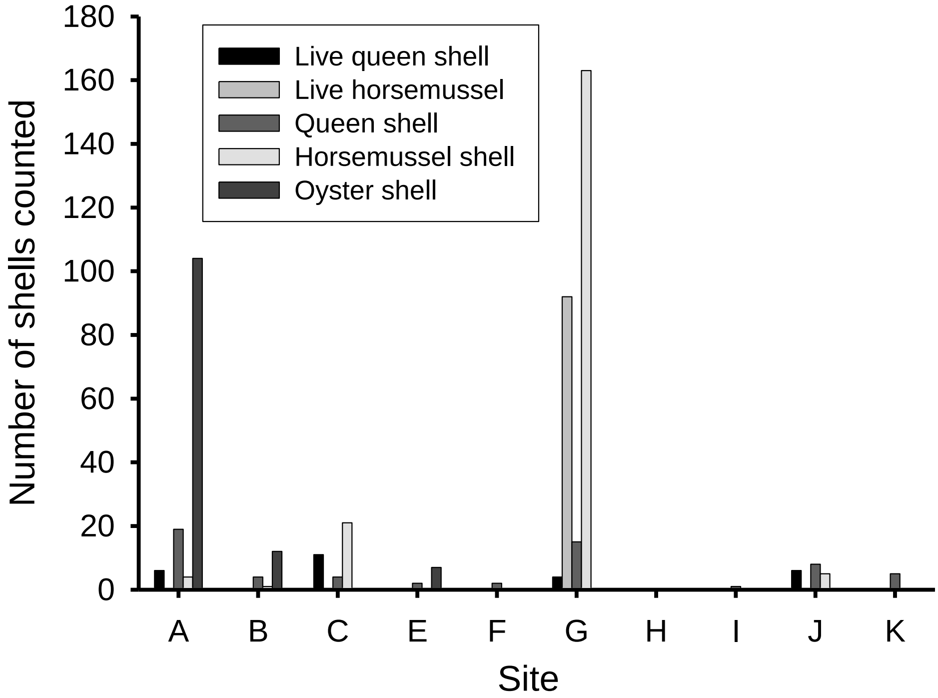

Figure 22. Number of live shellfish and shells counted at each site within 10 1m^2 quadrats in the Firth of Forth. Shell remains do not necessarily represent the number of individuals as most shells were not found in pairs.

4.5.4 Shell community analysis

This section shows results from the sediment cores taken at sites from the Firth of Forth. Cores were taken at all sites apart from site A where a core could not be obtained because hard ground was encountered about 20 cm below the surface sediment. As for Caldey Island sites, it is assumed that the surface of the cores (i.e. 0 cm) represent present day communities. Again I assume that shell-remains that occur deeper in the core are from earlier periods of time and that as they died sediment has accumulated on top of them; hence communities from earlier periods of time are based at deeper depths in the core. Figure 23 show changes to shell biomass (of both identified and unidentified species) from the Firth of Forth at different depths throughout the sediment cores. Sites D, J and K show declines in shell biomass with increasing depth. Sites B, H and I show increases with depth. Site F shows an increase whilst site G seems to decline then increase again. Sites C and E show little overall change with depth.

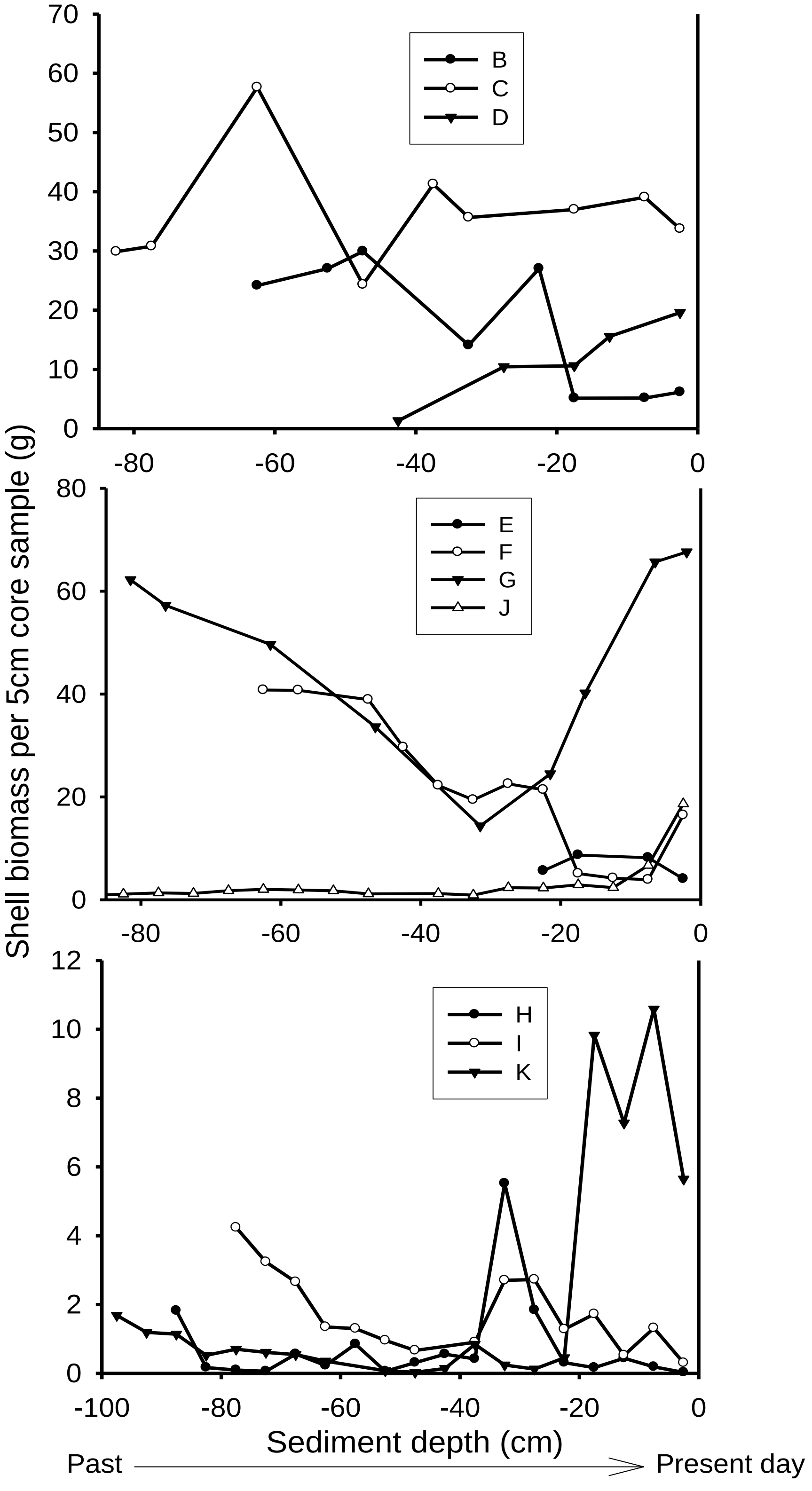

Figure 23. Shell biomass at different depths from Firth of Forth cores, note differences in scale between graphs.

Figure 24 shows changes in the number of identified species with depth for a selection of cores (chosen to show differences between sites). Species richness decreases over time at sites B and G, so that species richness is lower in upper samples of the core, whilst sites D and K increase over time. In addition to the figures shown, site J increased in species richness over time. Species richness at sites F and I decreased over time, whilst sites C, E and H showed little change overall. These sites will be shown in detail in the dating analysis section.

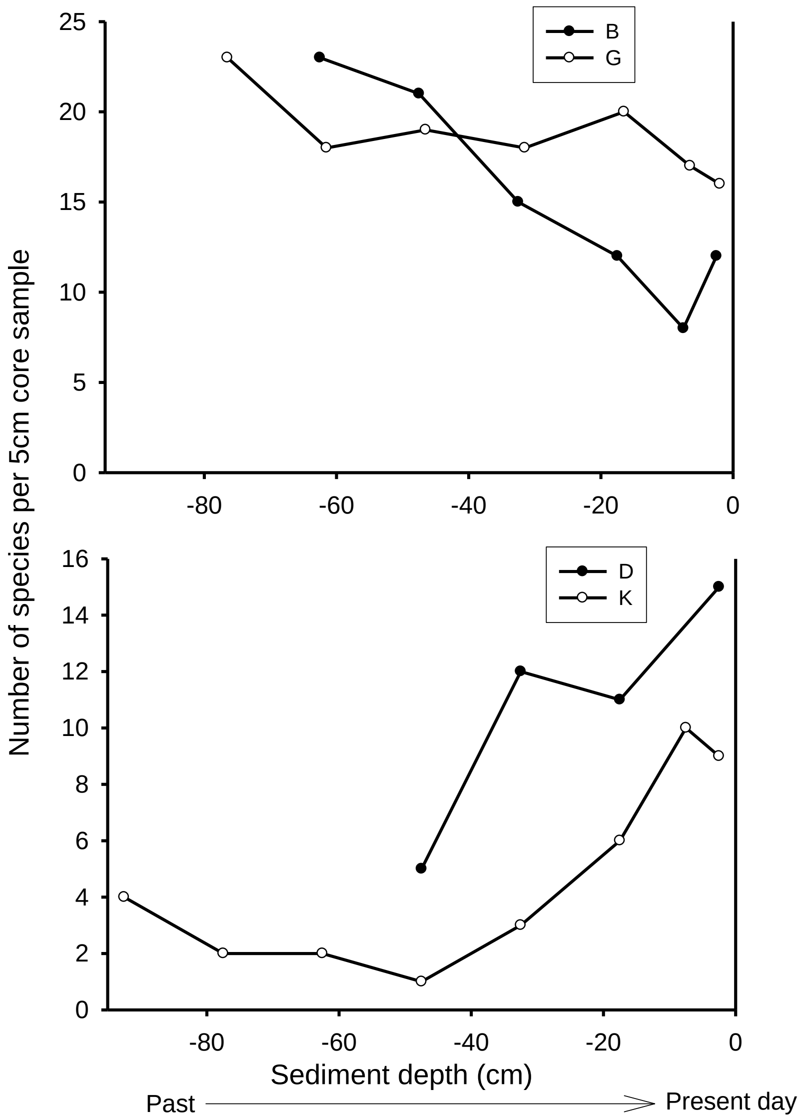

Figure 24. Changes to number of species at different core depths in the Firth of Forth.

Figures 25 and 26 show the most dominant species ranked by proportional biomass for samples from the top, middle and bottom of cores J and G from the Firth of Forth. Site J shows the shallower, later sample to be more dominated by a single species than samples from greater sediment depths (Figure 25). However other samples showed no distinct trends with depth (for example, site G, Figure 26).

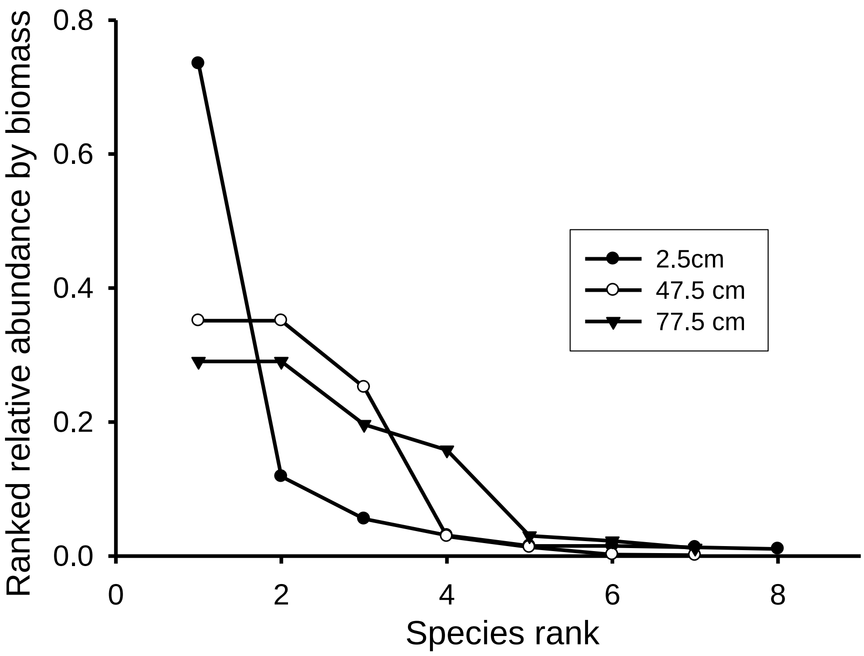

Figure 25. Firth of Forth site J, 8 most dominant species ranked by proportional biomass abundance at different depths throughout the core.

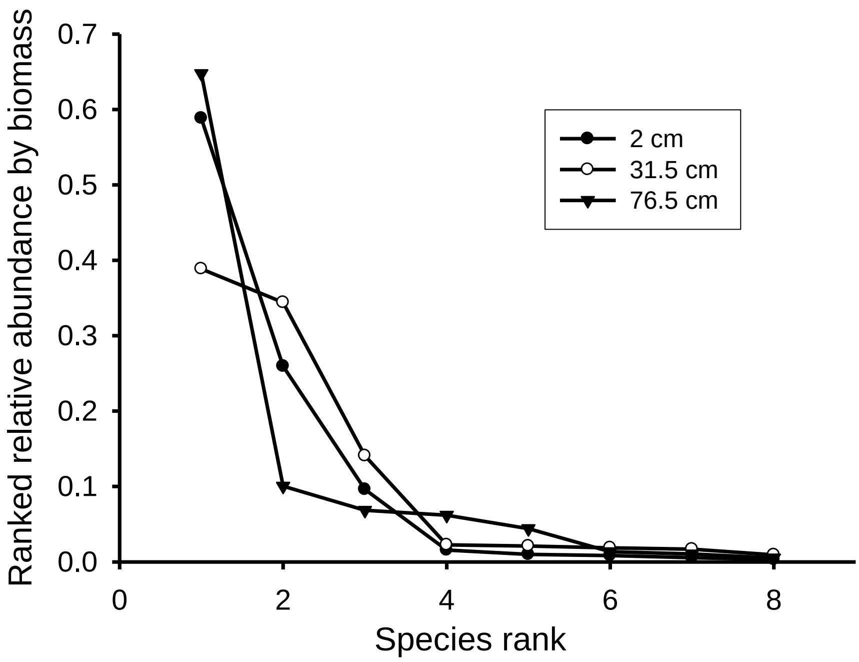

Figure 26. Firth of Forth site G, 8 most dominant species ranked by proportional biomass abundance at different depths throughout the core.

As for the Caldey Island sites, I also recorded changes to species diversity using Simpson's Reciprocal Index of Diversity and Evenness measure. Two examples are provided in Figures 27 and 28. No significant changes over time were seen at sites B, C, F, H or K. At sites I (Figure 27) and J, diversity declined with time but trends were weak (R^2 = 0.43 and 0.33 respectively). Diversity has increased over time at sites D, E and G (Figure 28), but once again trends are weak (R^2 = 0.63, 0.38 and 0.32 respectively). Evenness was also measured, but most cores showed either weak trends or little difference with depth.

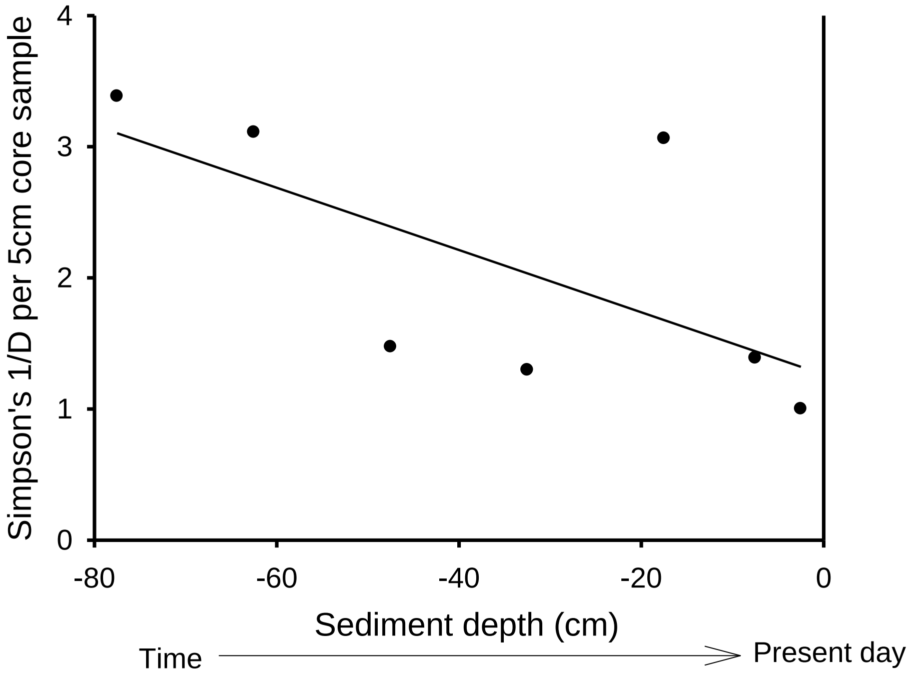

Figure 27. Firth of Forth site I, Simpson's Reciprocal Index of Diversity from samples at different depths using biomass of each species (R^2 = 0.43).

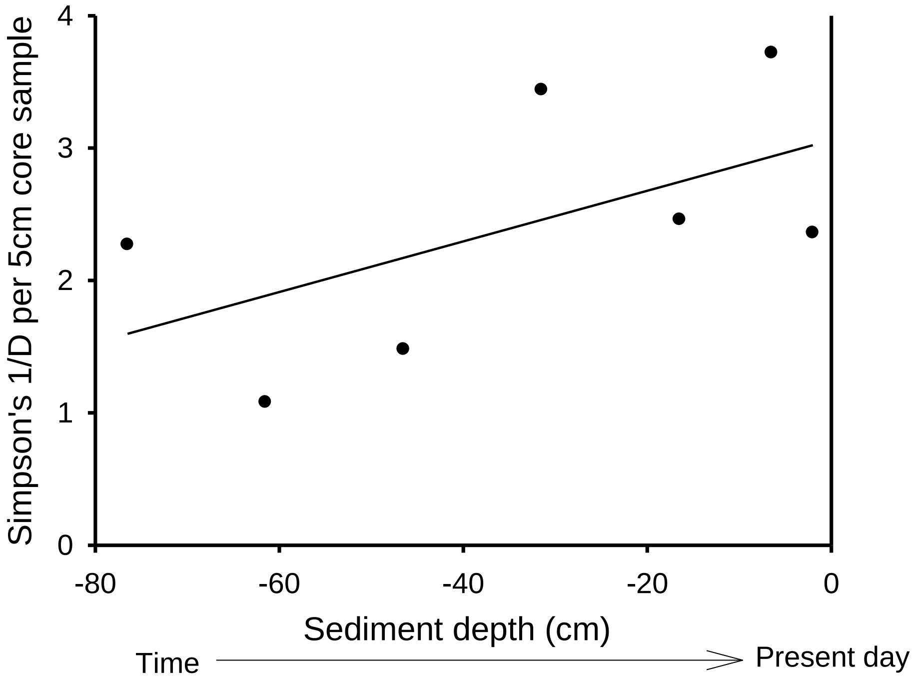

Figure 28. Firth of Forth site G, Simpson's Reciprocal Index of Diversity from samples at different depths using biomass of each species (R^2 = 0.32).

Figures 29 and 30 show examples of the four most abundant species by biomass taken from three samples throughout each core (top, mid and bottom of core) to determine whether dominant species differed over time. If different species dominate at different levels in the core, this could infer an alteration to habitats or conditions over time, or differential preservation. Apart from sites D and E, there was little overlap between the most dominant species. However, the majority of species recorded are found in a variety of habitats, hence this result cannot be used to assess changes to habitat or substrate.

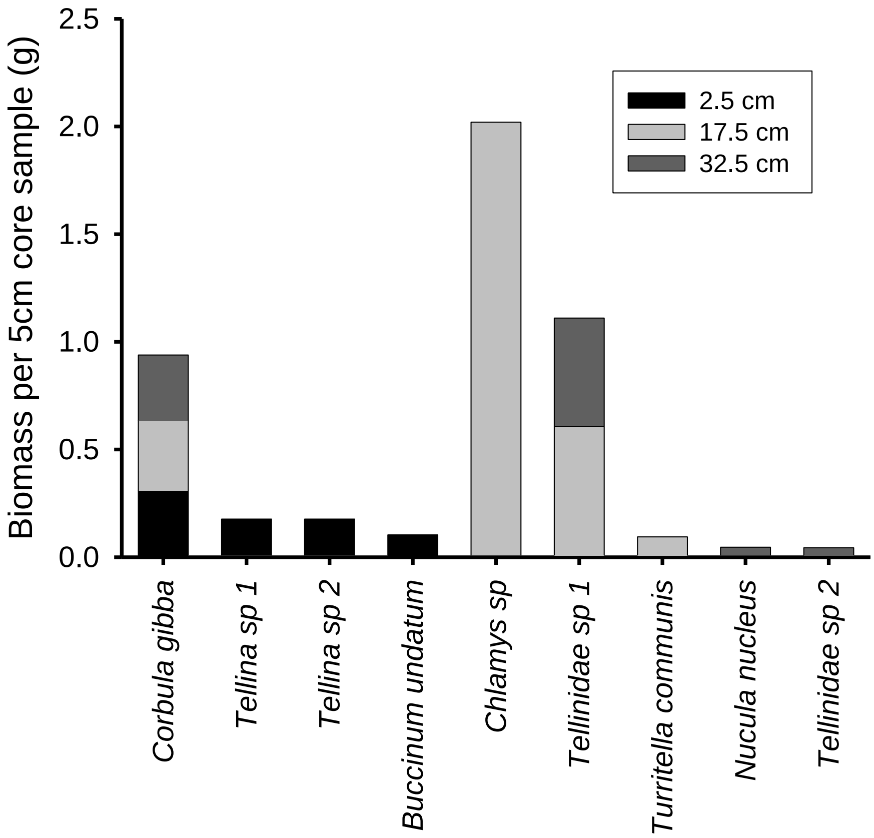

Figure 29. Four most dominant species by biomass at three different depths (equivalent to different points in time) at Firth of Forth site E.

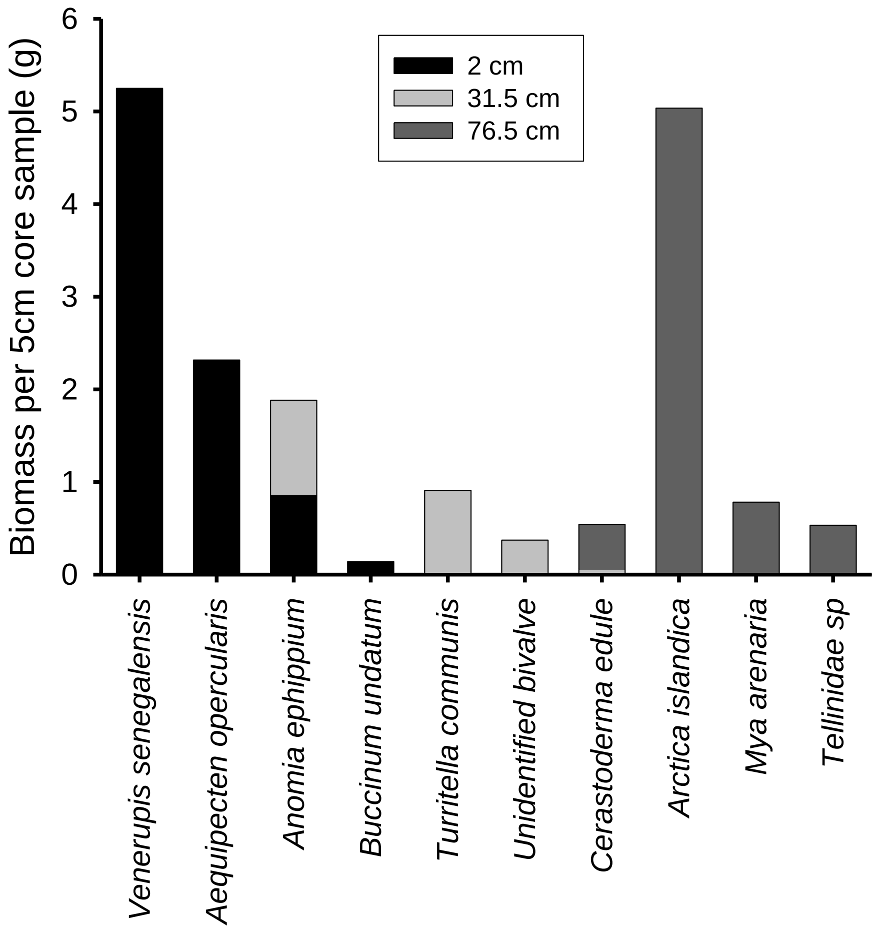

Figure 30. Four most dominant species by biomass at three different depths (equivalent to different points in time) at Firth of Forth site G.

4.5.5 Radioisotope dating analysis

The previous section shows changes in mollusc community composition (using death assemblages) with sediment depth. I assumed that shallower depths correspond to more recent periods of time as sediment has accummulated and buried shells. The application of dating techniques can help to confirm this trend and provide specific dates, thus allowing calculations of sediment accumulation rates. This section brings together the results of these dating analyses undertaken at Southampton National Oceanography Centre.

An Itrax core scanner was used to determine the concentrations of heavy metals such as lead, zinc and copper throughout the core. These elements increased in the Firth of Forth as industrial sites opened and introduced pollution into the estuary. Figures 31 and 32 show examples of results from the Itrax analysis. In Figure 31, site H shows a clear increase in copper and zinc in the top 45 cm of the core. Site C (Figure 32) does not show such a sharp rise, but the top 20 cm does show an increase in these elements. The image on the left of the figure is a visual image of the surface of the core. In Figure 31 a darker layer can be seen in the top 42 cm of the core which may correspond to elevated levels of hydrocarbons (Ian Croudace *pers. comm.*).

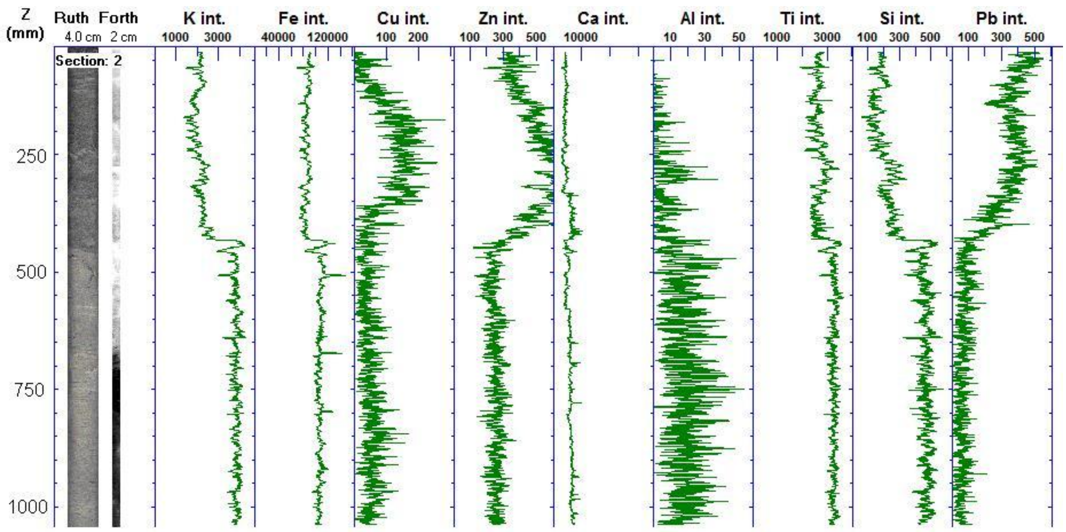

Figure 31. Itrax results for Firth of Forth site H. Sediment depth is shown on the left-hand side. The next column shows a visual image of the core along with a representation of sediment density. Remaining columns show concentrations of various metal elements in the sediment.

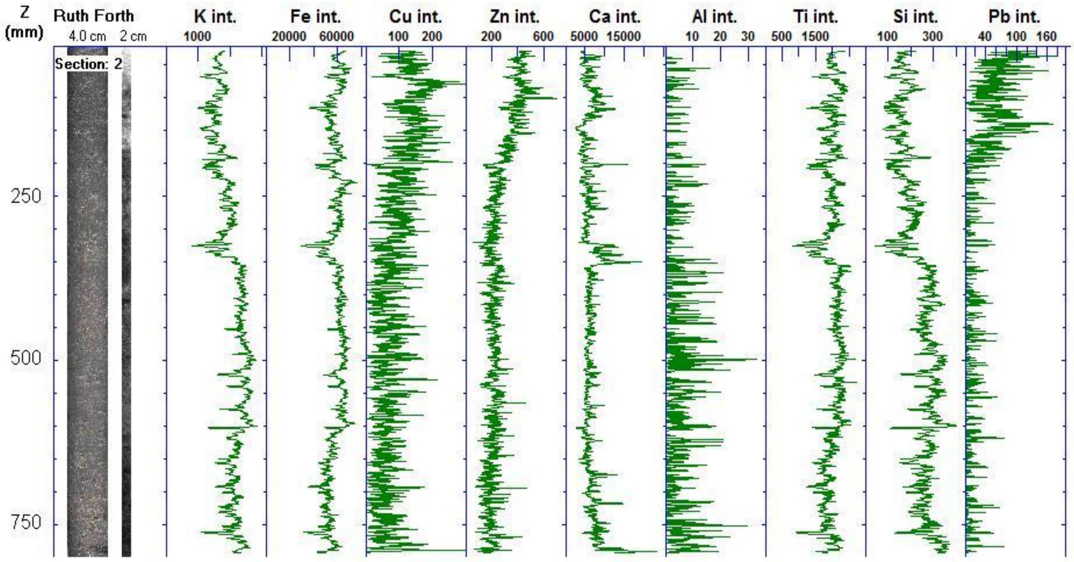

Figure 32. Itrax results for Firth of Forth site C. Sediment depth is shown on the left-hand side. The next column shows a visual image of the core along with a representation of sediment density. Remaining columns show concentrations of various metal elements in the sediment.

Figures 33 to 35 show examples of Cs-137 measurements at different depths from three sediment cores, sites B, F and I. Estimated dates are marked on each figure, corresponding to when Cs-137 was first released into the atmosphere (1954), when nuclear weapons testing reached its peak (1963) and when emissions from Sellafield peaked (1978).

In Figure 33, Cs-137 first appears at 25.5cm depth. However, as some leaching of the isotope into lower layers of sediment is to be expected (Ian Croudace *pers. comm.*) this leads me to assign a date of 1954 to a depth of 20.5cm, just before levels of Cs-137 begin to rise more quickly. The first 'peak' occurs at 18.5cm hence this depth is assumed to correspond to 1963. The expected decline in Cs-137 after this date due to decreased weapons testing (Appleby 2004) is however masked by increased outputs from Sellafield (Bell et al., 1997). These peak at 13.5cm which is thus assigned a date of 1978. This reasoning is applied to all cores tested for Cs-137.

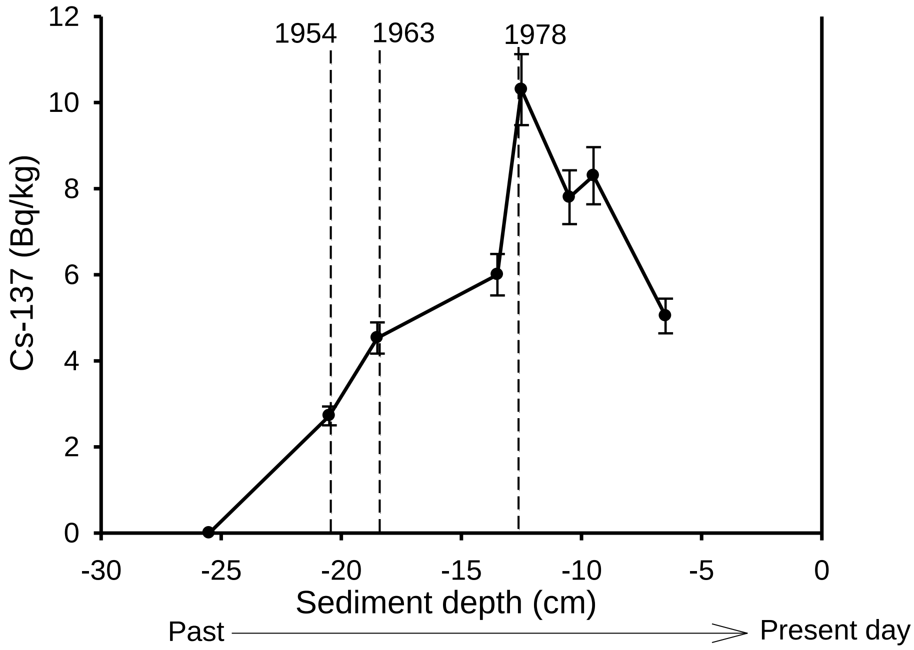

Figure 33. Cs-137 values from Firth of Forth site B with standard error, showing first appearance at 25.5cm depth due to leaching, estimated depth at 1954, first peak in 1963 due to weapons testing and second peak due to arrival of Sellafield effluent in 1978. Actual core = 80 cm deep.

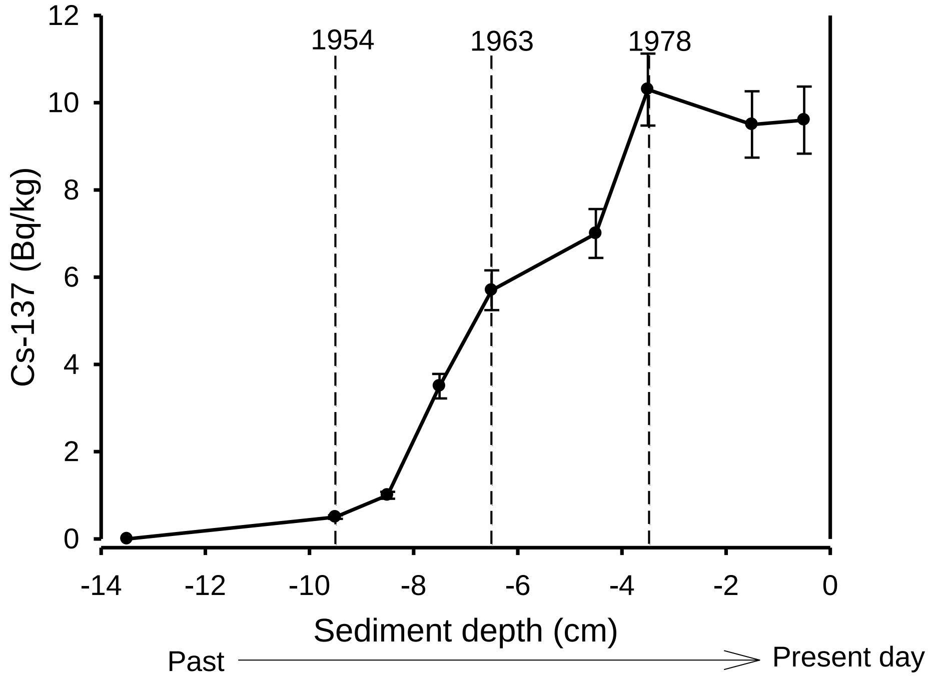

Figure 34. Cs-137 values from Firth of Forth site F with standard error, showing first appearance at 13.5cm depth due to leaching, estimated depth at 1954, first peak in 1963 due to weapons testing and second peak due to arrival of Sellafield effluent in 1978. Actual core = 65 cm deep.

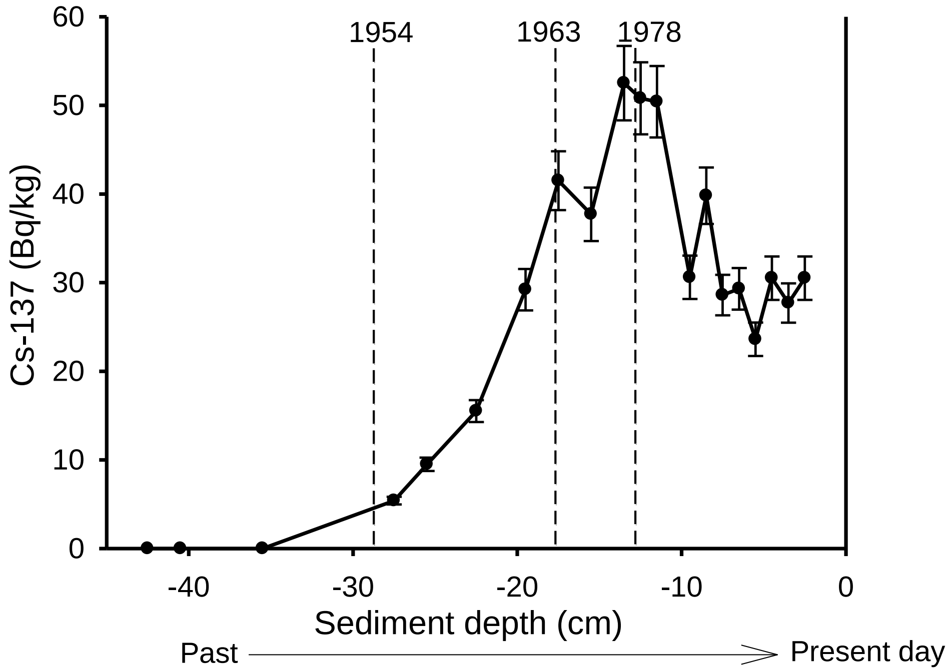

Figure 35. Cs-137 values from Firth of Forth site I with standard error, showing first appearance at 35.5cm depth due to leaching, estimated depth at 1954, first peak in 1963 due to weapons testing and second peak due to arrival of Sellafield effluent in 1978. Actual core = 88 cm deep.

Table 6 shows the depth of the 1978 and 1963 Cs-137 peak for each core analysed along with the depth when Cs-137 is first measured (allowing for leaching of Cs-137 through the sediment). These results can be cross-checked with each other by calculating annual sediment accumulation rates using the dates and depths at which peaks were measured. When annual accumulation rates were calculated for the 1963 and 1978 periods for each of the 9 cores, they corresponded well to each other (Table 6). However the 1954 date is more uncertain due to the problem of leaching through the sediment layers. If 1954 sediment accumulation rates did not correspond well with accumulation rates calculated from the 1963 and 1978 peaks, these results were disregarded when applying dating estimates to the cores. The 1954 date was disregarded for sites C, D and E, but is still shown in Table 6 for information purposes.

Estimated sediment accumulation rates were also calculated from the Itrax results (Table 6) based on the assumption that increases seen in copper (Cu) and zinc

(Zn) correspond to a period of time from 1900-1930. I decided upon these dates because industries in and around the Forth have been shown to be major contributors of Cu and Zn into the Firth of Forth (Davies 1987). In particular, sites at Grangemouth, Rosyth and Burntisland (in the Forth estuary and on the north coast of the Firth of Forth respectively) used to discharge large quantities of these metals, hence the period of time during and shortly after these industries began (1900-1930) was used as a reference point (Bell et al., 1997; Elliott and Griffiths 1987; Elliott and Kingston 1987).

Table 6. Reference dates from Cs-137 and Itrax analyses and corresponding depths within each core. AR = calculated accumulation rate (cm.year^{-1}).

Site	Depth of 1978 peak (cm)	**AR for 1978**	Depth of 1963 peak (cm)	**AR for 1963**	Depth of 1954 peak (cm)	**AR for 1954**	Depth of Cu/Zn rise (cm)	**AR for 1900**	**AR for 1930**
B	12.5	**0.39**	18.5	**0.39**	20.5	**0.37**	30	**0.27**	**0.38**
C	7.5	**0.23**	10.5	**0.22**	23.5	**0.42**	20	**0.18**	**0.25**
D	8.5	**0.27**	15.5	**0.33**	30	**0.54**	35	**0.32**	**0.44**
E	1.5	**0.05**	3.5	**0.07**	10.5	**0.19**	8	**0.07**	**0.10**
F	3.5	**0.11**	6.5	**0.14**	9.5	**0.17**	25	**0.23**	**0.31**
G	11	**0.34**	14.5	**0.31**	20	**0.36**	45	**0.41**	**0.56**
H	-	**-**	-	**-**	-	**-**	45	**0.41**	**0.56**
I	13	**0.41**	17.5	**0.37**	27.5	**0.49**	40	**0.36**	**0.50**
J	4.5	**0.14**	6.5	**0.14**	13.5	**0.24**	15	**0.14**	**0.19**
K	4.5	**0.14**	10.5	**0.22**	14.5	**0.26**	-	**-**	**-**

Figures 36 to 38 show the results of the Pb-210 analysis for three of the seven cores tested. In accordance with its half life, Pb-210 levels should halve every 22.3 years and in theory around five half lives can usually be seen before Pb-210 activity can no longer be measured. In practise however this is often closer to three half lives (Appleby 2004). In Figures 36 to 38 an initial sharp decline is seen, at which point Pb-210 concentrations come more constant, suggesting that at this point background levels of Pb-210 have either been reached or that mixing has occurred in lower layers. Concentrations of Pb-210 appear to decline very quickly throughout the cores and have low levels of activity. This leads me to conclude that Pb-210 is unlikely to be a reliable dating reference.

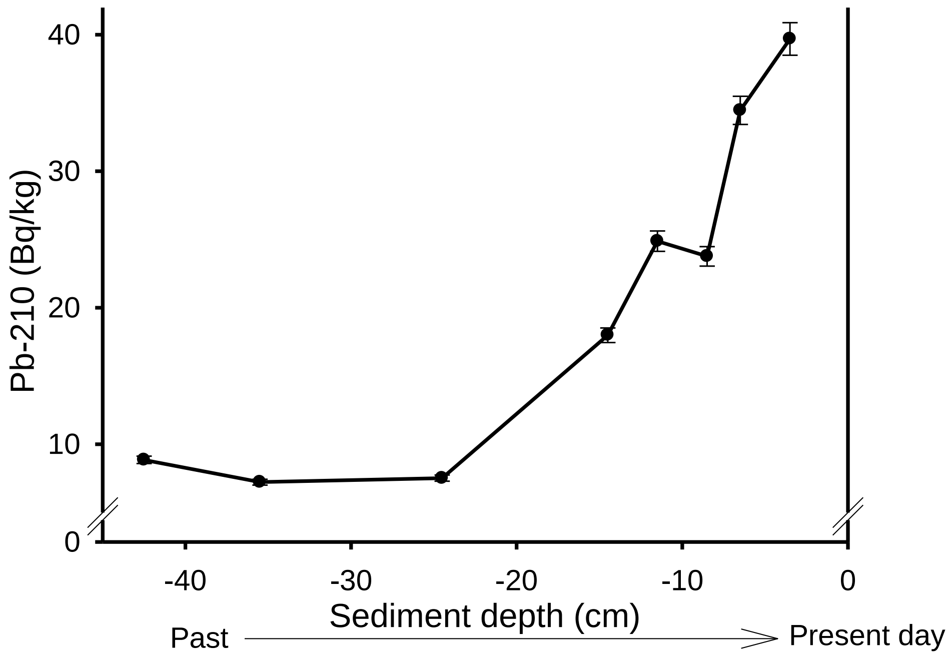

Figure 36. Pb-210 values from Firth of Forth site C with standard error. Actual core = 90 cm deep.

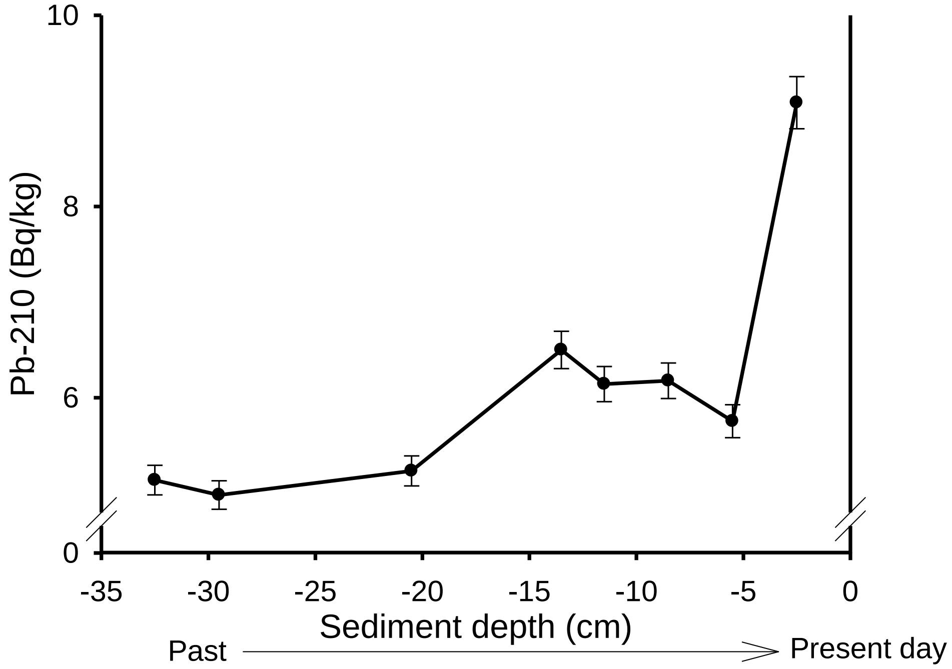

Figure 37. Pb-210 values from Firth of Forth site F with standard error. Actual core = 65 cm deep.

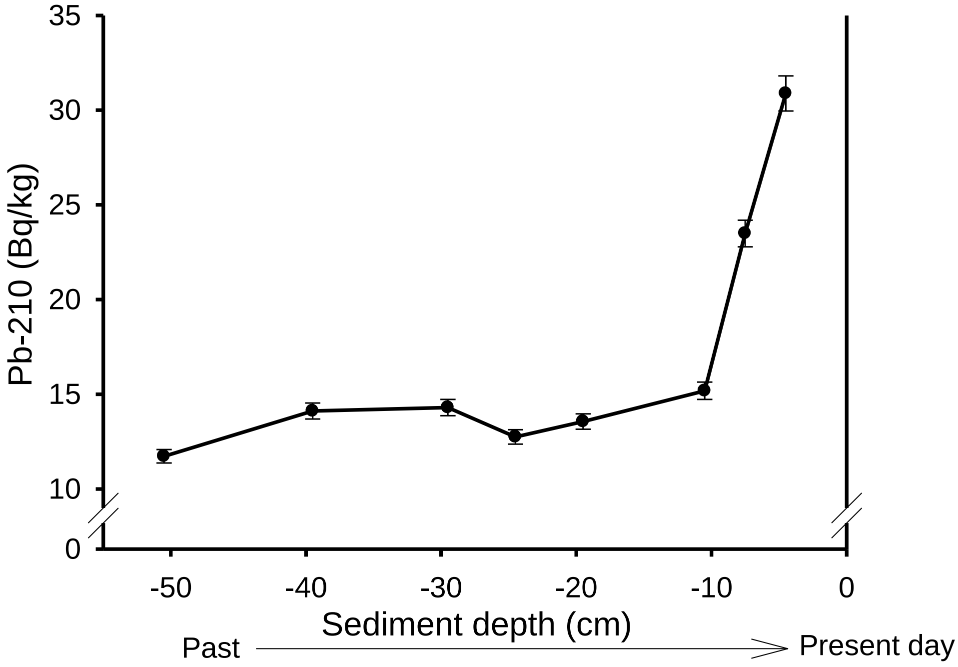

Figure 38. Pb-210 values from Firth of Forth site J with standard error. Actual core = 100 cm deep.

4.5.6 Applying dating references to Firth of Forth sediment cores

The following figures show changes to species richness and shell biomass throughout nine of the cores with estimated reference dates applied. Site H was not plotted as Cs-137 depths were not calculated. Dates from the Cs-137 and Itrax analyses were applied to provide a reference in determining when changes to mollusc biomass and species richness took place. It is assumed that increases in Cu and Zn correspond to 1900-1930.

Figure 39 shows estimated dates from Cs-137 and Itrax analyses at site B. These dates correspond well to each other showing that the observed decline in species richness and shell biomass most likely occurred prior to the 20th century. During the 20th century, species richness continued to decline whilst some recovery in shell biomass was seen, however then trends continue to decline. Recovery seems to have occurred during more recent years. Estimated dates for site C (Figure 40) correspond well using Itrax and Cs-137 analyses, with depths below 20 cm likely to correspond to a time before the 20th century. There are no obvious declines in species richness or shell biomass in recent years, but results suggest that these may have been higher during the 19th century or before.

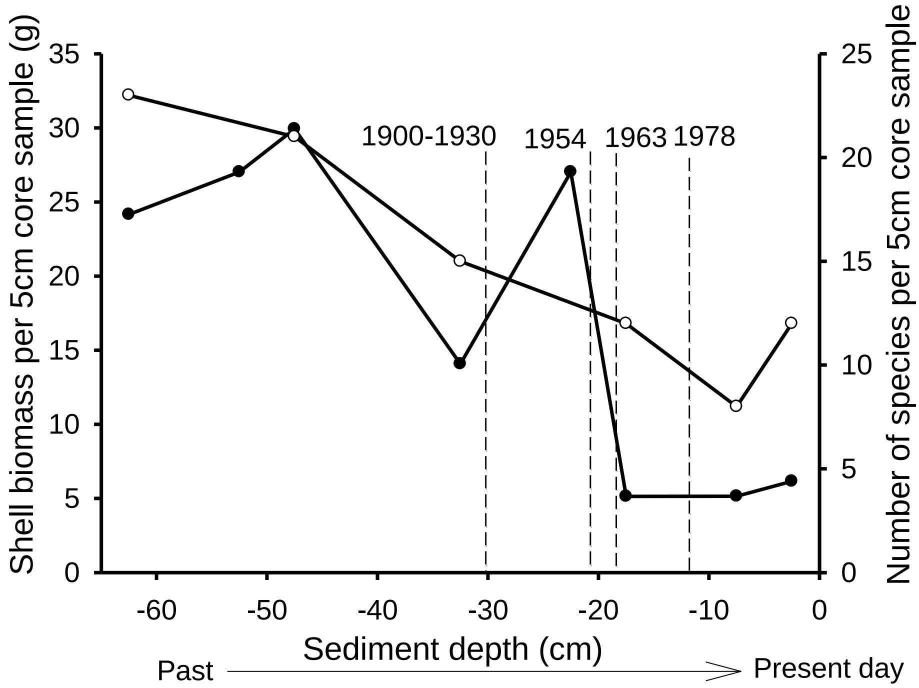

Figure 39. Changes to mollusc species richness (open circles) and shell biomass (closed circles) per 5 cm core sample over time at Firth of Forth site B.

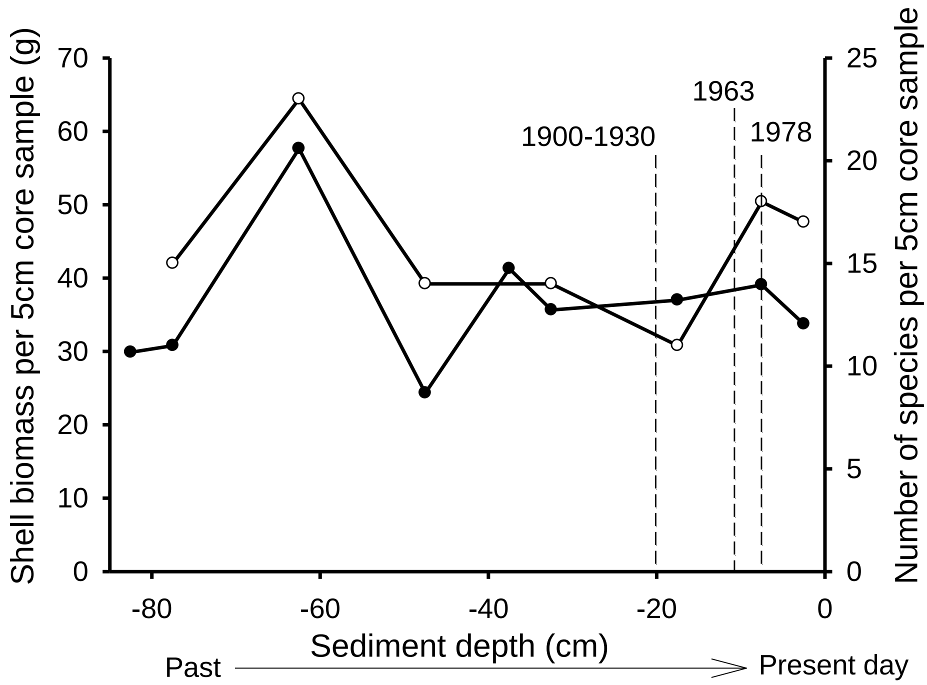

Figure 40. Changes to mollusc species richness (open circles) and shell biomass (closed circles) per 5 cm core sample over time at Firth of Forth site C.

Reference dates for site D (Figure 41) do not include the 1954 Cs-137 reference date as this did not correspond to the dates of the 1963 and 1978 peaks. Using the two Cs-137 peaks and the increase in Cu and Zn as a guide it would appear that both species richness and shell biomass increase during the 20th century, however the core was not long enough to provide earlier information. Site E does not appear to show much change over time in mollusc species richness or shell biomass (Figure 42).

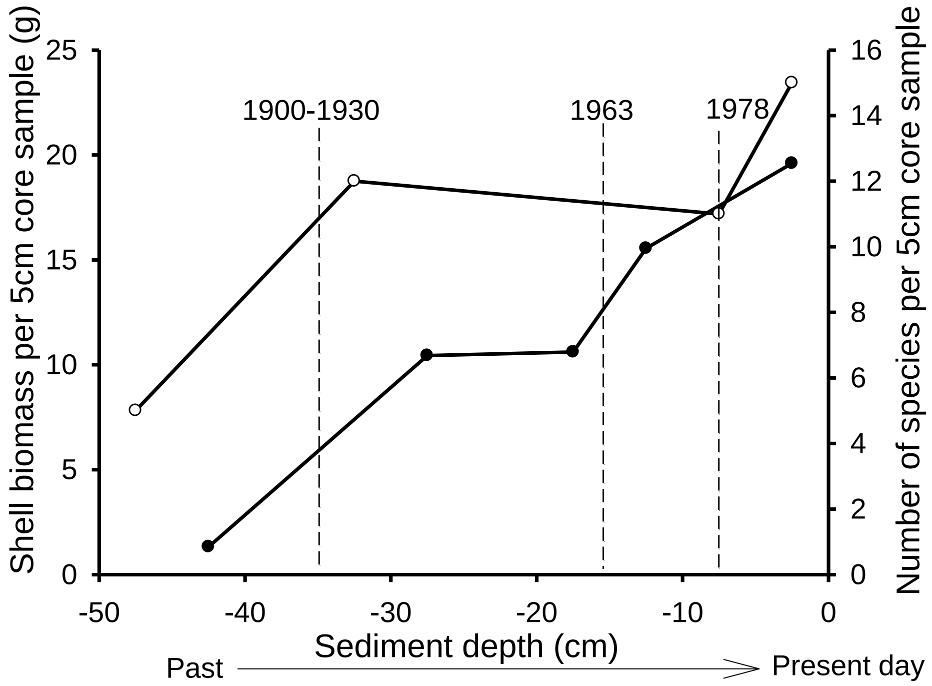

Figure 41. Changes to mollusc species richness (open circles) and shell biomass (closed circles) per 5 cm core sample over time at Firth of Forth site D.

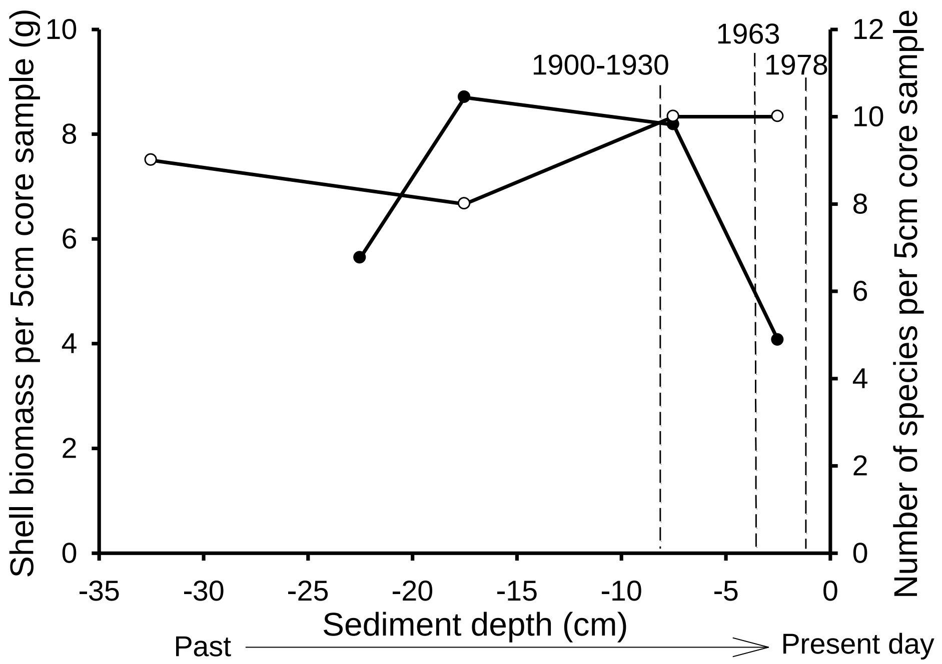

Figure 42. Changes to mollusc species richness (open circles) and shell biomass (closed circles) per 5 cm core sample over time at Firth of Forth site E.

Figure 43 shows results from site F. The Cs-137 and Itrax analyses correspond well. Trends in shell biomass and mollusc species richness show that declines occurred before the onset of the 20th century and continued until the mid-20th century when both saw some recovery. Site G (Figure 44) shows a decline in shell biomass prior to 1900-1930, with recovery during the 20th century. Species richness shows a slight decline overall but remains more stable than shell biomass. Dates correspond well with each other.

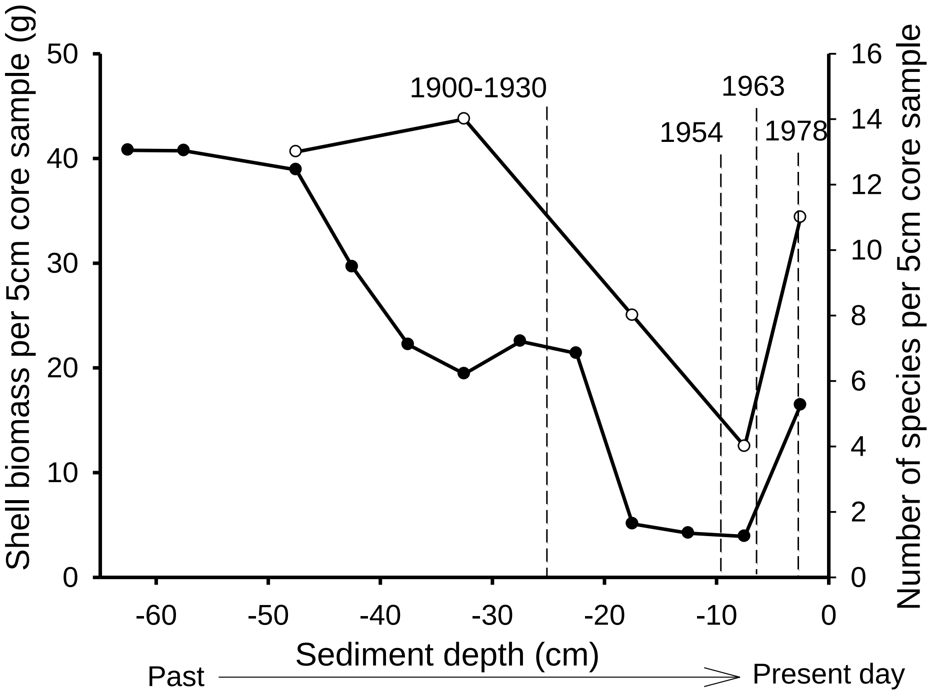

Figure 43. Changes to mollusc species richness (open circles) and shell biomass (closed circles) per 5 cm core sample over time at Firth of Forth site F.

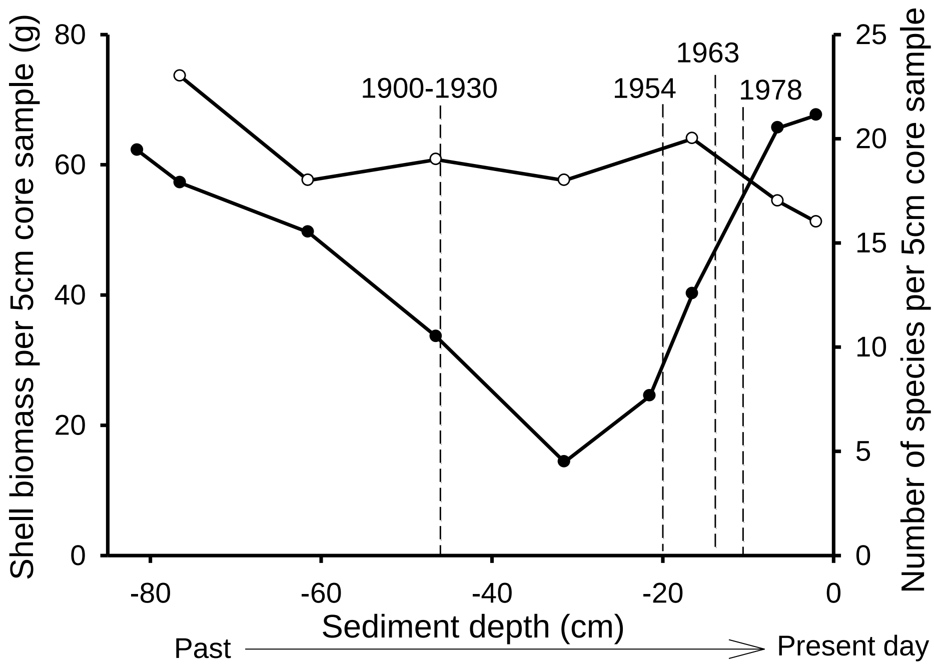

Figure 44. Changes to mollusc species richness (open circles) and shell biomass (closed circles) per 5 cm core sample over time at Firth of Forth site G.

Figure 45 shows that past shell biomass and species richness at site I were greater than the present day. Some recovery is seen during the early and mid-20th century, however in recent years shell biomass and species richness have declined to low levels. Cs-137 and Itrax dates correspond well.

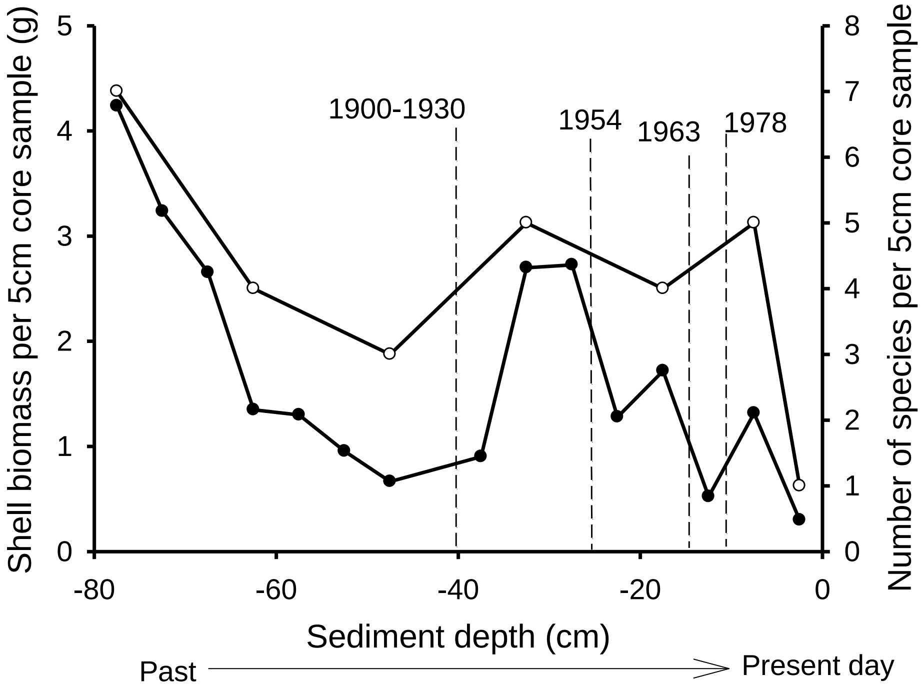

Figure 45. Changes to mollusc species richness (open circles) and shell biomass (closed circles) per 5 cm core sample over time at Firth of Forth site I.

Figure 46 shows results from the sediment core at site J. This shows a different pattern to preceding figures, in that shell biomass and richness were lower in earlier years with increases seen during the 20th century. Similar patterns were also seen at site K (Figure 47). Itrax analysis was not performed on this core due to cost constraints. However due to its proximity to site J and similarity in Cs-137 calculated accumulation rates I have assumed that the 1900-1930 dates occur at a similar depth to site J (Figure 46).

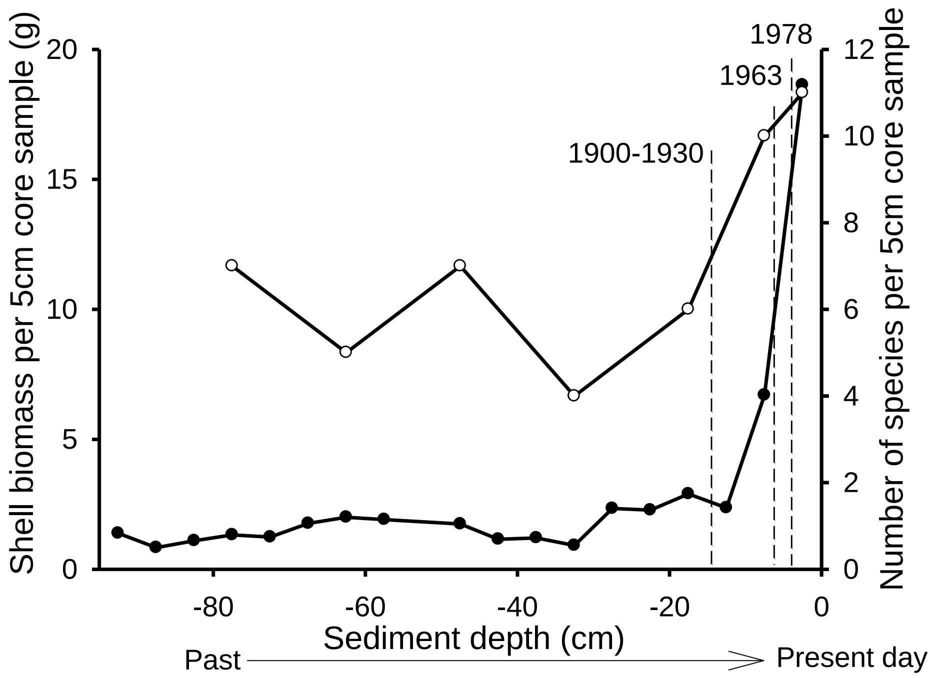

Figure 46. Changes to mollusc species richness (open circles) and shell biomass (closed circles) per 5 cm core sample over time at Firth of Forth site J.

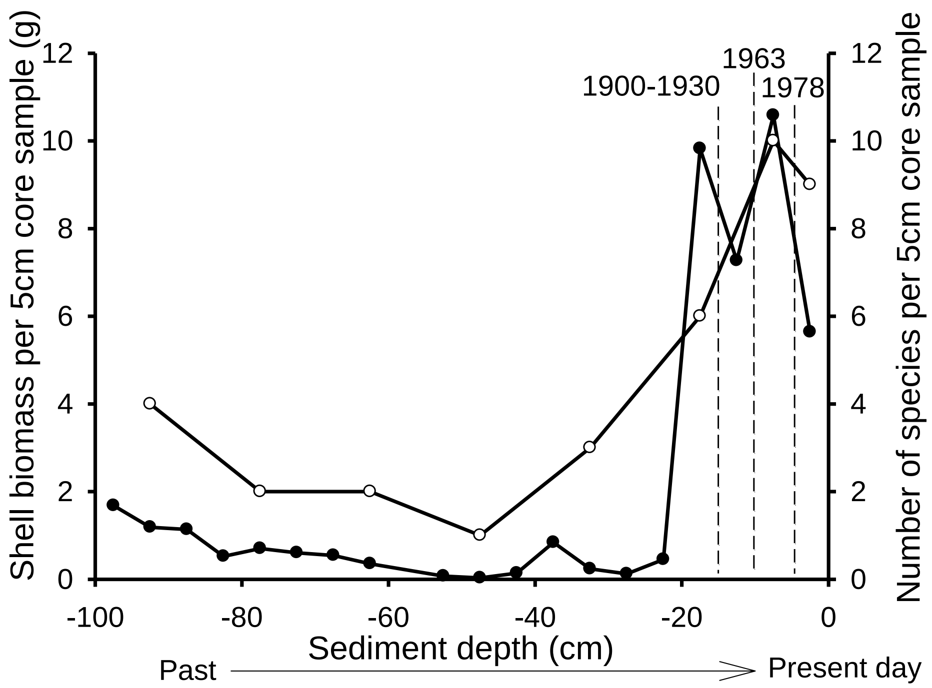

Figure 47. Changes to mollusc species richness (open circles) and shell biomass (closed circles) per 5 cm core sample over time at Firth of Forth site K.

4.6 DISCUSSION

Alterations to marine habitat and benthic communities over time are difficult to record and quantify. Anecdotal evidence of change does exist but is limited. In this chapter I have used historical research, field surveys and chemical dating methods of sediment deposits to build up a picture of change over time for three sites around the UK and to attempt to derive reference dates for these changes. My work cannot be directly compared to past field sampling because the methodology which gave rise to the historical results was so different to the method of data collection that I performed in the field. Whilst I used SCUBA to sample quadrats with photographic and video equipment, Fulton (1896) and Wright (1932) used dredges to obtain their data. Despite the differences in approach it is clear from the results that habitats have altered substantially since the first scientific surveys were undertaken.

4.6.1 Quadrat and video transect analysis

Great changes have taken place amongst benthic communities in the Firth of Forth. During the last 150 years, oyster beds have disappeared while queen scallops and horse mussel populations have declined. Starfish and brittlestars still occur in some quantity, but in general I saw few crustaceans or live bivalves in my samples. By contrast the presence of phosphorescent seapens at site H and the presence of horse mussels at site G suggests that in recent times at least, these sites have been relatively undisturbed. Except for site G, few hard substrates were present. Surveys conducted at Swansea did not produce live oysters and very few oyster shells compared to surveys conducted 80 years ago. Whilst I do not have past scientific surveys for Caldey Island, the presence of oyster beds shown on Admiralty charts suggests that there were significant numbers of oysters in the early-19th century. This is not the case today.

4.6.2 Shell community analysis

Using mollusc shells to determine past community composition requires careful interpretation since post-mortem processes may result in shell remains that do not always reflect past realities (Kidwell and Bosence 1991). For example, the composition of the shell assemblage may be modified by differential preservation e.g. some shells break down more quickly than others due to size, shape or chemical composition. Assemblages from different periods might also have been mixed together (time-averaged) by physical or biological processes i.e. bioturbation (Kidwell and Bosence 1991). Differential preservation can reduce or skew past measures of species richness and/or biomass, whilst time averaging may increase perceived species richness as species from different layers of sediment become mixed together over time (Kidwell 2002). Despite these caveats, Kidwell and Bosence (1991) state that mollusc remains are generally considered to provide a good indication of the original rank order of these species, hence should provide a reasonable comparison of changes over time.

Results from shell community analysis in the Firth of Forth showed varying degrees of change with sediment depth. Species diversity indices and dominance patterns did not seem to vary significantly with depth, or at best showed weak trends. Most sites were dominated by one or a few species, a pattern that has persisted. At Caldey Island the greatest shell biomass occured in the top layers of sediment. Here currents are strong and it is likely that sediment is moved before it can settle, thereby leaving large shells on the surface. Whilst this is backed up by the presence of old oyster shells I could not apply dating techniques to verify this due to the sandy nature of the sediment.

I applied a range of dating techniques to the Firth of Forth cores to try to provide reference dates for the shell community analysis. Clear Cs-137 peaks appear to suggest that a sequential chronology exists for at least the last 50 years. Bell et al. (1997) also stated that Cs-137 dating was reliable in the Forth environment, however this work took place further inland within the Forth estuary, so may not be applicable to my results. Itrax scans also provided evidence for the existence of a sediment chronology as they show Cu and Zn to increase in shallower parts of the core. Literature searches reveal industrial effluent to be a major contributor of Cu and Zn (Balls and Topping 1987) hence increases in these metals were likely to coincide with a rise of industry in the Forth. The greatest growth in industry appears to be just after the turn of the 20th century when large industrial plants were set up around Grangemouth, Rosyth and Burntisland. Whilst patterns of Cs-137 activity levels and heavy metals suggest the presence of a sediment chronology, the Pb-210 analysis did not work as hoped. Leaching of Pb-210 through the sediment may have affected the results by masking declines of Pb-210 in deeper sediments. An alternative explanation is that past increases in sediment accumulation rates caused a decline in initial Pb-210 levels i.e. because atmospheric fall-out of Pb-210 is constant, increased levels of sediment cause dilution of Pb-210 concentrations as the same amount of isotope bonds to a greater number of sediment particles (Appleby 2004). Measurements of Pb-210 throughout the core would thus have different initial concentrations as a result of varying accumulation rates over time, therefore not decline in concentration with depth as expected. This explanation corresponds with land-use changes and increasing urbanisation that occurred around many estuaries during the past 100-200 years (Pasternack et al., 2001; Swales et al., 2002). Another explanation is that sediment mixing has masked declines in levels of Pb-210 over time.

The mixing of sediments within the Forth is a factor that may significantly impact upon the reliability of radionuclide dating of sediments. Whilst mixing of sediments may affect shell remains by moving them vertically through the sediment, another important process is the mixing of sediments by live bivalves, annelids and other invertebrates (Kidwell and Bosence 1991). The potential for bioturbation processes to affect sediment chronology was not fully addressed by Edgar and Samson (2005), but has been shown to affect sediments in the Irish Sea and off the west coast of Scotland (Hughes et al., 1996; Kershaw et al., 1983). Kershaw et al. (1983) showed that bioturbation strongly influences the distribution of radionuclides over the upper few tens of centimetres of seabed sediments. Further work by Kershaw (1986) showed that mixing by infauna was able to disrupt the signal of Carbon-14 down to a depth of 55 cm.

Although my survey work showed a low abundance and diversity of epifauna in the Firth of Forth, it may be that a high biomass of infauna exists that would have been missed by dive surveys but are able to significantly mix the sediment. Burrowing molluscs have been found at depths of 50 cm or more in the Firth of Clyde (Hall-Spencer 1998), an environment similar in many respects to the Firth of Forth. Thoughout the inner Firth of Forth, infaunal communities of the Firth of Forth investigated by Elliott and Kingston (1987) were found to be dominated by burrowing bivalves such as *Venus* and *Abra* spp., both of which can burrow to depths of 40 cm (Allen 1983). Hence it is likely that bioturbation by infauna such as these stongly influences the distribution of radionuclides in the upper 40 to 50 cm of sediment, a factor that must be taken into account when attempting to date marine sediments.

Mixing may also have been as a result of physical processes, for example some fishing gear is able to penetrate the sediment to 15 cm depth (Kaiser et al., 1996). In addition, the shallow nature of some sites (less than 5 m depth at chart datum in places) means they are likely to have been affected by past storm events. The fact that later sediments appear to show more chronological stability (i.e. peaks occur in Cs-137 activity) may be a result of more intense mixing and sediment focussing in the upper layers by infauna.

If the reference dates applied were taken as estimates, the combination of methods used suggests that declines in overall mollusc species richness and biomass occurred before the onset of the 20th century at 4 sites (sites B, F, G and I). Declines continued throughout the early 20th century at all of these sites, with increases in biomass and species richness seen at three of the four sites from the mid-20th century onwards (sites B, F and G). Sites D, J and K showed an increase in species richness and biomass throughout the 20th century, although this pattern may have been different for site D had a longer sediment core been obtained (it was only 58 cm long). All of these sites are close to the southern shore of the Firth so may have been subjected to heavy fishing activity and localised pollution earlier than other sites. Sites C and E showed little change over time. However, these results must be interpreted with caution in light of the potential for bioturbation and other mixing effects to alter the chronology of sediment from different depths. Four of the ten sites analysed for shell biomass showed greater biomass in the upper part of the core. Whilst some infaunal molluscs such as *Mya* and *Ensis* spp. may live at a considerable distance below the surface (e.g. 40-60 cm) (Hall-Spencer 1998), many others occur closer to the surface (Eleftheriou and Holmes 1984) as they are limited by feeding behaviour and tolerance to oxygen-limited environments (Cardoso et al., 2010; Hines and Comtois 1985). It is therefore likely that the vertical distribution of mollusc shells is not just a function of time, but also related to the ecology of each species. Again, this did not appear to be taken into account in Edgar and Samson's (2005) study.

4.6.3 Evaluation of results

In this chapter I attempted to quantify habitat change using a variety of methods. Quadrat sampling was more effective than video transects as a result of the poor visibility conditions encountered in the field. I believe my quadrat samples provided a good representation of species richness of surface epifauna for sites sampled in the Firth of Forth, as it was clear during my dives that species richness and habitat diversity was low and did not vary greatly within a site. Horse mussels were an exception because they were patchily distributed and therefore may not have been adequately assessed by quadrat sampling on the scale I adopted. Species richness was generally greater at the more southerly Swansea and Caldey Island than in the Firth of Forth. Caldey Island sites did not differ greatly, so I believe that my sampling presents a good representation of the sites in this area. Swansea had a range of different habitats, so further sampling would bolster my results for current habitats and species present. However, other work in the area (Cooke 2003) has failed to find any remnant of oyster beds lending support to my findings.

Historical references show that oysters declined during the 19th century as a result of over-exploitation, however information is rarely available for other shellfish species. For the Firth of Forth, sediment cores and dating techniques allowed me to investigate changes that occurred in the wider mollusc community at a time when the area was heavily exploited for oysters and queen scallops using destructive fishing gears. As a result of bioturbation and other processes that mix the sediment, it is difficult to be confident of the chronology of patterns in the core results. Additional data on the ages of shells in the samples would allow me to come to more robust conclusions on this. Further core samples from the same areas as well as other sites throughout the Forth would also help verify biomass and species richness patterns.

4.6.4 Conclusions

Historic literature and contemporary field sampling show that oysters, queen scallops and horse mussels have declined over time and today have virtually disappeared from the Firth of Forth and South Wales. In the past the shells of these animals formed a hard substrate which provided a habitat for the settlement of young shellfish and other species. Nearly 250 species of animals and plants have been found to be associated with oyster beds, although not all from the same place (http://www.naturalengland.org.uk/ourwork/marine/protectandmanage/mpa/mcz/features/habitats/nativeoysterbeds.aspx).

Today in the Firth of Forth and at three of the sites in Swansea this shell base has disappeared, leaving mud and sand habitats dominated by different communities. For the Firth of Forth, descriptions of the quantity of oysters removed during the 19th century provides evidence that much of the shell base was removed or destroyed around this time, with queen scallops taken in later years as a targeted fishery. This removal of shell and other surface invertebrates was commented on in 1883 by W. Hunnam, a fisherman from Cockenzie on the south coast of the Firth of Forth,

"Just off Prestonpans, about a mile and a half, or two miles, there the trawlers come regularly down and put away their beam trawl; and I could take any fisherman […] about two miles off Cockenzie, and then six miles east and west, where they have taken away the upper crust of the ground. And, mark you, it is the upper crust that the scallops and clams live amongst. […] [The crust] is just a ground made up of broken shells, and all the like of these sort of things; and

underneath that is mud. If we give our dredge half a fathom too much rope, she goes down altogether into the mud.” (Royal Commission 1885)

Ultimately it may be that the Firth of Forth and areas of Swansea Bay have undergone a regime shift to an alternative stable state consisting of soft and mobile sediments which has made it difficult for shellfish beds to re-establish.

In his report on the Firth of Forth oyster beds Fulton (1896) stated that fishing was the main reason for their decline. The huge numbers of oysters removed for consumption during the 18^{th} and 19^{th} centuries lent weight to Fulton’s argument. Whilst pollution could have been a contributing factor, the continuation of other demersal fisheries such as for scallops suggests otherwise. Increased sedimentation rates over time may have altered conditions within the Firth of Forth and may also have been a factor at Swansea Bay as the area was dredged to deepen navigation channels. However, for the Firth of Forth at least, sedimentation rates increased from the 1750s onwards, long before oysters and other shellfish declined noticeably (Fulton 1896; Harding 1996). Declines only commenced once oysters started to be removed on a large scale for human consumption and to restock other beds. Whilst it is likely that other species were affected by fishing activities during the last couple of centuries, I was not able to show this conclusively using shell remains and dating references. This is in contrast to Edgar and Samson (2004) who did show declines of non-target mollusc species from Tasmanian estuaries over time in line with fishing activity. Longer-term, more intensive fishing activities in the Firth of Forth, along with different environmental conditions less conducive to preservation may be the reason for the different findings between the studies. However, as with my research, it is also likely that Edgar and Samson’s core samples would have been affected to some degree by bioturbation. Whilst they discussed in detail the possibility of post-mortem transport of shells affecting observed trends in species abundance and diversity in different layers, very little mention was made of bioturbation processes and the effect this could have on sediment age and depth. This brings the reliability and accuracy of some of their sediment-dating results into question.

Coring and dating techniques similar to those used in my field research have been used with some success in other studies, most often in areas of salt marsh or intertidal mudflat (e.g. Armentano and Woodwell 1975; Cundy and Croudace 1995), but occasionally in estuarine environments (Bell et al., 1997; Edgar and Samson 2004). This demonstrates their potential value in determining wider benthic community changes over time as a result of human activities such as fishing. Most historical data is only concerned with species that were fished and rarely provide insights into broader community changes. For areas where little historical information exists sediment cores and dating techniques could be useful to improve environmental baselines. More appropriate sites than I was able to use for these methods may be found with effort. The characteristics of these sites would most likely be sheltered, muddy areas with limited currents. This would reduce mixing by physical processes and sediment redistribution, whilst muddy sediment allows the application of Pb-210 and Cs-137 dating techniques. As this chapter demonstrates, strong evidence for alterations to habitats as a result of fishing can be found in the historic literature. However historical information is not available for all sites, hence coring techniques could be of value in these cases if environmental conditions permit the reliable use of radioisotope dating techniques.

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Chapter 5: Health recommendations and global fish availability: are there enough fish to go around?

5.1 PREFACE

Historical analysis of ecosystems can show the extent of change as a result of human activities and help provide a reference for recovery or management of a habitat or resource. Historical analyses can also be of value for looking at what the future holds. The pattern of exploitation seen in preceding chapters where fisheries expand into unexploited areas and adopt increasingly effective, but often damaging technologies in order to maintain catches as the resource base depletes, is occurring around the world.

Industrial nations such as the UK have exhausted many of their own fish stocks, so they continue to exploit distant fishing grounds whilst increasing imports of fish from other countries. A report by Esteban and Crilly (2010) showed that if European Union citizens only ate fish from their own waters for a year, supplies would run out by July 8th. This date is becoming earlier each year as the EU becomes more reliant upon imports (Esteban and Crilly 2010).

This in turn impacts upon developing nations, many of whom are reliant upon fish for protein (Garcia and Rosenberg 2010). As our global population increases it is likely that demands for fish protein will rise. This paper explores historical trends in the amount of fish available per capita, first for the UK and then on a global level. I then investigate what this means for fish consumption recommendations today, and fish consumption in future years, when the global population is predicted to rise to over 9 billion people.

This work is written in the style of Proceedings of the Royal Society, Biological Sciences journal, where I intend to submit this paper. I declare the work submitted is my own.

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Inconsistencies between health recommendations and global fish availability: are there enough fish to go around?

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Summary

Fish and shellfish are increasingly promoted as a healthy alternative to other forms of animal protein by governments, health professionals, the fishing industry and retailers. However, global fish supplies are in decline. We ask whether there are enough fish to meet levels of intake recommended to sustain good health, in the UK and globally. Since the 1880s domestic fish landings in the UK have declined by 35%, whilst the UK population has almost doubled. Factoring in processing losses, the lower needs of children and human population increase, the amount of fish available per capita today – 206 $g.capita^{-1}.week^{-1}$ – falls well below recommended consumption levels of 280 $g.capita^{-1}.week^{-1}$. On a global scale it is known that wild fish landings have been in decline since the late 1980s; however when human population increase is taken into account availability of wild fish per capita has been in decline since 1970. Per capita availability today, at 207 g, is 20% less than recommended consumption levels averaged across 14 countries (260 $g.capita^{-1}.week^{-1}$). Filling the growing supply gap to 2050 would require aquaculture production to increase by 2.9 times today's levels. Our findings raise serious questions about future food security and the aspiration of many countries to increase the amount of fish people consume.

Key index words

Historical fisheries, fisheries decline, sustainable fisheries, food security

Introduction

In recent years it has become clear that a crisis is developing in fish supply. If you exclude highly variable catches from Peruvian anchoveta and unreliable catch statistics from China, global landings from marine capture fisheries have declined since the late 1980s as the percentage of over-exploited stocks has risen [1]. The rate of commercial fisheries undergoing collapse is accelerating over time [2], whilst the biomass of large predatory fish has declined steeply [3,4,5]. An increasing number of marine species are threatened with extinction [6,7] and global marine biodiversity is in decline [8]. This reduces the quality of ecosystem services we receive and makes future recovery of marine communities less likely [2].

At the same time, the health benefits of eating fish are becoming better appreciated. Fish protein (including shellfish) is typically lower in saturated fats than red meat, whilst oily fish is high in essential fatty acids (http://www.eufic.org/page/en/faqid/fatty-acids-oily-fish/). The latter are known to promote cardio-vascular and cerebral health [9]. These properties have led to recommendations by various national and international bodies on how much fish we should eat to benefit health (See Table 1). With a rising global population and falling fish supply, the question is, can these recommendations be met? In this paper we ask whether there are enough fish to go around, both now and in the future. We examine the question at a national scale for the UK using a detailed 120 year database of fish landings, imports and exports, and at a global scale using FAO data.

Methods

UK fisheries

Figures for total landings of wetfish (both pelagic and bottom-living) and shellfish (mainly molluscs and crustaceans) into the UK came from Ministry of Agriculture, Fisheries and Food (MAFF) statistical tables (1965-2009) (landings of wetfish were reported as the weight of head on, gutted fish) and comprised of landings by UK vessels into the UK. Before 1965 landings were taken from separate statistical tables for England and Wales (MAFF), Scotland (1903-1964, Fishery Board for Scotland) and Northern Ireland (1903-1921, Department of Agriculture and Technical Instruction for Ireland; 1922-62, Department of Commerce, Report on Sea and Inland Fisheries). Prior to 1903, MAFF statistical tables provided landings for Ireland and Scotland as well as England and Wales. Prior to 1965 many shellfish landings were provided in numbers of individuals rather than weight. These were converted to metric tonnes, either using guidelines present in the statistical tables, or by estimating the average weight per specimen based on the results of literature searches.

Import and export data for the whole of the UK were provided by MAFF statistical tables. Fish products such as fish meals and oils were not included as the vast majority are used for livestock and aquaculture feeds rather than direct human consumption.

Data on aquaculture production were taken from FAO FishStat Plus database (http://www.fao.org/fishery/statistics/software/fishstat/en), and included marine, freshwater and brackish aquaculture production in the UK.

Conversion of landed weight to processed weight (which is what is actually available for consumption) was based on formulae in a document produced by HM Revenue and Customs (HMRC), Business Economic Note 24, and can be found at http://webarchive.nationalarchives.gov.uk/20100512173947/http://www.hmrc.gov.uk/bens/ben24.htm. We used an average of HMRC estimations of the proportion of usable whitefish and herring after conversion to fillets as a proxy conversion factor for all finfish. Shellfish conversion weights were an average of the different conversion rates for all shellfish provided. This included 11 species of crustaceans and molluscs; crab, lobster, prawn, scampi, shrimp, cockle, oyster, mussel, scallop, whelk and winkle. We assumed that imports and exports were already prepared in some measure (e.g. processed fish cakes, shelled prawns etc.), so no conversions were made for imported weight.

UK population size data were taken from a range of censuses from 1891 to 2008. The Office of National Statistics provided Great Britain population data every 10 years, and the Central Statistics Office in Ireland provided yearly Irish and Northern Irish population data from 1891 to 2008 (until 1921 the population of the UK included all of Ireland, from 1922 just Northern Ireland). To provide a population estimate for each year, the rate of change of population was calculated between each census and applied to the interval between. Numbers of children under 15 years were gathered from separate censuses for Ireland, England and Wales, and Scotland for the years 1891, 1901, 1911, 1931, then every 10 years from 1971. From 1881-1931, census data were provided by www.histpop.org. From 1971 onwards this was provided by the Office of National Statistics. Data were interpolated for the years in between to provide a yearly estimate of the number of children under 15 years old.

Global fisheries

We obtained figures for global capture fisheries and aquaculture (freshwater, brackish and marine) production from the United Nations Food and Agriculture Organisation (FAO) [10,11] and FAO FishStat Plus (http://www.fao.org/fishery/statistics/software/en). Landings of aquatic plants or inedible species (e.g. corals, sponges) were disregarded from the analysis, as these were unlikely to be used for direct human consumption, or were not sources of animal protein. World population estimates for 2008 were provided by the Population Reference Bureau (www.prb.org). Projected data for 2050 were provided by the United Nations Population Division (http://esa.un.org/unpp/index.asp).

Results

UK fish availability

Figure 1 shows the total landings of wetfish by UK vessels between 1888 and 2008. Landings peaked in 1913 and then declined throughout the remainder of the 20th century to the present. The two earlier dips in the series correspond to the world wars when fishing was dangerous and boats were largely put to other uses. Present landings are the lowest at any point in the last 120 years except for 1941.

Shellfish landings have increased since the 1960s, but have not compensated for the decline in wetfish landings.

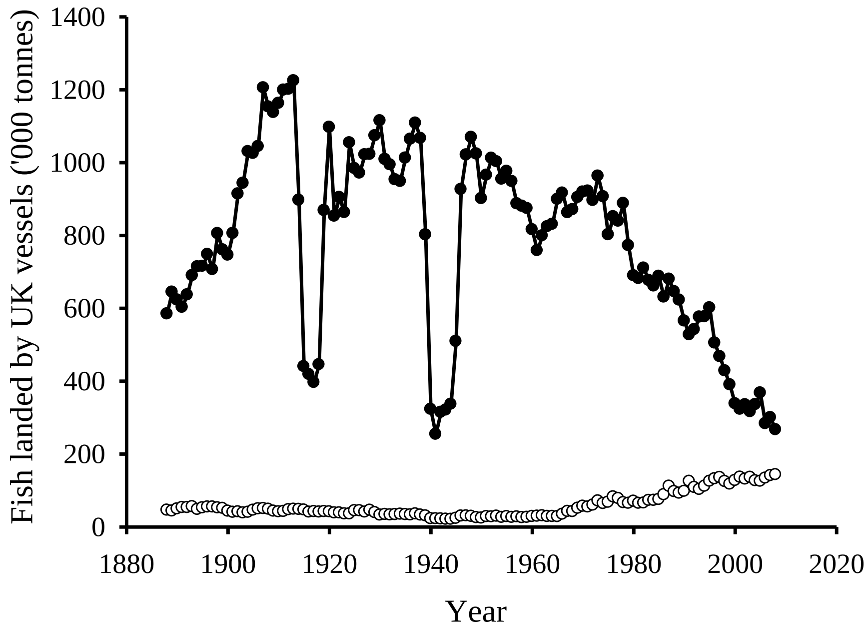

Figure 1. Landings of wetfish (closed circles) and shellfish (open circles) into the UK by UK vessels (source: MAFF, Scottish Fishery Board and Department of Commerce sea fisheries statistics).

UK capture fisheries only represent one source of fish for UK consumers, the others being imports and aquaculture. We examined imports over the same period to determine their contribution to fish availability (Figure 2). Imports have increased since the 19th century. In 1888, less than 100,000 tonnes were imported into the UK, but by 2008 this had risen to 781,000 tonnes (before exports, and excluding products such as fish meals and oils). There was a sharp upward change in the rate of increase in imports from the 1970s onwards, which corresponds to the point when domestic landings began to fall steeply (Figure 1). Hence, imports made up some of the expanding deficit left by declining landings.

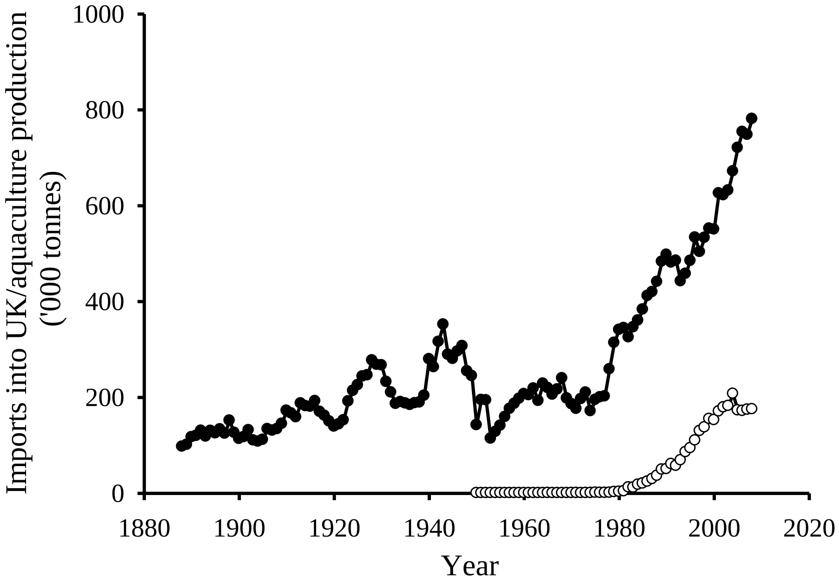

Figure 2. Imports of fish and fish preparations into the UK (closed circles) (these include fish imported by all means of transport, and also includes direct landings of fish by foreign vessels, but excludes fish meals and oils) and UK aquaculture production (marine and freshwater, open circles) (source: MAFF sea fisheries statistical tables and FAO FishStat database 2010).

Domestic aquaculture production (marine and freshwater) has also increased in importance in the last fifty years (Figure 2), rising from 30 tonnes in 1950 to 179,000 tonnes in 2008 (the contribution of overseas aquaculture is incorporated into import figures shown in Figure 2).

Figure 3 shows the amount of fish available to the UK population once both capture and aquaculture fish have been converted to their processed weight and exports have been deducted. The UK Food Standards Agency (www.eatwell.gov.uk) recommends that we eat two portions of fish per week (or 280 grams in total, dashed horizontal line on Figure 3). We assumed that the fraction of the UK population under 15 years old require half this amount of fish. After correcting for this, we can show the amount of fish available in $g.capita^{-1}.week^{-1}$ on an annual basis from 1888-2008 (Figure 3). With imports, this has slowly increased since the 1970s, but without imports, available fish has been in decline since prior to WWI, showing our increasing reliance upon imports. As yet, this deficit has not been filled by aquaculture production which made up only 13% of UK fish consumption in 2008.

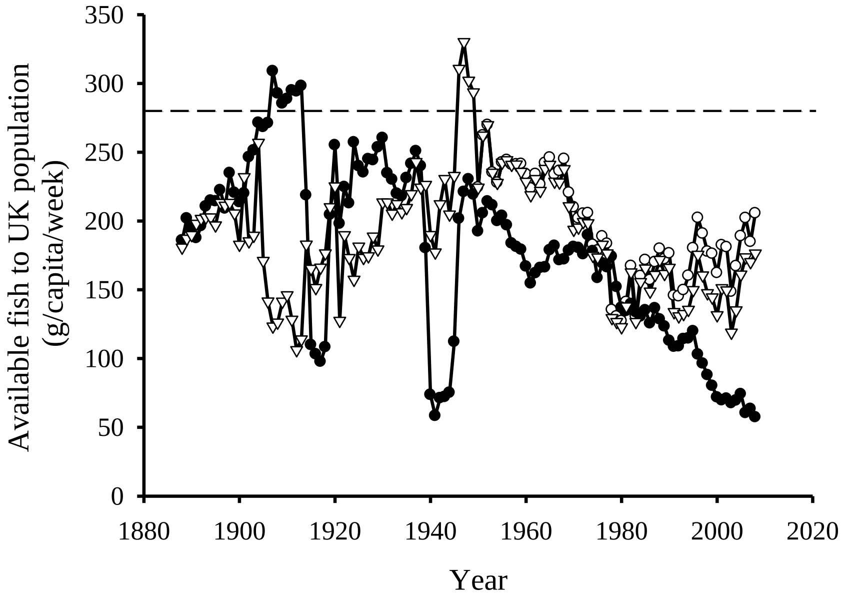

Figure 3. Fish available (g.capita^{-1}.week^{-1}) on an annual basis in the UK after adjustment for proportion of children in the population. Closed circles show fish available from capture fisheries after processing. Open triangles show fish available when imports minus exports are included, open circles when aquaculture is added to the latter. The dashed line shows the amount of fish we should be eating according to the Food Standards Agency.

Global fish availability

FAO [11] provided data on global landings and consumption in 2008. Total world fisheries production (including inland and marine capture fisheries and aquaculture) was estimated at 148 million tonnes [11]. 115 million tonnes were available for direct human consumption, with 33 million tonnes going for other uses, such as the manufacture of fish meals and oils. This translated as 17.1 kg per capita landed weight equivalent per year (i.e. unprocessed) (or 329 g.capita^{-1}.week^{-1}) for the human population of 6.8 billion in 2008 [11].

Table 1 lists recommended fish/shellfish intake for 14 countries for which we could find official guidance. The average recommended weekly intake was 257 g.capita^{-1}.week^{-1} (rounded to 260 g.capita^{-1}.week^{-1}). Available landed weight of fish lies above this value. However, when processed weight conversions were applied and the percentage of children in the world population corrected for (who require only half portions), this declined to 8.60 kg available per capita.year^{-1}, or 166 g.capita $^{-1}$.week^{-1}, 94 g less per week than the international average recommended intake.

To achieve a level of fish intake of 260 g.capita^{-1}.week^{-1} on a global scale in 2008, 65 million tonnes extra fish would have been needed before processing (landed weight). FAO statistics do not capture the breadth of small-scale fisheries, many of which go unrecorded. Chuenpagdee and colleagues [12] estimate that small-scale fisheries land around 21 million tonnes per year, although how much of this is recorded in FAO landings is uncertain. If we assume that none of these catches are recorded in official statistics, this provides 21 million extra tonnes of available fish, or 10.3 million tonnes after processing. In addition, legally caught and traded fish are not the only source available. Illegal fishing should be factored into present global fish supplies. Agnew et al. [13] estimated that the worldwide extent of illegal and unreported fishing was between 11 and 26 million tonnes (median 18.5 million tonnes) in recent years. If we assume this is available for human food use and that overall processed conversion rate is the finfish average of 0.49, that provides us with 9.1 million tonnes of additional fish. Hence the shortfall in fish production in 2008 comes to just 25.5 million tonnes before processing. However, due to our assumptions that no small-scale fisheries landings are included in official statistics, this estimate is likely to be conservative and in reality the shortfall may be considerably higher.

Table 1. National dietary guidelines for eating fish, based on recommendations for adults. When a range of values was provided, amount per week was calculated using the median value.

Country	**National guidelines**	**Recommended amount per week (g)**	**Source**
United Kingdom	2 portions (140g each) per week, one of which should be oily	280	www.eatwell.gov.uk
United States	2 average meals (6oz) per week (excluding species with a high mercury content e.g. swordfish, marlin)	340	www.fda.gov
Australia	2-3 servings per week (serving = 150g) not including species with a high mercury content	375	www.foodstandards.gov.au
New Zealand	3-4 servings per week (serving = 150g) not including species with a high mercury content	525	www.nzfsa.govt.nz
Canada	At least 150g each week	150	www.hc-sc.gc.ca
Denmark	200-300g fish per week	250	1
Iceland	300g fish per week	300	2
Austria	1-2 portions per week (total 150g)	150	1
Germany*	1 portion of seafood per week	100	1
Greece*	5-6 servings per week	550	1
Georgia	12.8-15g fish per day	97	1
Ukraine	20g fish per day	140	1
Estonia	2-3 servings per week (serving = 50g)	125	1
Armenia	30g fish per day	210	1

*No portion or serving size provided, therefore assumed that one portion/serving equals 100 grams as this is in line with a number of other countries. 1) WHO. 2003 *Food based dietary guidelines in the WHO European Region*. Nutrition and Food Security Programme, World Health Organisation, Copenhagen. 2) Gunnarsdottir, I., Gustavsdottir, A. & Thorsdottir, I. 2009 Iodine intake and status in Iceland through a period of 60 years. *Food & Nutrition Research,* 53. (DOI 10.3402/fnr.v53i0.1925).

Since the 1950s, global fish availability (after processing conversions) has increased by 603%. However, since the 1980s wild capture fisheries have levelled off and it is aquaculture that has been responsible for the continued growth (Figure 4). Figure 5 shows fish availability to the global population once adjusted for the number of children. Capture fisheries production per capita has been in decline since 1970, but growth in aquaculture has slightly increased global fish availability over the same period because aquaculture growth has outpaced human population increase. However, this growth may not be sustainable (see discussion).

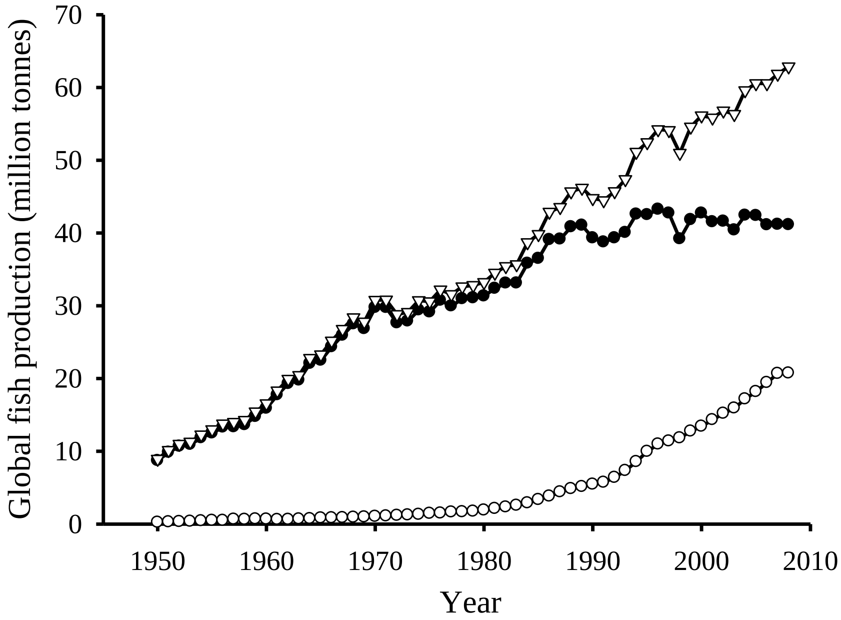

Figure 4: Global landings of finfish and invertebrates 1950-2008 after applying processing conversions (source: FAO FishStat Plus). Open circles show aquaculture production, closed circles capture fisheries landings, and open triangles total fish available. Global recorded landings have levelled off since the late 1980s, with aquaculture responsible for continued growth in supply.

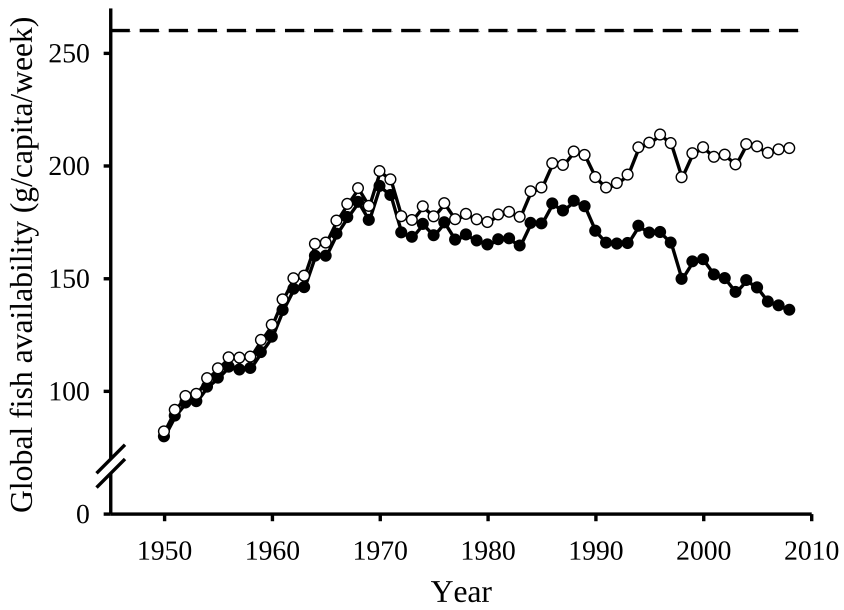

Figure 5. Global fish availability (g.capita^{-1}.week^{-1}) on an annual basis after adjustment for proportion of children in the population. Closed circles show fish available from capture fisheries alone after processing. Open circles show fish available when aquaculture is added to the latter. The dashed line indicates the average global recommended amount of fish (260 g.capita^{-1}.week^{-1}).

Looking ahead to the world in 2050, the human population is projected to reach 9.1 billion (of whom 20% are predicted to be under 15) [14]. To supply this population with the equivalent of 260 g.capita^{-1}.week^{-1}, fish production would have to increase by 98.5 million tonnes above 2008 levels (excluding wild capture fishery landings in 2008 that were destined for fishmeal production, and assuming for simplicity that current estimates of illegal and unrecorded landings remained the same) (Table 2).

Table 2. Summary of fish available for consumption in 2008, fish availability after processing conversions have been applied and projected fish availability after processing in 2050.

Source of fish	**Million metric tonnes**		
	Available for consumption (2008)	**Available after processing (2008)**	**Projected availability (2050)**
Wild catch/aquaculture	115.1	50.4	50.4
Illegal/unreported	18.5	9.1	9.1
Artisanal	21	10.3	10.3
Discards	-	-	3.6
Total	154.6	69.8	73.4
Fish needed to meet requirements	-	**25.5**	**91.2**

Discarded fish could be utilised more fully in a future in which discarding is prohibited, as has been a successful policy in Norway [15]. According to the Norwegian model, unsaleable fish rather than being discarded are converted to fishmeal. If the same principle was applied at the global scale, we make the assumption that it would free up for human consumption an equivalent amount of the wild fish catch that is currently diverted to fishmeal and oil production. This is a much-simplified scenario, as some of the fish currently discarded could be used for direct human consumption. In addition, Diamond and Beukers-Stewart [16] show that a combination of discard bans and real-time area closures implemented by Norway have contributed to the recovery of some northeast Arctic fish stocks. Banning discards has helped improve estimates of fishery mortality and encouraged fishers to fish more selectively. However, for the purposes of this study we assume that as global discards are estimated to be 7.3 million tonnes [15], converting to processed weight (using the finfish conversion as described in the methods section), would give an extra 3.6 million tonnes for human consumption.

This extra fish would make a small contribution to meeting human needs, reducing the required increase in fish production by 2050 to 91.2 million tonnes. It seems unlikely to us that capture fisheries will be able to increase further. Therefore this increase in demand would have to be met by aquaculture. In 2008, global aquaculture (inland and marine) produced 52.5 million tonnes. To meet our world demand projections for 2050, aquaculture would need to increase by 174% by 2050. This is equivalent to an annual growth rate from 2008 to 2050 of 1.5%.

In 2005, 57% of fishmeal destined for non-human consumption, or 20.3 million tonnes was used for aquaculture [10]. Whilst it is predicted that aquaculture species will become more reliant upon plant-based foods in the future, and there will be a shift to raising less predatory species [17], at current levels an additional 34 million tonnes of wild fish would need to be caught or produced for fishmeal.

Discussion

This paper makes the assumption that fish consumption is desirable for every human being on the planet, and that recommendations on levels of fish consumption from 14 countries (260 g.capita^{-1}.week^{-1}) might be extrapolated to the world. In reality, fish intake across the world is uneven. Some countries consume very little fish, whilst others depend on it as their main source of animal protein. We have shown that present global fish production from all sources (excluding discards) fell 14.1% below recommended intake levels for the world population. Although fish availability has slowly increased over the last several decades due to aquaculture growth exceeding human population growth, it will be difficult, in view of this continuing human population growth, to carry on to increasing fish protein availability into the future. Aquaculture may still be growing, but the rate of increase for finfish aquaculture is in decline [18].

Our UK example illustrates how developed country consumers have so far been insulated from the consequences of domestic overexploitation of fish. Fish availability and landings around the UK have plunged during the last century as fishing intensified [5]. The UK has therefore become more reliant upon imports, whilst domestic aquaculture has become more significant since the 1980s (http://www.fao.org/fishery/statistics/software/fishstat/en). Due to increases in the UK population, these sources only just stem the rapid 20th century decline in fish availability. Recommended levels of consumption have only been achieved in two brief periods totalling 10 years out of 119: immediately prior to WWI when the UK exploited highly productive fisheries for small pelagic species like herring and pilchards, and following WWII when domestic production of bottom living fish like cod and haddock peaked. In the former period, however, much was exported, reducing per capita availability well below present recommendations, while in the latter, recommended levels of intake were achieved only with extra imported fish.

A report by the UK Scientific Advisory Committee on Nutrition [9] emphasised the need to encourage fish consumption, as the British population does not eat the recommended levels of fish. Yet recommended levels cannot be met by UK fisheries alone. Even with consumption well below recommendations, our reliance upon imports results in a reduction of available fish protein in developing nations and encourages the expansion of unsustainable fishing practices [19]. Any further increase in consumption by developed nations will further amplify these problems.

Global landings, excluding Peruvian anchoveta, which is mostly converted to fishmeal, have been in decline since the late 1980s [20]. However, when an increasing world population is taken into account, per capita fish availability has been in decline since 1970. Whilst rate of aquaculture production currently outpaces world population growth [10], this rate of increase in beginning to slow (from 10.8% average yearly increase during the 1980s, to 9.6% average yearly increase during the 1990s, down to 6.5% average from 2000-2008) (http://www.fao.org/fishery/statistics/software/fishstat/en). Liu and Sumaila [18] show that the growth in finfish aquaculture peaked in 1984, with the rate of increase declining by 0.34% every year since then. Experts predict that this rate of increase cannot be sustained [1,10,11], and that aquaculture production will continue to slow due to constraints such as reductions in availability of fish meal and oil from wild fish stocks, lack of coastal space and lack of freshwater for inland farms [10,18]. Although lower than the 8.3% annual growth in aquaculture production from 1970 to 2008 [11], for 1.5% annual growth to be sustained until 2050 changes will have to be made within the aquaculture sector (a challenge discussed by Duarte and colleagues [21]).

At the present level of fish production, there is not enough fish available to meet developed nation aspirations for fish protein intake on a global scale. For developed countries such as the UK who depend heavily on imports, and for the developing nations whose fisheries they have turned to, it raises many questions about future food security. For nations dependent upon fish as a primary source of protein (approximately 1 billion people) (http://www.who.int/nutrition/topics/3_foodconsumption/en/index5.html), the outlook is particularly serious and underpins the importance of managing fish stocks for long-term sustainability.

There is a possibility that present global wild fishery production could transition to sustainability. Populations of top predators have been greatly reduced from unexploited levels, whilst many exploited fisheries are in decline [3,5]. Fisheries theory suggests that rebuilding them to higher levels (e.g. 50% of unexploited sizes) would lead to greater landings and more sustainable catches. Such a change could be achieved by cutting fishing effort, introducing large scale networks of marine protected areas, eliminating destructive fishing methods and reducing illegal fisheries [1,5]. But the window of time available for such a transition is narrowing as biodiversity is lost [2]. People have enjoyed a diet rich in fish and shellfish since the dawn of humanity [22,23], however unless political will can be found to make these reforms our future as fish consumers looks highly uncertain.

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Chapter 6: Are highly protected marine reserves and recreational activities compatible? A global analysis of marine reserve regulations.

6.1 PREFACE

The preceding chapters investigated the extent of change to marine populations and habitats using historical evidence to show how we have altered our marine environment over time. Another way of investigating changes to the marine environment caused by humans is to halt damaging activities such as fishing and monitor how the environment recovers. Whilst the removal of certain species or habitats may lead to shifts to alternative stable states from which it is difficult to recover, often marine wildlife and habitats do have the ability to bounce back from exploitation (Babcock et al., 1999; Barrett et al., 2009; Lester et al., 2009).

Protection of an area often enhances its appeal to visitors, which can have positive influences in improving people's perception and knowledge of the seas, as well as generating revenue. However, tourism also brings its own impacts and these may negatively affect wildlife or habitats within the protected area. This chapter investigates whether non-consumptive activities do cause harm and whether they should be permitted within highly protected areas.

This chapter is written in the journal style of Biological Conservation. The paper was submitted on 1st March 2011 for consideration for publication. Apart from the risk assessment methodology which was adapted from original work by Luiza Neves, I declare that the work submitted is my own.

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Are highly protected marine reserves and recreational activities compatible? A global analysis of marine reserve regulations.

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Abstract

Highly protected marine reserves (HPMRs) are places where wildlife and habitats are protected from extractive, depositional and damaging uses of the sea. They are widely considered to be the gold-standard in marine conservation, but many permit non-consumptive activities with little or no regulation. This paper examines current practice for regulating non-consumptive activities in highly protected marine reserves (HPMRs), or their equivalents. We examined 91 HPMRs from 36 countries and found little agreement or consistency in what is allowed and how these activities are regulated. For 16 non-consumptive activities that included scuba diving, sailing, scientific research, anchoring and motor boating, we determined whether they were prohibited, allowed, allowed with regulation or not mentioned in management documents. We then assigned a risk score for the likely level of threat to wildlife and/or habitats that each activity could produce. Activities most commonly allowed, or regulated within HPMRs, were sailing (82%), motorised boating (81%), scientific research (80%) and scuba diving (70%). Our risk analysis suggests that two of these, motorised boating and scuba diving, have a high potential to negatively impact wildlife and habitats if inadequately managed, as do snorkelling and jet skiing.

Protection against extractive or depositional activities alone is insufficient to secure the high standard of protection intended by HPMR designation. For this to be achieved activities typically considered as benign must receive appropriate management, especially with increasing recreational use. We recommend that jet skiing, water-skiing and catch and release angling are prohibited in HPMRs.

Keywords: marine protected areas; MPAs; management effectiveness

1. Introduction

It is recognised that marine habitats and species throughout the oceans are affected by a multitude of human impacts including fishing, chemical and noise pollution (Halpern et al., 2008). As a result, species have declined in abundance, diversity has decreased and habitat complexity has been reduced (Sala and Knowlton, 2006). Highly protected marine reserves (HPMRs), sites that aim to ban extractive activities, are increasingly seen as a way to help address many of these impacts (Lauck et al., 1998; Roberts, 2007) and have been shown to effectively protect biodiversity and enable ecosystem recovery (Halpern, 2003; Lester et al., 2009; Worm et al., 2006). They are seen as the 'pinnacle of protection' for marine life and as a way to provide resilience against future stressors such as climate change (Roberts et al., 2005).

Highly protected marine reserves have been variously defined. Ballantine (1999) states that the aim of "**marine reserves"** is to "maintain (or restore) the intrinsic biodiversity and natural processes [within the marine environment]. No fishing is permitted or any removal of material. No dredging, dumping, construction or any other direct disturbance is allowed". Roberts and Hawkins (2000) defined **"no-take marine reserves"** as "areas completely closed to fishing and all other types of exploitation or harmful use". The IUCN recognise six categories of protected areas, of which category 1a (Strict Nature Reserve) and 1b (Wilderness Area) are the most highly protected and restrict public access. In contrast to this many HPMRs encourage non-consumptive uses (i.e. activities which do not result in extraction of a resource or deposition of materials).

In New Zealand **“marine reserves**” are “specified areas of the sea and foreshore that are managed to preserve them in their natural state as the habitat of marine life for scientific study […]. Within a marine reserve, all marine life is protected and fishing and the removal or disturbance of any living or non-living marine resource is prohibited, except as necessary for permitted monitoring or research. This includes dredging, dumping or discharging any matter or building structures”[1]. In Australia the term **“marine reserve”** is used to define “an area of sea especially dedicated to the protection and maintenance of biological diversity and of natural and associated cultural resources, and managed through legal or other effective means”[2]. **“Preservation zones”** in Australia’s Great Barrier Reef Marine Park, do not allow public access. In California, a highly protected marine reserve is called a “**state marine reserve”**. Here it is “unlawful to injure, damage, take or possess any living, geological or cultural marine resource, except under a permit or specific authorization from the managing agency for research, restoration or monitoring purposes.” The aim is also to manage these reserves for “public enjoyment”, whilst maintaining them “to the extent practicable in an undisturbed and unpolluted state”. This means that “access and use (such as walking, swimming, boating and diving) may be restricted to protect marine resources”[3].

In Wales in the United Kingdom, the establishment of highly protected marine reserves which will be known as **“highly protected marine conservation zones (HPMCZs)”** is currently underway. These are defined as “sites that are protected from extraction and deposition of living and non-living resources, and all other damaging or disturbing activities” (Thurstan et al., 2009). Damaging activities are defined as “acts that potentially result in permanent or temporary physical harm or injury to species, or cause permanent or temporary alteration to natural features within the marine environment”. Disturbing activities are defined as “acts that interfere with the normal functioning of populations beyond the natural variability of the ecosystem”.

This may preclude some forms of non-consumptive activities, whilst others can be regulated to minimise potential damage or disturbance (Thurstan et al., 2009).

In general anything which is intended to be a HPMR will provide regulations to protect against extractive activities and aim to provide a more natural state in which marine life can thrive. Hence this should mean protection against activities such as fishing, collection of organisms or mining. Some HPMRs around the world do not allow public access, however this is unusual, and many positively encourage non-consumptive recreational activities. This creates a potential problem in that, unless suitably managed, some non-consumptive activities have the potential to cause significant environmental damage, especially for HPMRs with high numbers of visitors (Hardiman and Burgin, 2010). For example, scuba diving, which is a popular activity within HPMRs, can break fragile organisms such as corals, sponges and hydroids which are particularly vulnerable to diver impacts (Barker and Roberts, 2004). Where poorly managed this supposedly non-consumptive use can undermine the ecosystem recovery objective of HPMRs (Hawkins et al., 1999; Zakai and Chadwick-Furman, 2002).

In this study, we review experience from across the world in managing HPMRs or their equivalents. We examine what activities or uses are prohibited, which are allowed, and how, if at all, permitted activities are regulated. We then explore the risks to wildlife associated with the various managed or unmanaged activities. Finally, we make recommendations for activities that are compatible and incompatible with HPMR protection, and recommend how permissible activities should be regulated to ensure that conservation objectives are met.

2. Methods

2.1 Non-consumptive activities in HPMRs

We examined 91 HPMRs or their equivalent (i.e. sites offering a high degree of protection from exploitation that fit one or more of the definitions given in the introduction) from 36 countries to determine how they are managed. We identified the following 16 activities as ones which were commonly allowed: catch and release angling, diving, snorkelling, swimming, mooring, anchoring, scientific research, jet skiing, kayaking, wildlife observation, motorised boating, water skiing, surfing, windsurfing, sailing and kite surfing. For each individual HPMR in our sample, we then categorised each activity as being either prohibited, allowed, regulated, or not mentioned. Doing this required the following assumptions. Catch and release fishing was assumed to be "prohibited" unless it was explicitly stated as "allowed", while boating was assumed to be "allowed" in cases where it wasn't specifically mentioned, but where anchoring and mooring were listed as permitted or regulated activities. Where boating or watercraft activities were mentioned but specific activities were not detailed, we assumed that this included sailing, motor boating and kayaking. If regulations included a category that was termed 'motorised watersports' then we assumed jet skiing to be included in that.

For each of the 16 activities we then determined whether there were grounds for subdivision into 'high' or 'low' impact versions. This was based on the potential for inappropriate behaviour during the activity or high intensity of use to negatively impact upon species or habitats within the HPMR (see Table 1). In classifying an activity as high impact we assumed that no-take regulations would be adhered to but that otherwise it was unregulated. On the basis of personal knowledge and the scientific literature we considered scientific research, motor boating, scuba diving, snorkelling, anchoring, mooring, catch and release angling, and wildlife observation as activities which all had the potential to be both 'high' and 'low' impact (Bartholomew and Bohnsack, 2005; Boyes et al., 2006; Constantine, 1999; Davenport and Davenport, 2006; Hemingway et al., 2006; Kelly et al., 2004; Medio et al., 1997; Rouphael and Inglis, 1995; Wells and Scott, 1997). The other activities were not subdivided.

2.2 Risk analysis

We performed a risk analysis to identify the level of threat of each activity, including high and low impact versions, to determine risk scores for the activities. This was done by assessing each activity against the eight criteria listed in Table 2. A risk score was attributed to each criterion and an overall risk score for each activity was calculated by averaging across the eight criteria.

To evaluate whether the riskier activities were typically excluded from HPMRs, the average level of risk for each activity was plotted against the percentage of HPMRs in our sample that either allowed or regulated that activity.

Table 1. Conditions where activities are considered to be high or low impact.

Activity	Description
Motor boating	High impact: high intensity of use where inappropriate behaviour = driving at high speeds, dropping anchors inconsiderately, getting too close to marine wildlife and habitats, producing lots of noise, discharging pollution (Constantine, 1999; Wells and Scott, 1997)
	Low impact: opposite of High impact attributes
Catch and release angling	High impact: inappropriate use of boats (as above), possibly within a restricted area at high intensity of use (Bartholomew and Bohnsack, 2005)
	Low impact: shore-based angling at low intensity that avoids wildlife sensitive areas and leaves no rubbish (Bartholomew and Bohnsack, 2005)
Scuba diving	High impact: inappropriate use of boats (as above), high intensity of use. Underwater, much direct contact with marine organisms and considerable sediment disturbance (Medio et al., 1997; Rouphael and Inglis, 1995)
	Low impact: careful and considerate use of boats, avoidance of sensitive areas, careful access from shore: otherwise opposite of High impact attributes (Barker and Roberts, 2004)
Snorkelling	High impact: as for scuba diving
	Low impact: as for scuba diving
Wildlife observation	High impact: inappropriate use of boats (as above), high intensity of use. Disregard for codes of conduct, crowding or harassment of wildlife, noisy behaviour (Constantine et al., 2004)
	Low impact: careful and quiet access in designated areas; otherwise opposite of High impact attributes (Boyes et al., 2006)
Anchoring	High impact: no designated anchoring areas, high intensity of use, fragile habitats present, use of over-long chains (Hemingway et al., 2006)
	Low impact: designated anchoring zones in areas of mobile sediment, well advertised and marked, levels of use monitored and controlled, regulations in force on chain length
Mooring	High impact: mooring blocks not properly fixed, placement among fragile habitats susceptible to dragging, over-long chain used (Hemingway et al., 2006)
	Low impact: appropriate fixings used for the habitats present, chain buoyed to lift from bottom, levels of use monitored and controlled
Scientific research	High impact: inappropriate use of boats (as above), destructive sampling methods used, high intensity of use, performed in fragile habitats/sensitive breeding areas without adequate precautions, no permits required, no monitoring of use undertaken (Hemingway et al., 2006)
	Low impact: opposite of High impact attributes

Table 2. Scoring scheme for criteria against which non-consumptive activities were assessed in our risk analysis.

Criterion (i): **Potential to change animal behaviour**	***Risk score***
Permanent avoidance of important feeding/resting/breeding areas AND/OR Permanent masking of communication and/or echolocation AND/OR Long-term change in parental behaviour	4
Temporary avoidance of important feeding/resting/breeding areas AND/OR Temporary masking of communication and/or echolocation AND/OR Temporary alteration of group cohesion AND/OR Short-term change in parental behaviour	3
Temporarily affects group dynamics of a species AND/OR Short-term change in parental behaviour BUT Does not mask communication or cause an area to be avoided	2
Any disturbance is very temporary with behaviour returning to normal shortly after the activity stops	1
No behavioural change	0
Criterion (ii): **Potential to cause injury/stress to animals or habitats**	
Severe and long lasting injury or stress i.e. permanent tissue damage, haemorrhages to vital organs, mass stranding events, permanent auditory damage AND/OR Death to individual animals AND/OR Irreversible or long-term degradation to an area of habitat	4
Serious but temporary injury or stress i.e. physiological damage that may be life threatening but can be recovered from over time	3
Moderate and temporary injury or stress i.e. non-life threatening physiological damage or raised stress levels. Limited and reversible degradation to a habitat	2
Slight and temporary injury or stress i.e. activity is unlikely to cause physiological damage, but high levels of activity may increase levels of stress over time	1
No physiological damage occurs	0
Criterion (iii): **Likelihood of collision**	
Very high	4
High	3
Moderate	2
Low	1
No risk of collision	0
Criterion (iv): **Likelihood of causing death**	
Very high	4
High	3
Moderate	2

Low	1
No risk of death	0
Criteria (v) **Potential to create pollution** Pollution includes any of the following: deterioration of water quality, addition of solid waste, wastewater, fuel leaks and exhaust emissions, invasive species and oil spills. The degree of impact is a combination of lethality, area affected and duration of effects.	
Very high	4
High	3
Moderate	2
Low	1
No pollution effects	0
Criteria (vi) **Potential to cause scouring damage**	
Very high	4
High	3
Moderate	2
Low	1
No scouring effects	0
Criteria (vii) **Potential to result in trampling damage or sediment disturbance**	
Very high	4
High	3
Moderate	2
Low	1
No breakage or sediment disturbance	0
Criteria (viii) **Likely duration period of damage or disturbance**	
Very prolonged (months to years)	4
Prolonged (weeks)	3
Moderate length (days)	2
Short (minutes to hours)	1
No noticeable impacts to species or habitat	0

(Table 2 continued).

3. Results

3.1 Activities in HPMRs

A summary of the 91 HPMRs reviewed and which of the 16 non-consumptive activities they prohibit, regulate or allow is provided in Appendix A. Figure 1 summarises the findings from this sample.

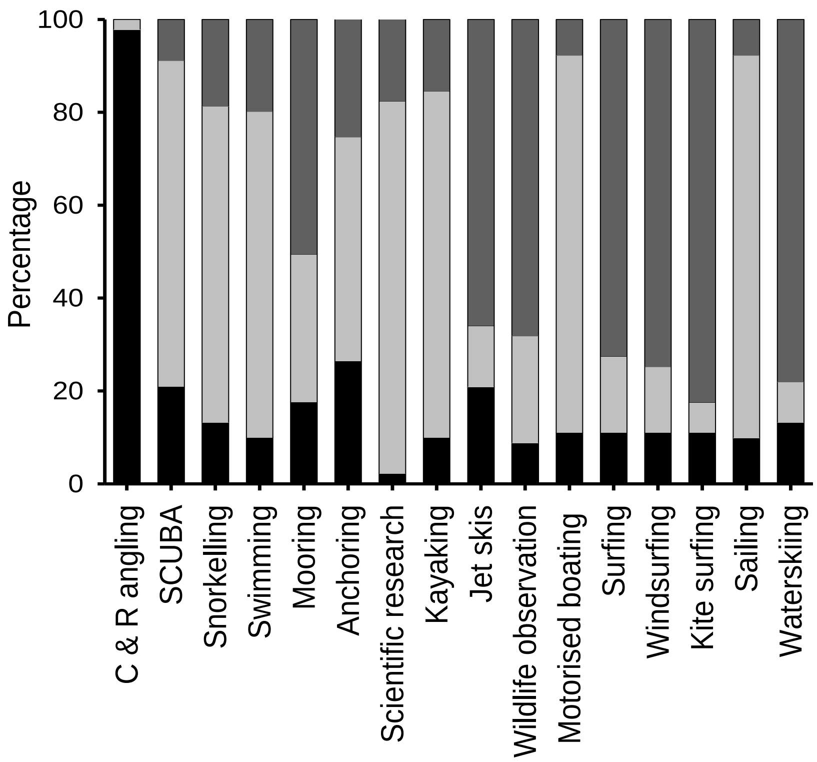

Figure 1. Management approaches taken by 91 HPMRs for 16 activities that are allowed/allowed with regulation within at least one HPMR. C&R angling = catch and release angling. Black bars represent percentage of HPMRs that prohibit an activity, light grey bars percentage of HPMRs that allow an activity or allow with regulation, and dark grey bars percentage of HPMRs that do not mention an activity.

The most commonly prohibited activities (excluding all those discussed earlier as being fundamental to HPMR status such as extractive or depositional activities) are catch and release angling (prohibited in 98% of sampled reserves), anchoring (prohibited in 26%) and scuba diving (prohibited in 21%). Jet skiing was only mentioned as allowed in 13% of HPMRs sampled, but since many HPMRs do not specifically mention permitted motorised watersports by name (66%), then in reality jet skis may actually be allowed in a higher fraction of reserves than 13%.

Activities which were most commonly allowed or permitted with regulation in HPMRs were sailing (82%), motorised boating (81%), scientific research (80%) and scuba diving (70%). The least mentioned activities were: kite surfing (mentioned in 18%), waterskiing (mentioned in 22%), windsurfing (mentioned in 25%), surfing (mentioned in 27%) and wildlife observation (mentioned in 32%).

3.2 Risk assessment of non-consumptive uses

Table 3 shows the results of our assessment of the risks different activities pose to biodiversity. Where we defined an activity as having high and low impact variants, we assigned risk scores to each based on characteristics of the activity described in Table 1. In reality, these variants bracket upper and lower ends of the range of possible risks from an activity depending on how it is conducted. Scores for activities ranged between a low of 0.5 and a high of 3.4. The ranking of the activities makes intuitive sense, with low impact variants of most activities in the bottom half of score and high impact variants in the top half. On the basis of our assessment, we considered ‘low impact’ versions of wildlife observation (risk score 0.5), scientific research (0.9), snorkelling (1.3) and scuba diving (1.3), the activities least likely to cause environmental impact to HPMRs. By contrast, high impact versions of commonly permitted activities such as scuba diving (3.1) and snorkelling (3.1), involving reckless and inappropriate use of boats, scored up among activities more commonly associated with high risk to wildlife, i.e. motor-boating (3.4) jet skiing (3.1) and water skiing (3.0).

Table 3. Risk scores from risk analysis for 16 non-consumptive activities allowed within a sample of 91 HPMRs. Each activity is assessed using eight criteria, which are then averaged. HI = high impact, LI = low impact.

Activity	i) Change in behaviour	ii) Injury/ stress	iii) Collision risk	iv) Lethality	v) Pollution	vi) Scouring damage	vii) Trampling	viii) Damage duration	Average risk score
Motor boating HI	3 [a]	4	4	4	4	2 [b]	2	4	3.4
SCUBA diving HI	3 [a]	4	4	3	2	2 [b]	4	3	3.1
Snorkelling HI	3 [a]	4	4	3	2	2 [b]	4	3	3.1
Jet Skiing	3 [a]	4	4	3	2	3 [b]	2	4	3.1
Waterskiing	3 [a]	4	4	4	2	3 [b]	1	3	3.0
Anchoring HI	1	4	2	4	1	4	4	4	3.0
Scientific research HI	3	4	4	3	1	1	3	2	2.6
Catch and release HI	3	4	4	3	2	0	2	3	2.6
Wildlife Observation HI	3	4	4	3	2	0	2	3	2.6
Mooring HI	1	4	0	4	0	3	2	4	2.3
Catch and release LI	1	4	1	3	2	0	2	3	2.0
Sailing	2	1	2	1	2	2	2	2	1.8
Mooring LI	1	1	1	1	0	2	2	4	1.5
Anchoring LI	1	1	1	2	1	2	2	2	1.5
Kite surfing	1	2	1	1	0	2	2	2	1.4
Motor boating LI	1	2	1	1	2	1	2	1	1.4
Wind surfing	1	1	1	1	0	2	2	2	1.3
Kayaking	1	1	1	1	0	2	2	2	1.3
Surfing	1	1	1	1	0	2	2	2	1.3
Swimming	1	1	1	1	1	2	2	1	1.3
SCUBA diving LI	1	1	1	1	1	2	2	1	1.3
Snorkelling LI	1	1	1	1	1	2	2	1	1.3
Scientific research LI	1	1	1	1	1	0	1	1	0.9
Wildlife Observation LI	1	0	1	1	0	0	1	0	0.5

[a] At high intensities of use this score could be 4.
[b] For boating activities, the potential to cause scouring will depend on depth.

Figure 2 plots risk scores for activities against the degree of regulation those activities received in our sample of HPMRs. Jet skiing and water skiing, as noted above, are generally excluded or regulated, but many other activities requiring boat access are allowed. It is evident that these activities have the potential to highly impact habitats and/or wildlife if not managed appropriately.

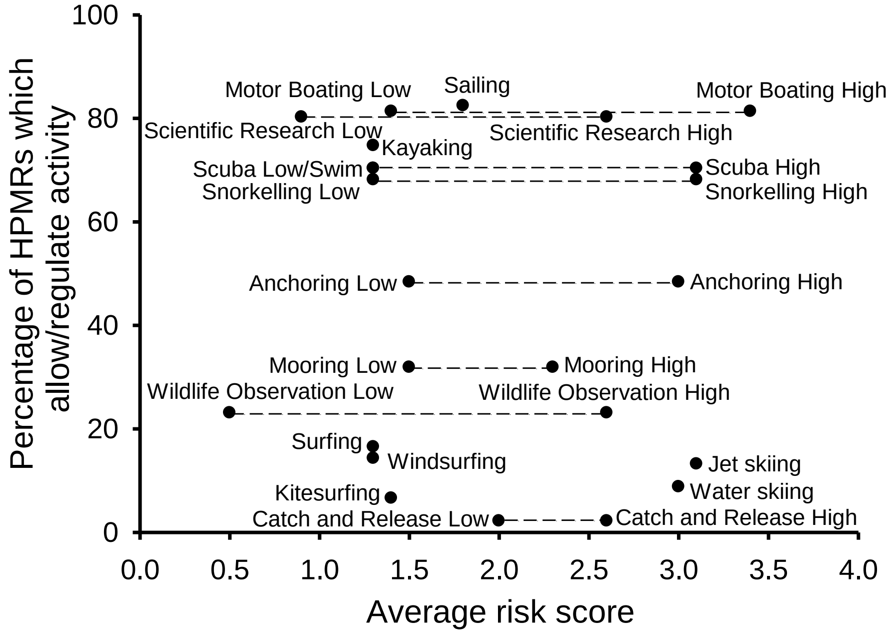

Figure 2. Average risk score from Table 3 for activities in relation to the percentage of 91 HPMRs examined that either allow or allow with regulation the activity in question. Dashed lines indicate the range between risk scores for high and low impact versions of an activity, labelled high and low respectively. Scuba = scuba diving, Swim = swimming, Catch and release = catch and release angling.

4. Discussion

It is often said that a purpose of HPMRs in addition to wildlife and habitat protection is to provide places for recreation and inspiration. Their advocates are quick to point out that exclusion of extractive and depositional uses does not mean that HPMRs are off limits to people. Indeed, as our survey confirmed, most embrace a wide variety of non-consumptive uses. However, our risk analysis reveals that many activities that are typically considered to be benign can carry significant risks to habitats and species within marine protected areas. Given that HPMRs are intended to provide a very high standard of protection, the high risk scores attached to some activities suggest that certain activities should not be allowed whilst others should only be allowed if at low intensity or tightly managed. This is particularly the case given that wildlife protection in HPMRs enhances their attractiveness to visitors. For example, 44% of 139 visitors interviewed on the Caribbean Island of St. Lucia said that the existence of the Soufriere Marine Management Area had positively influenced their choice of St. Lucia as a holiday destination (Barker, 2003). In reality, with two exceptions (catch and release angling and scientific research) the most risky activities – i.e. the high impact versions of most activities, involve use of motorised boats.

Our analysis shows the vital importance of regulating against, or providing appropriate management for, high impact variants of the pursuits within HPMRs. In the following section we discuss each activity examined in our risk analysis and explore considerations governing whether or not it should be allowed within HPMRs. Where the decision is contingent on how the activity is managed, we examine how impacts can be kept to an acceptable level. Table 4 provides a summary of possible mitigation measures.

4.1 Catch and release angling

The great majority of HPMRs in the world prohibit catch and release angling and our risk analysis confirms that this is a wise management approach. Although mortality rates associated with catch and release vary greatly within and among species (ranging from none to nearly 95% killed) (Bartholomew and Bohnsack, 2005), mortality is difficult to quantify due to the time lag after a fish is released during which death might occur (Cooke et al., 2006). Even if an animal appears to survive catch and release, the event may have caused it harm and/or stress which could reduce fitness although not cause death. Schroeder and Love (2002) demonstrated that this could be particularly significant for populations of long-lived, relatively sedentary species where individuals can be subjected to numerous hooking events throughout their lives. All of these factors indicate that catch and release angling in any form and at any intensity would undermine the objectives of HPMRs and should be prohibited.

Table 4. List of 16 non-consumptive activities from a sample of 91 HPMRs. These were identified as being the most commonly allowed that may cause disturbance or damage. Circumstances are listed under which damage could arise and possible mitigation measures are suggested. Adapted from Thurstan et al. (2009).

Activity	Circumstances under which damage may arise	Possible mitigation
Catch and release angling	All circumstances	None likely
Scientific research and education	Damage to sensitive habitats	Code of conduct
	Disturbance to sensitive species	
	High numbers of people	
	Temporary removal of species	Performed only under permit
SCUBA diving and snorkelling	High numbers of divers/snorkelers resulting in trampling/sediment stirring/abrasion	Permits to regulate user numbers, code of conduct, zoning
	Poorly skilled divers	Signs to raise awareness, specified areas for beginners, zoning
	Presence of sensitive wildlife or habitats	Seasonal closures, code of conduct, signs to raise awareness
	High numbers of boats resulting in noise and visual disturbance	Permits to regulate numbers
Swimming	Trampling of sensitive intertidal populations	Demarcation of access points
	Disturbance to sensitive species	Code of conduct, zoning
Non-motorised boating	Visual disturbance during wildlife breeding/feeding/resting times	Code of conduct, seasonal restrictions
Motorised boating	Noise disturbance or physical impact on species	Seasonal closures, code of conduct, speed restrictions
	Noise disturbance or physical impact on wildlife with dependent young	
	Anchoring in sensitive habitat	Provision of moorings, zoning

Personal water craft	Visual disturbance during wildlife breeding/feeding/resting times	Unlikely
	Noise disturbance or physical impact on species	
	Noise disturbance or physical impact on wildlife with dependent young	
	Damage to sensitive habitats by scour/wash/propellers	
Wildlife observation	High numbers of boats resulting in noise and visual disturbance	Permits to regulate numbers
	Noise/disturbance during wildlife breeding/feeding/resting times	Code of conduct
	Harassment of wildlife	
Anchoring/ mooring	Presence of sensitive habitats	Restrictions on anchoring, moorings, code of conduct

(Table 4 continued).

4.2 Scientific research

Non-extractive scientific research is generally allowed in most HPMRs, however to be compatible with 'highly protected' ideology it also needs to be of the 'low impact' version described in this paper. Hence research should create as little noise, physical and visual disturbance as possible since these side-effects can all negatively affect sensitive marine life (Hemingway et al., 2006). Since problems from non-extractive research are predominantly associated with boating activity and scuba diving to collect data, these can be reduced by targeted obligatory regulations which aim to minimize impact. Since research is essential to evaluate the effects of HPMRs, low impact research should be allowed in all.

4.3 Motorised boating

Motor boats can stress and disturb animals whilst they are resting or feeding (Boyes et al., 2006; Davenport and Davenport, 2006) and pose a particular risk to marine mammals through collisions and by affecting echolocation and communication (Erbe, 2002). Wells and Scott (1997) recorded incidences of boat strikes on bottlenose dolphins (*Tursiops truncatus*) during busy summer months in Sarasota, Florida and found that inexperienced juveniles or individuals that were compromised in some way (e.g. mothers with young calves) were the most likely to be struck and injured. The wake of motorised boats can cause erosion of sediments and vegetation (UK CEED, 2000), and these vessels may also play a role in exotic species' introductions (Davenport and Davenport, 2006). Pollution from motor boats occurs through fuel leaks, leaching of anti-fouling compounds, and the discharge of sewage and liquid and solid waste (Backhurst and Cole, 2000; Jennings, 2007), although the latter is not generally a problem in HPMRs because it is usually prohibited.

In general motorised boating is normally allowed within HPMRs. Given the potential for adverse impacts, we suggest that all HPMRs should have regulations which include speed restrictions, activities permitted and number of vessels allowed. Boaters should not be allowed to discharge litter, organic waste or ballast into HPMRs and parks should provide mooring buoys and/or specify anchor sites where damage to the seabed will be minimal. At times and in places where motor boats are particularly disturbing to wildlife, stricter restrictions should be required to prevent this. These measures are particularly important given that HPMR designation is likely to increase boat traffic (Roberts and Hawkins, 2000).

4.4 Water-skiing

This activity is dependent entirely upon 'high impact' motorised boating which is highly threatening to HPMRs for the reasons described above. We recommend that it should be prohibited in HPMRs.

4.5 Jet skiing

Jet skiers travel at high speeds in shallow water, where a variety of sensitive marine habitats occur. They pose a serious risk of collision to marine megafauna such as cetaceans and seals (Davenport and Davenport, 2006) and to people in the water (Anderson, 1998), mainly because skiers fail to notice them. Jet-ski collisions with animals usually result in serious injury or death (Davenport and Davenport, 2006). Disturbance from jet skis to wildlife in HPMRs has severe consequences for animals' resting, feeding and breeding behaviour (Davenport and Davenport, 2006). Since jet skiers like to circle, the disturbance they cause tends to be localised and prolonged (Koschinski, 2008; Nowacek et al., 2001). Marine life can also be harmed by launch of jet skis from undesignated access points, by the pollution they emit and from being used in shallow water (Richins, 2007). For the danger and disturbance that jet skis pose to wildlife and people we recommend this activity should not be allowed within HPMRs.

4.6 Wildlife observation

Wildlife observation has become extremely popular (Constantine, 1999) and if conducted responsibly can be a powerful tool to raise public awareness of environment and marine conservation issues. However, it needs careful regulation to ensure that boats in particular do not cause problems (Richter et al., 2006). Studies have shown that boats which take tourists to observe wildlife are generally less disturbing than other forms of motorcraft, particularly jet skis (Mattson et al., 2005). Nevertheless, underwater noise from vessels such as whale-watching boats has the potential to affect echolocation and behaviour of cetaceans by masking communication signals and causing auditory damage (Erbe, 2002). For example, Constantine et al. (2004) found that dolphin-watching boats disrupted bottlenose dolphin (*Tursiops truncatus*) behaviour in New Zealand by dramatically reducing their resting times, which could affect their long-term health and fitness. Collisions of wildlife watching boats with animals may also occur, especially if boats try to get too close (Kelly et al., 2004).

Wildlife observation within HPMRS should be governed by regulations which define minimum distances, and possibly angle of approach, toward animals, particularly those with young. Regulations should stipulate that boats do not circle wildlife and maximum speed limits should be set in order to minimise wash and noise. People should be kept away from sensitive breeding populations and required to watch wildlife quietly. Limits on the number of boats or people in particular areas or within certain distances of particular populations at any one time, should be developed on a site-specific basis. For example in Horoirangi Marine Reserve in New Zealand, no more than three boats at a time are allowed around any marine mammal, and all marine animals have to be approached slowly without sudden boat movements or loud noise (Department of Conservation, 2006).

4.7 Anchoring and mooring

An anchor that is dropped by a boat will usually damage or destroy any marine wildlife that it hits directly (Davenport and Davenport, 2006; Hawkins and Roberts, 1993). If anchors and their chains or ropes are dragged across the sea floor then damage will proliferate. A single anchoring event can cause considerable impact for which recovery may be prolonged (Creed and Filho, 1999; Lloret et al., 2008; Milazzo et al., 2004). As a general rule, we recommend anchoring not be allowed within HPMRs except in emergencies or in designated areas, as in some New Zealand HPMRs (see Appendix A). Compulsory use of moorings within HPMRs will remove the problem of anchor damage (Harriott, 2002; Jameson et al., 2007; Milazzo et al., 2004), but some benthic disturbance will be inevitable during their installation. In the face of rapidly growing tourism within many HPMRs it may be sensible to limit the number of boats allowed to use each mooring in order to relieve overcrowding.

4.8 Non-motorised watersports i.e. sailing, kayaking, kite surfing, wind surfing and surfing

Research suggests that small sailing boats and the other forms of non-motorised watersports considered in our risk analysis, i.e. kayaking, surfing, wind-surfing and kite-surfing, usually cause little environmental impact so long as yachts don’t drop anchors. However, the presence of these vessels and their occupants may disturb some animals (Davenport and Davenport, 2006). For example, Lelli and Harris (2001) found that non-motorised craft created significant disturbance to resting seals (*Phoca vitulina*) in the Gulf of Maine. At access sites, some trampling or scouring may be detrimental to habitats such as saltmarshes or seagrasses (Richins, 2007). Wind and kite-surfers rarely collide with marine animals although kite-surfers can potentially disturb birds such as waders, terns and gulls in near-shore areas by interfering with the birds' flight or whilst they are feeding at the water's edge (Smith, 2004 cited in Davenport and Davenport, 2006).

While non-motorized watersports don't generally pose a significant risk to wildlife within HPMRs, we recommend regulations are implemented to prevent wildlife disturbance by paddling or sailing too close to resting or breeding places, including possible seasonal restrictions. At present many HPMRs either regulate the use of non-motorised craft or allow them free access.

4.9 Scuba diving and snorkelling

It is now widely recognised that scuba diving and snorkelling can detrimentally affect marine life, particularly in sensitive habitats such as coral reefs (Allison, 1996; Hawkins and Roberts, 1992a; Hawkins and Roberts, 1993; Davenport and Davenport, 2006; Leujak and Ormond, 2008). Divers and snorkellers can break corals directly by trampling, touching or accidentally kicking them and can also stress corals with sediment raised by fins (Hawkins and Roberts, 1993; Hawkins et al., 1999; Leujak and Ormond, 2008; Zakai and Chadwick-Furman, 2002). Novice divers with poor buoyancy control, and underwater photographers can be particularly destructive (Barker and Roberts, 2004). Branching corals are easily broken but massive growth forms are also affected (Hawkins et al., 1999; Tratalos and Austin, 2001; Zakai and Chadwick-Furman, 2002). Ecological consequences of diving and snorkelling include a reduction in the diversity of corals and structural complexity of reefs (Hasler and Ott, 2008), which has implications for reef resilience (Bellwood et al., 2004; Nyström and Folke, 2001). Reduced reef complexity can also affect the number of fish species that a reef can sustain (Wilson et al., 2006). Divers and snorkellers can also disturb reef creatures by approaching, touching or riding them (Valentine et al., 2004). If fish feeding is allowed, problems may develop from animals becoming aggressive through habituation to humans (Davenport and Davenport, 2006).

The great majority of HPMRs permit recreational scuba diving and snorkelling, although a few include areas that are off limits to diving e.g. Ashmore Reef Reserve and Cartier Reserve in Australia (Commonwealth of Australia, 2002). For tropical coral reefs, several scientists have concluded that the carrying capacity for diving is around 5,000 to 6,000 dives per site per year (Dixon et al., 1993; Hawkins and Roberts, 1992b; Zakai and Chadwick-Furman, 2002). However, higher diving intensities may be sustained on reefs whose biological and physical characteristics make them particularly resistant to diver impacts or in places where divers are trained to minimize the damage they might cause (Medio et al., 1997). After studying diver impacts in New Zealand's MPAs, McCrone (2001) concluded that strategies for managing divers need to be determined on an individual site basis and that these should be evaluated through scientific monitoring and reactive management. The need for regular reassessment of permitted diving activity is underscored by the fact that sensitive species are likely to increase in HPMRs over time due to protection from exploitation. With appropriate regulation, diving and snorkelling are suitable activities for a HPMR, especially as they are also very beneficial in helping raise public awareness about marine conservation.

4.10 Swimming

Swimming with wildlife is popular but can affect some animals. For example minke whales (*Balaenoptera acutorostrata*) and whale sharks (*Rhincodon typus*) have been shown to alter their behaviour following exposure to groups of swimmers (or snorkellers) (Valentine et al., 2004). Swimmers can also trample marine life in the water and when they access the sea (Davenport and Davenport, 2006; Hawkins and Roberts, 1993; Leujak and Ormond, 2008). On the whole swimming is a benign activity allowed in the majority of HPMRs. However we recommend that HPMRs should establish obligatory code of conduct regulations to prevent harm to animals, particularly during breeding seasons or periods when megafauna such as basking sharks (*Cetorhinus maximus*) are present. For particularly sensitive shorelines the demarcation of access points for swimmers would help prevent more widespread trampling damage.

5. Conclusions

Highly protected marine reserves provide the pinnacle of protection against extractive and depositional activities that damage marine life. However, we found that some activities traditionally considered benign have the potential to damage HPMRs and are commonly allowed within them with little or no regulation. Most of these are associated with recreational use, and thereby help generate revenue for HPMRs and provide benefits for wider communities. However if HPMRs are to provide the strong protection intended these activities must be strictly managed.

In the case studies examined, strategies to mitigate harm from potentially damaging non-consumptive activities commonly found within HPMRs included: provision for codes of conduct, visitor education, limits on visitor numbers, specified access routes, speed and anchoring restrictions on boats, seasonal access restrictions, and zoning schemes.

Most non-consumptive activities practised within HPMRs are suitable in their ‘low impact’ form, with appropriate management. The exceptions are jet skiing, water skiing and catch and release angling which undermine high levels of protection. The operation of motor boats within HPMRs needs strict regulation, including their use for scuba diving, snorkelling, wildlife observation and scientific research. However if recreational use is particularly heavy, regulation alone may not be sufficient to prevent degradation. Ultimately managers of HPMRs have to make difficult decisions about what to allow and it may be that limits on visitor numbers have to be considered for some HPMRs.

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Chapter 7: Discussion

7.1 SUMMARY OF THESIS AIMS AND RESULTS

The aim of my research was to build up a picture of historical change to the marine environment around the United Kingdom as a result of fishing.

In chapter two I used witness statements from the 1860s and 1880s to analyse perceptions of change during a time when trawling activities were expanding around the British Isles. Fishers' testaments from this time have provided new evidence that the marine environment, particularly inshore habitats, were significantly impacted by bottom trawling long before fisheries statistics began to be collected in the late 1880s.

In chapter three I used fisheries landings statistics and fishing vessel data to measure the commercial productivity of UK fisheries over a period of 118 years. I created an index of landings per unit of fishing power (LPUP) which allowed for adjustment of recorded landings as technology improved. I found that since the 1880s the availability of fish has fallen by 94%, hence the UK fishing fleet has to work 17 times harder to catch the same amount of fish today than when statistics started to be collected. This research represents one of the first uses of long-term statistics on a national scale to illustrate how the rewards of fishing have fallen since the 19th century.

The aim of chapter four was to investigate change to habitats such as oyster fisheries as a result of bottom trawling and dredging. I undertook field surveys to examine the current status of old oyster beds and collected sediment cores to investigate wider community changes as a result of fishing. These enabled me to show that major changes to seabed habitats occurred before the turn of the 20th century. In some parts of the Firth of Forth, it appears that untargeted mollusc species, in addition to oysters, declined in line with intensive fishing.

In chapter five I explored the availability of fish to consumers and how this corresponds with Government recommendations on the amount of fish we should consume for health reasons. This is some of the first research to investigate fish availability trends using historical data. Currently within the UK fish availability per capita falls well below recommended consumption levels and most of our fish is imported from abroad. Certainly government recommendations cannot be met unless we become even more reliant on other countries. However, worldwide the situation looks similarly bleak: wild fish landings are in decline and cannot meet recommended consumption levels per capita at present. When aquaculture production is included into the figure global fish availability remains at more stable levels, although still below recommended amounts per capita. However, as human populations continue to grow, protein demand from fish is likely to increase, raising questions about future food security and how we will meet future needs.

Highly protected marine reserves (HPMRs) are areas where marine populations and habitats are protected from fishing and other extractive activities. In chapter six I investigated the potential for non-consumptive activities to cause damage to habitats or animal populations in HPMRs, together with strategies to mitigate harm. Catch and release angling, jet skiing and water skiing are unsuitable activities for HPMRs. Other activities also have the potential to cause harm and must be controlled if highly protected sites are to allow wildlife and habitat recovery. These findings have important implications for UK protected area management and are currently being used by stakeholders to determine management measures for future protected areas around the UK. They also have wider significance in that many potentially harmful non-consumptive activities receive little or no management within supposedly highly protected marine reserves.

7.2 FUTURE RESEARCH

My research has shown how fishing activities, in particular trawling, have altered marine ecosystems around the UK during the last 150 years. This conclusion was drawn from field research, dating analysis, and the examination of historical charts, literature, landings statistics and witness statements. The findings expand our knowledge of marine environmental baselines at a national scale and can be used to inform future marine management decisions. However, there is still much to be learnt and I discuss future research directions below.

More in-depth regional studies of long-term change would provide much needed historical baseline information for marine management at a local level, and may increase people's interest in conserving the marine environment in their area. For example the Community of Arran Seabed Trust (COAST), based in the Firth of Clyde, is a community-based initiative which campaigned to set up a no-take zone in Lamlash Bay to protect it from fishing impacts and to allow the area to recover. Prior to my PhD, I conducted an historical study of the Clyde and found it to have changed greatly as a result of fishing (Thurstan and Roberts 2010). This research was used by COAST to campaign for greater protection of the Clyde sea area from fishing hence this sort of historical research may benefit other areas in the same way.

A difficult type of historical study to perform is finding information about how benthic habitats have altered over time. Field research such as the work I did in chapter four can provide information on change when historical sources are limited or do not exist. The strength of the results I obtained in chapter four could be bolstered with more core samples from the sites I investigated. The same methodologies could also be used in other areas such as the Firth of Clyde to provide additional evidence of changes to seabed habitats over time. As further historical information on fisheries and marine habitats comes to light it will help direct where to conduct this sort of future research.

Little is known about the current status of horse mussel beds in the Firth of Forth. Other Forth horse mussel beds to those I studied have been mentioned in past literature and I would like to find out more about these and whether they still exist. Further surveys of the Firth of Forth which target past locations of horse mussel beds would enable habitat maps to be built in order to inform appropriate management strategies.

7.3 CONCLUSIONS

There are few areas in the world that still have pristine marine environments, and those that do often exhibit very different characteristics to exploited ecosystems (Sandin et al., 2008). Activities such as fishing can quickly alter an ecosystem to a state that would not be recognised by earlier generations (Saenz-Arroyo et al., 2005). This can make it difficult to believe historical descriptions of past abundance and contributes to a collective belief that current marine ecosystems are natural, or at least have only been impacted in recent years (Saenz-Arroyo et al., 2006). Whilst long-term data exists for assessing some commercial species, understanding wider community change can be difficult due to a lack of quantitative sources (Fortibuoni et al., 2010). Growing numbers of studies provide strong evidence that we have impacted our oceans on a global level (e.g. Halpern et al., 2010), and research into historical change demonstrates to what extent we have altered these marine ecosystems. Without this knowledge our continuing impacts, as well as the effects of conservation and recovery measures, cannot be evaluated effectively.

A difficulty inherent within studies of the marine environment is how to disentangle the effects of fishing from other impacts such as pollution, land reclamation and increased siltation, which may have been ongoing for centuries. For example, during the 1860s most fishers were quick to blame declining stocks on destructive trawling methods, but some were also concerned about increases in pollution and the potential for habitat smothering by coal and ash deposited overboard from steamers. Despite the challenges, my research makes a strong case that fishing, in particular bottom trawling and dredging, has been a powerful driver of change during the last 150 years. In saying this I recognise that instances where factors other than fishing have caused declines in populations do occur. For example, we know that some UK oyster stocks were extirpated by disease or extended periods of cold weather (e.g. Shelmerdine and Leslie 2009; Wright 1932). Even so, many of these populations had been previously decimated by fishing and it is likely that overexploitation left them less resilient to pressures such as disease or environmental change (Gross and Smyth 1946).

Today, improvements in technology and the globalisation of fisheries enable the developed world to carry on with 'business as usual' in the face of marine habitat loss and fish population decline (Esteban and Crilly 2010). However, as the emerging issues of climate change and ocean acidification (Fabrey et al., 2008; Hall-Spencer et al., 2008; Harley et al., 2006) threaten to compound these problems, it is increasingly recognised that marine ecosystems need to be managed differently to how they have been in the past (Botsford et al., 1997; Roberts 2007). Over the next few years UK fisheries management is due to change: Marine Conservation Zones will be implemented, some with highly protected site status where no extractive activities will be allowed. Despite this step forward, the many conflicting interests that will continue in the sea mean that it will always be difficult for governments and managers to make conservation a priority. Hence it is important that historical sources are never over-looked but rather researched and findings made known so that our environmental baselines do not continue to shift. This will enable informed decisions to be made now and in the future. Recovering our seas to a healthy state is vital as we face the challenges of the 21st century and beyond.

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Appendix A. **Non-consumptive activities prohibited, allowed or regulated in the 91 HPMRs examined. In many examples no-take principles do not apply throughout the entire park, but to core zones, where this is the case the information presented in this table refers solely to no-take zone activities abbreviated to NTA. Activities listed are not exhaustive and instead refer to the 16 activities identified for this paper. EI= extra information.**

			Activities	
Name of HPMR	**Country**	**Prohibited**	**Allowed**	**Regulated**
Folkestone Park and Marine Reserve Cumberbatch (2001) http://www.coastal.gov.bb	Barbados	**NTA:** All fishing and extractive activities		Motorised craft; boating; swimming; scientific research; jet skis; snorkelling
Hol Chan Marine Reserve http://www.holchanbelize.org/rules.html	Belize	**NTA:** Fishing; collecting;	Scientific research	Boating; anchoring; diving; snorkelling **EI:** all boats must be registered
Glover's Reef Marine Reserve http://www.gloversreef.org	Belize	**NTA:** All fishing and extractive uses	Scientific research	Access; diving, catch-and-release angling; boating; anchoring; mooring **EI:** Special permission required to visit Wilderness zone where no boats allowed except in emergency

Name of HPMR	Country	Prohibited	Activities Allowed	Regulated
Blue Hole Natural Monument Geoghegan et al (2001) http://www.ecoroute.org	Belize	Anchoring **NTA:** All fishing; extraction of shells or plants	Scientific research	Diving and snorkelling require guides; anchor only on moorings
Montego Bay Marine Park http://www.mbmp.org	Jamaica	**NTA:** All fishing and extractive uses	Diving; snorkelling; swimming; mooring .	Scientific research; anchoring **EI:** Dredging, excavating, filling or building need written permission; fishing in permitted areas requires written permission which may be over-ruled; collection of natural or living specimens requires written permission.
Soufriere Marine Management Area http://www.smma.org.lc/Zoning.htm	St Lucia	Anchoring **NTA:** All fishing and extractive uses		Diving; snorkelling; scientific research
Saba Marine Park http://www.mina.vomil.an/Wetgeving/SABA_meo.htm, www.mina.vomil.an/Pubs/fernandes-EvalSMP.pdf	Netherlands Antilles	Anchoring on reefs; touching marine life by visitors; littering **NTA:** Fishing, collection of any marine life	Snorkelling; swimming; boating	Diving **EI:** Spearfishing by snorkel by residents in designated areas

			Activities	
Name of HPMR	**Country**	**Prohibited**	**Allowed**	**Regulated**
Buccoo Reef Marine Park Mukhida (2003) Tompkins et al. (2002)	Tobago	**NTA:** All fishing and extractive uses	Diving; swimming; snorkelling; windsurfing **NB these activities are monitored**	Vessel access; jet skis (require license); **NB Future plans to prohibit jet skis**
San Andres Islands (Seaflower Biosphere Reserve) http://whc.unesco.org/en/tentativelists/5166/	Colombia	**NTA:** All fishing and extractive uses	Research and monitoring	Non-consumptive activities **EI:** Some areas of no-take specifically for research and monitoring, others allow non-consumptive uses
La Rinconada Marine Reserve http://www.sernapesca.cl Ortiz et al. (2009)	Chile	**NTA:** All fishing and extractive uses		Scientific research; access; recreation and educational activities
Fernando de Noronha Marine National Park www.fernando-de-noronha.org/environment/marine-reserve.php	Brazil	**NTA:** All fishing and extractive uses	Scientific research	Swimming; diving (requires supervision); anchoring; access; vessels and vehicles require authorization **EI:** Tourism and recreation are strictly regulated, access restricted to certain times of day and specified areas
Abrolhos Marine National Park http://www.abrolhos.net	Brazil	**NTA:** All fishing and extractive uses	Scientific research	Diving; access; anchoring **EI:** Artisanal fishing in zoned

Name of HPMR	Country	Activities Prohibited	Allowed	Regulated
				areas under supervision
Isla Bastimentos National Marine Park http://www.anam.gob.pa/images/stories/parque_bastimento/PM_BASTIMENTOS.pdf	Panama	**NTA:** All fishing and extractive uses	.	Scientific research; visitor numbers; diving; anchoring; boating **EI:** Anchor only in pre-defined areas and with authorization; navigation and speed of vessels is regulated cane sport fishing allowed in defined zones; construction of tourist and recreational facilities is regulated; zoning systems
Cocos Island National Park http://www.unep-wcmc.org/sites/wh/pdf/Cocos%20I.pdf	Costa Rica	**NTA:** All fishing and extractive uses	Snorkelling; diving; swimming	Anchoring restricted to two bays; scientific research
Paracas National Reserve http://www.parkswatch.org/parkprofile.php?l=eng&country=per&park=panr&page=man	Peru	**NTA:** All fishing and extractive uses		

		Activities		
Name of HPMR	**Country**	**Prohibited**	**Allowed**	**Regulated**
Galapagos www.darwinfoundation.org, http://www.unep-wcmc.org/sites/wh/pdf/Galapagos.pdf, http://www.galapagosonline.com/nathistory/nationalpark/nationalpark.htm	Ecuador	**NTA:** Fishing and removing other marine life	Swimming; windsurfing; kayaking	Access; surfing; scientific research (requires permit); diving; snorkelling **EI:** Tourism is regulated by limiting access and charging entrance fees
Loreto Bay National Park Brochure	Mexico	**NTA:** Fishing		
Northwestern Hawaii Islands - Papahanaumokuakea Marine National Monument http://hawaiireef.noaa.gov/	Hawaii	Anchoring on coral **NTA:** All fishing and extractive uses		Swimming; snorkelling; diving; anchoring (requires permit); boating; access **EI:** Bottom-fishing is being phased out and will be prohibited from 2011.
Dry Tortugas http://floridakeys.noaa.gov/regs/zoning.html	USA (Florida)	Anchoring; touching or standing on living or dead coral; diving and snorkelling prohibited in Tortugas Ecological Reserve **NTA:** All extractive uses		Boating; diving; snorkelling; access; research; jet skiing; mooring **EI:** In Tortugas MR vessels may only enter (without permits) if they remain in continuous transit with all fishing gear stowed

		Activities		
Name of HPMR	**Country**	**Prohibited**	**Allowed**	**Regulated**
Exuma Cay Land & Sea Park www.exumapark.info	Bahamas	**NTA:** All extractive uses	Mooring for boats visiting the park (fee charged).	Anchoring; boating; jet skiing; access **EI:** Anchoring not allowed in the mooring fields, on coral reefs and certain other designated areas in the park.
Channel Islands MPA network e.g. Richardson Rock, Anacapa, Santa Barbara Island, Skunk Point, South Point http://www.dfg.ca.gov/marine/channel_islands/regs.asp	USA (California)	**NTA:** All extractive uses	Swimming; diving; snorkelling; boating; surfing; anchoring	Scientific research; restoration measures; monitoring
Punta Gorda State Marine Reserve http://www.dfg.ca.gov/mlpa/mpa_regs.asp	USA (California)	**NTA:** All extractive uses	Swimming; diving; snorkelling; boating; surfing; anchoring	Scientific research; restoration measures; monitoring
Natural Bridges State Marine Reserve http://www.dfg.ca.gov/mlpa/mpa_regs.asp	USA (California)	**NTA:** All extractive uses	Swimming; diving; snorkelling; boating; surfing; anchoring	Scientific research; restoration measures; monitoring
Elkhorn Slough State Marine Reserve http://www.dfg.ca.gov/mlpa/mpa_regs.asp	USA (California)	**NTA:** All extractive uses	Swimming; diving; snorkelling; boating; surfing; anchoring	Scientific research; restoration measures; monitoring

Name of HPMR	Country	Activities Prohibited	 Allowed	 Regulated
Moro Cojo Estuary State Marine Reserve http://www.dfg.ca.gov/mlpa/mpa_regs.asp	USA (California)	**NTA:** All extractive uses	Swimming; diving; snorkelling; boating; surfing; anchoring	Scientific research; restoration measures; monitoring
Lovers Point State Marine Reserve http://www.dfg.ca.gov/mlpa/mpa_regs.asp	USA (California)	**NTA:** All extractive uses	Swimming; diving; snorkelling; boating; surfing; anchoring	Scientific research; restoration measures; monitoring
Ano Nuevo State Marine Conservation Area http://www.dfg.ca.gov/mlpa/mpa_regs.asp	USA (California)	**NTA:** All extractive uses	Swimming; diving; snorkelling; boating; surfing; anchoring	Scientific research; educational activities; recreational activities; hand harvest of giant kelp
Edmonds Underwater Marine Park http://www.ci.edmonds.wa.us/Discovery_programs_website/Marine_Sanctuary_Info.html	USA (California)	Waterskiing or operating any type of watercraft within 200 feet of the park **NTA:** All extractive uses		Diving **EI:** Inflatable rafts or boats propelled manually may be used for instructional purposes by a certified instructor
Edgecumbe Pinnacles Marine Reserve http://www.cf.adfg.state.ak.us/region1/finfish/grndfish/pinnacles/pinnacles.php	USA (Alaska)	Commercial fishing Recreational fishing	Anchoring	

			Activities	
Name of HPMR	**Country**	**Prohibited**	**Allowed**	**Regulated**
The Gully http://www.mar.dfo-mpo.gc.ca/oceans/e/essim/gully/essim-gully-e.html	Canada	**NTA:** All extractive uses	Search and rescue; international navigation rights; activities related to national security and sovereignty	Scientific research and monitoring **EI:** Zone 1 is preserved in a near-natural state with full ecosystem protection Zone 2 imposes strict protection. Zone 3 has lesser amounts of protection Zone 2 and 3 allow fishing for halibut, tuna, shark and swordfish under a federal fishing license and approved management plan
Lundy Marine Nature Reserve http://www.lundynotakezone.org	UK	Anchors or diver shotting lines within 100m of the Knoll Pins **NTA:** All extractive uses	Scientific research	
Lamlash Bay Marine Reserve www.arrancoast.com, http://www.legislation.gov.uk/ssi/2008/317/pdfs/ssien_20080317_en.pdf	UK	Fishing	Fishing for scientific purposes; environmental tourism; diving; snorkelling; boating	**EI:** A fisheries management zone adjacent to the NTA will be regulated, allowing for the regeneration of scallops (in particular) and other shellfish
Cerbere-Banyuls Nature Reserve Vandeperre et al. (2006)	France	**NTZ:** Fishing; diving; anchoring.	Swimming	Boating, scientific research

		Activities		
Name of HPMR	**Country**	**Prohibited**	**Allowed**	**Regulated**
Cote Bleue (Carry-le Rouet & Cap Couronne) Vandeperre et al. (2006)	France	**NTZ:** Fishing; anchoring; diving	Swimming, snorkelling; cruising and boating	Scientific research **EI:** Trawling is prohibited within 3 nautical miles from the coast
Bouches de Bonifacio Nature Reserve Vandeperre et al. (2006)	France	**NTZ:** Fishing; diving	Boating; anchoring; swimming	Scientific research
Scandola Nature Reserve www.unep-wcmc.org/sites/pa/0825v.htm	France	NTZ: Fishing; diving, extractive activities	Snorkelling; swimming	Mooring
Ustica Island Marine Protected Area Vandeperre et al. (2006)	Italy	**NTZ:** All activities including access		Scientific research **EI:** Swimming permitted in two small beaches
Tuscany Archipelago Vandeperre et al. (2006)	Italy	**NTZ:** Fishing; diving; swimming; boating; anchoring		Scientific research
Penisola del Sinis-Isola di Mal diventre Marine Reserve www.federcoopesca.it Vandeperre et al. (2006)	Italy	**NTZ:** Fishing; diving; swimming; boating (navigation and stop access to all vessels)		Scientific research
Rdum Majjiesa-Ras ir-Raheb Marine Protected Area Vandeperre et al. (2006)	Malta	**NTZ:** Fishing; diving; swimming; anchoring; boating		Scientific research

			Activities	
Name of HPMR	**Country**	**Prohibited**	**Allowed**	**Regulated**
Blue Bay and Balaclava Marine Park http://www.gov.mu/portal/site/fisheries/menuitem.e61d99aec66b8dde7f7a98ada0208a0c/?content_id=d73f057968dfc010VgnVCM1000000a04a8c0RCRD	Mauritius	**NTZ:** Extractive activities; anchoring; boating or surface water sports in swimming zone	Transport of divers	Boating; scientific research; swimming **EI:** Zoned marine park with different areas for swimming, fishing and waterskiing
Safata No-take Zone http://www.mnre.gov.ws/documents/fact_sheets/MPA%20info%20sheet%20Safata.pdf	Samoa	**NTA:** No extractive activities	Canoeing; diving; snorkelling; surfing	**EI:** Fishing outside of the no-take zone within the wider reserve is allowed but is monitored
Tabarca Marine Reserve http://www.alicante-spain.com/tabarca-island.html , www.medpan.org, Vandeperre et al. (2006)	Spain	**NTA:** Fishing; diving; swimming; anchoring; motorized sport activities	Boating	Scientific research
Columbretes Islands Marine Reserve Vandeperre et al. (2006)	Spain	**NTA:** Fishing; anchoring; swimming; diving	Boating; scientific research	
Cabo de Gata Nijar www.medpan.org	Spain	**NTA:** Fishing; diving; mooring; anchoring	Swimming; navigation of vessels; sailing	Scientific research
Ses Negres www.medpan.org	Spain	**NTA:** Fishing; diving; mooring; anchoring	Swimming	Navigation of vessels; sailing; scientific research
Medes Islands Vandeperre et al. (2006)	Spain	**NTA:** No extractive activities	Boating; navigation	Scientific research; diving, swimming; anchoring

		Activities		
Name of HPMR	**Country**	**Prohibited**	**Allowed**	**Regulated**
La Graciosa e Islotes del Norte de Lanzarote Marine Reserve Vandeperre et al. (2006)	Canary Islands	**NTA:** All activities except scientific research		Scientific research
Larvotto Marine Reserve www.medpan.org	Monaco	**NTA:** Fishing; mooring or anchoring	Swimming	Navigation; sailing; diving; scientific research
Limski Zaljev Marine Reserve www.medpan.org	Croatia	**NTA:** Fishing; mooring; anchoring		Swimming
Kornati Marine Reserve www.medpan.org	Croatia	**NTA:** Fishing; diving; mooring; anchoring; swimming; navigation; sailing		Scientific research
Zembra & Zembretta Marine Reserve www.medpan.org	Tunisia	**NTA:** Fishing	Scientific research	Navigation of vessels; sailing; diving; mooring; anchoring
Aliwal Shoal Marine Protected Area http://www.bcb.uwc.ac.za/pssa/articles/includes/Aliwal_Shoal_Notice.pdf	South Africa	**NTA:** Extractive activities; personal watercraft	Educational activities; vessel transit	Mooring; anchoring; scientific research; diving
Cape Peninsula Marine Protected Area http://www.bcb.uwc.ac.za/pssa/articles/includes/CPNP_Notice.pdf	South Africa	**NTA:** Extractive activities; personal watercraft	Educational activities; vessel transit	Mooring; anchoring; scientific research; diving

		Activities		
Name of HPMR	Country	Prohibited	Allowed	Regulated
Pondoland Marine Protected Area http://www.environment.gov.za//PolLeg/GenPolicy/2004Feb16_1/Pondoland_Notice.pdf	South Africa	**NTA:** Extractive activities; personal watercraft	Educational activities; vessel transit	Diving; scientific research
Kisite Marine National Park McClanahan et al. (2006) http://www.kws.org/parks/parks_reserves/KMNP.html	Kenya	**NTA:** No extractive activities	Diving; snorkelling; wildlife observation; environmentally friendly recreational activities; windsurfing; waterskiing	
Chumbe Island Marine Sanctuary http://www.chumbeisland.com http://www.marineparktz.com/pdf/dmrs_gmp_for_dar_es_salaam_marine_reserves_system.pdf	Tanzania	Diving; jet skiing, extractive activities	Snorkelling; sailing; windsurfing; swimming	Anchoring; mooring; diving for permitted research and filming; scientific research
Fungu Yasin Island http://www.marineparktz.com/pdf/dmrs_gmp_for_dar_es_salaam_marine_reserves_system.pdf	Tanzania	No extractive activities	Research and education; guided recreational activities	Anchoring; scientific research; diving; mooring
Bongoyo Island Marine Reserve http://www.marineparktz.com/pdf/dmrs_gmp_for_dar_es_salaam_marine_reserves_system.pdf	Tanzania	No extractive activities	Research and education; guided recreational activities	Anchoring; scientific research; diving; mooring
Mbudya Island Marine Reserve	Tanzania	No extractive activities	Research and	Anchoring; scientific research;

			Activities	
Name of HPMR	**Country**	**Prohibited**	**Allowed**	**Regulated**
http://www.marineparktz.com/pdf/dmrs_gmp_for_dar_es_salaam_marine_reserves_system.pdf			education; guided recreational activities	diving; mooring
Ras Mohammed National Park http://cdws.travel/environment/default.aspx, http://sea.unep-wcmc.org/protected_areas/archive/parks/8_2.pdf#page=33	Egypt	**NTA:** No extractive activities; anchoring on reefs	Scientific research; swimming; snorkelling; diving	**EI:** Artisanal fishing is allowed in some areas for Bedouin communities to protect traditional way of living
Nabq Managed Resource Protected Area http://www.eeaa.gov.eg/English/main/regulations.asp	Egypt	Anchoring on reef **NTA:** No extractive activities		Diving at designated access points
Sumilon Islands Marine reserve White (1989), www.unep.org, Russ and Alcala (1999)	Philippines	**NTA:** No extractive activities or recreational activities in Sanctuary Zone		**EI:** Recreational activities allowed in buffer zone around NTA, but artisanal fishing also allowed
Apo Island Russ and Alcala (1999)	Philippines	**NTA:** No extractive activities; anchoring	Diving; snorkelling	
Tubbataha Reefs Natural Park http://www.tubbatahareef.org/downloads/park_rules.pdf	Philippines	Navigation with unstowed fishing gear; motorised sports equipment; anchoring on reefs; swimming, snorkelling or diving around islets; access to islets; disturbance of wildlife		Boating; diving; snorkelling; swimming; scientific research.

Name of HPMR	Country	Activities Prohibited	Allowed	Regulated
		NTA: No extractive activities; catch and release; jet skis or other motorised sports equipment		
El Nido Marine reserve (part of Palawan Biosphere Reserve) http://www.pcsd.ph/protected_areas/elnido.htm, http://www.earthdive.com/site/news/newsdetail.asp?id=1643	Philippines	**NTA:** No extractive activities or human activities		
Waitabu Marine Reserve http://www.waitabu.org/park-management/admission-rules/	Fiji	**NTA:** No extractive activities	Diving; snorkelling; swimming	Anchoring; mooring
Namena Marine Reserve http://namena.org/park-management/admission-rules/	Fiji	**NTA:** No extractive activities	Diving; snorkelling; swimming	Anchoring; mooring
Ashmore Reef & Cartier Island Marine Reserve Commonwealth of Australia (2002)	Australia	**NTA:** No extractive activities; diving; snorkelling		Access; scientific research; diving and snorkelling outside of core zone

Name of HPMR	Country	Activities Prohibited	Allowed	Regulated
Macquarie Island Commonwealth Marine Reserve www.environment.gov.au	Australia	**NTA:** No extractive activities; diving; snorkelling	Swimming; other non-consumptive recreational activities	Scientific research; diving and snorkelling outside of core zone
Coring-Herald and Lihou Reef National Nature Reserves (Coral Sea National Nature Reserves) www.environment.gov.au	Australia	**NTA:** No extractive activities	General access; diving; snorkelling	Scientific research; tourism and charters require approval
Mermaid Reef Marine National Nature Reserve Commonwealth of Australia (2002), www.environment.gov.au	Australia	No extractive activities; anchoring; recreational water sports such as surfing, water skiing and jet skis	Access/visitation; mooring on designated areas; diving; snorkelling	Scientific research requires a permit; commercial tourism and charters require approval from the Director of National Parks
Heard Island and McDonald Islands Marine Reserve http://www.heardisland.aq/protection/marine_reserve/index.html	Australia	**NTA:** No extractive activities	Wildlife observation	**EI:** Area is zoned and allows different categories of uses
Lord Howe Island Marine Park http://www.environment.gov.au/coasts/mpa/publications/pubs/lordhowe-plan.pdf	Australia	**NTA:** No extractive activities	Commercial shipping; diving; recreational boating and yachting	Diving; scenic tours; scientific research

Name of HPMR	Country	Activities Prohibited	Allowed	Regulated
Solitary Islands Marine Park Sanctuary area http://www.environment.gov.au/coasts/mpa/publications/pubs/solitary-user-guide-map.pdf	Australia	**NTA:** No extractive activities; anchoring	Recreational boating; jet skiing; snorkelling; transit if fishing gear is stowed; diving	Commercial wildlife watching; diving; surfing; sailing
Cod Grounds Commonwealth Marine Reserve http://www.environment.gov.au/coasts/mpa/cod-grounds/index.html	Australia	No extractive activities; commercial fishing vessels must not enter reserve; recreational vessels must have any fishing gear stowed		Diving; scientific research **EI:** Commercial activities assessed on a case-by-case basis
Montebello/Barrow Islands Marine Conservation Reserves (Sanctuary Zones) Department of Environment and Conservation (2007)	Australia	**NTA:** No extractive activities	Recreational motorised and non-motorised boating and surface water sports (although maybe restricted in specific areas if a clear need); diving; snorkelling; wildlife observation; surfing	Scientific research; moorings
Point Cooke Marine Sanctuary http://www.parkweb.vic.gov.au/resources07/07_1962.pdf	Australia	**NTA:** No extractive activities; mooring	Wildlife observation; kiteboarding; windsurfing; sailing; anchoring; diving; snorkelling; surfing; swimming; water	Motorised boating; jet skis

Name of HPMR	Country	Prohibited	Activities Allowed	Regulated
			skiing	
Ricketts Point Marine Sanctuary http://www.parkweb.vic.gov.au/resources07/07_1417.pdf	Australia	**NTA:** No extractive activities; mooring	Wildlife observation; kiteboarding; windsurfing; sailing; anchoring; diving; snorkelling; surfing; swimming; water skiing	Motorised boating; jet skis
Jawbone Marine Sanctuary http://www.parkweb.vic.gov.au/resources07/07_1987.pdf	Australia	**NTA:** No extractive activities; mooring	Wildlife observation; kiteboarding; windsurfing; sailing; anchoring; diving; snorkelling; surfing; swimming; water skiing	Motorised boating; jet skis
Great Barrier Reef Marine Park http://www.gbrmpa.gov.au/corp_site/management/zoning	Australia	**NTA:** All extractive activities	Swimming; snorkelling; diving; boating; anchoring (except in certain areas).	Scientific research **EI:** The most highly protected zones include the Preservation Zone (no access) and Marine National Park Zone (no-take but non-consumptive activities permitted).

Name of HPMR	Country	Activities Prohibited	Allowed	Regulated
Cape Rodney-Okakari Point Marine Reserve http://www.doc.govt.nz/conservation/marine-and-coastal/marine-protected-areas/	New Zealand	No extractive activities	Scientific research; snorkelling; diving; swimming; kayaking; anchoring	Motorised boating (including jet skis); intrusive scientific research
Taputeranga Marine Reserve www.gw.govt.nz, http://www.doc.govt.nz/conservation/marine-and-coastal/marine-protected-areas/	New Zealand	No extractive activities	Scientific research; snorkelling; diving; swimming; kayaking; anchoring	Motorised boating (including jet skis); mooring; intrusive scientific research
Horoirangi Marine Reserve http://www.doc.govt.nz/parks-and-recreation/places-to-visit/nelson-marlborough/motueka-area/horoirangi-marine-reserve/activities/	New Zealand	No extractive activities	Scientific research; snorkelling; diving; swimming; kayaking; anchoring; wildlife observation	Motorised boating (including jet skis); intrusive scientific research
Kapiti Marine Reserve http://www.doc.govt.nz/upload/documents/conservation/marine-and-coastal/marine-protected-areas/kapiti-marine-reserve-conservation-management-plan.pdf	New Zealand	No extractive activities	Swimming; boating; diving; snorkelling; scientific research; anchoring	Motorised boating (including jet skis); Intrusive scientific research

Name of HPMR	Country	Activities		
		Prohibited	Allowed	Regulated
Kermadec Marine Reserve http://www.doc.govt.nz/conservation/marine-and-coastal/marine-protected-areas/marine-reserves-a-z/kermadec/facts/	New Zealand	No extractive activities	Anchoring	Intrusive scientific research
Long Bay Marine Reserve http://www.doc.govt.nz/conservation/marine-and-coastal/marine-protected-areas/marine-reserve-information/	New Zealand	No extractive activities	Swimming; boating; diving; snorkelling; scientific research; anchoring	Motorised boating (including jet skis); intrusive scientific research
Fjordland Marine Reserve network http://www.doc.govt.nz/upload/documents/conservation/marine-and-coastal/marine-protected-areas/fiordland-marine-reserves.pdf	New Zealand	No extractive activities	Swimming; boating; diving; snorkelling; scientific research; anchoring	Motorised boating (including jet skis); intrusive scientific research
Poor Knights Marine Reserve http://www.doc.govt.nz/conservation/marine-and-coastal/marine-protected-areas/marine-reserves-a-z/poor-knights-islands/	New Zealand	No extractive activities	Swimming; boating; diving; snorkelling; scientific research; anchoring	Intrusive scientific research

Name of HPMR	Country	Prohibited	Activities Allowed	Regulated
Tapuae Marine Reserve http://www.doc.govt.nz/upload/documents/conservation/marine-and-coastal/marine-protected-areas/tapuae-marine-reserve-brochure.pdf	New Zealand	No extractive activities	Swimming; boating; diving; snorkelling; scientific research; anchoring	Motorised boating (including jet skis); intrusive scientific research
Auckland Islands Marine Reserve and World Heritage Site Ballantine (1999), http://www.unep-wcmc.org/sites/wh/pdf/NZ%20Sub-Antarctic%20Is.pdf, http://www.doc.govt.nz/upload/documents/parks-and-recreation/places-to-visit/southland/subantarctic-islands.pdf	New Zealand	No extractive activities		Scientific research; access for visitors; anchoring; wildlife observation