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# Taking Stock – the changes to New Zealand marine ecosystems since first human settlement: synthesis of major findings, and policy and management implications

New Zealand Aquatic Environment and Biodiversity Report No. 170

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New Zealand has a short and uninterrupted archaeological, historical and contemporary record of human exploitation of marine resources compared to most other places globally. Moreover, the human population trajectory for New Zealand is known from first settlement, a key parameter when estimating rates of resource exploitation. A large multi-disciplinary project ("Taking Stock" ZBD200505) was conducted to determine the effects of climate variation and human impact on the structure and functioning of New Zealand marine shelf ecosystems over the timescale of human occupation in New Zealand from about AD 1250 to the present day. In all, 18 separate reports have been prepared, some of which present results for the whole New Zealand region, while others focus on changes occurring in one or both of two study regions; the Greater Hauraki Gulf and the Otago-Catlins coast. In this report we summarise and synthesise the major findings of the project and discuss the overall implications of the results for marine conservation and management.

The project indicates that from first human arrival, marine environments in the Greater Hauraki Gulf and Otago-Catlins study sites underwent a profound change over the period. Fur seals (*Arctocephalus forsteri*) and sea lions (*Phocarctos hookeri*) were eliminated from much of the New Zealand coast within a few hundred years of Māori arrival, and seabird populations were impacted by sustained human harvesting, as well as by the arrival of the Pacific rat (*Rattus exulans*). Despite a high reliance by Māori on marine resources in both the Greater Hauraki and Otago-Catlins regions, the abundance of fish, invertebrates, whales and dolphins was reported as remarkably high by the earliest European visitors and explorers. However, following European arrival, fur seals were hunted to local extinction in their remaining foothold around the southern coasts of the South Island and Stewart Island and almost eliminated from the sub-Antarctic Islands. Southern right whales (*Eubalaena australis*) were hunted almost to extinction by the late 1840s and the other large whales were severely exploited during the 19th and 20th centuries. There was increasing exploitation of a range of fish and invertebrates once commercial fisheries were established in the 1860s, initially to supply a growing European settler population, and later to supply rapidly developing export markets. Laws and regulations to control fishing practices were introduced as early as 1866.

The historical data shows that the abundance of some exploited species of fish and invertebrates declined noticeably in both study regions, in the late 19th century and early 20th century prior to the start of New Zealand's official landings records. The declines were first evident in species such as rock oysters (*Saccostrea commercialis*), grey mullet (*Mugil cephalus*), and flat fishes in sheltered, shallow, easily accessed areas, but later progressed to species with a wider distribution such as snapper (*Pagrus auratus*) and blue cod (*Parapercis colias*), or with a deep water refuge such as groper (*Polyprion oxygenios* and *P. americanus*). Declines in most species continued from the mid-1930s onwards during the 'statistical era' when fisheries landings data started to be comprehensively gathered nationwide and a variety of controls introduced. The most dramatic example during this period was the dredge fishery for green-lipped mussels (*Perna canaliculus*) in the inner Hauraki Gulf which collapsed in the 1960s, with significant ecological consequences, and has not recovered since.

Not until the introduction of the fisheries Quota Management System in the mid-1980s, were commercial harvests of marine fish and invertebrates finally brought under control allowing some stocks and populations to rebuild. Similarly, protection of most seabirds did not occur until the 1950s.

Marine mammals were not protected in New Zealand waters until the 1970s and whaling by some nations has continued to affect New Zealand whale stocks until very recently. The New Zealand fur seal is presently recolonizing its former range.

Assessing the historical impacts of humans on New Zealand shelf ecosystems depends in part on estimating the productivity of the ancient marine ecosystems compared to that of today. Two approaches were used to better describe large scale naturally occurring variations in New Zealand environmental processes. First, climate chronologies based on multiple sources of proxy evidence suggested that the last 1000 years can be divided into three different climatic eras. Conditions in the earlier half from 1000 to 1500, when New Zealand was first settled by Polynesians, were dominated by relatively settled warm weather. From about 1650 to the late 19th century wet conditions dominated the western South Island and drier conditions dominated in northern and eastern regions. European discovery and colonisation occurred in this period. Between these two periods from about 1500–1650 a climatic aberration brought cold temperatures and increased precipitation to all regions. During this period east coast nearshore habitats were probably significantly affected by sediment from increased river flows and coastal geomorphic processes.

Stable isotope analysis of snapper and red cod (*Pseudophycis bachus*) otoliths obtained from the middens of early Māori and from modern stocks has established that midden derived otoliths yield temperature data of similar quality to that obtained from freshly acquired otoliths. These results suggest that a more extensive analysis of otoliths from middens over the entire pre-European Māori period could yield a detailed description of marine temperature variation. Analysis of otoliths available from about 1450 and the present day indicated no discernible difference in oceanic temperature or fish growth in the Greater Hauraki Gulf and Otago-Catlins regions between these two periods.

Food-web models of the Greater Hauraki Gulf region were developed for five periods representing distinct phases of human marine resource exploitation over the last 1000 years: (1) present day, a period of controlled commercial catches of fish and shellfish, and seabird and cetacean conservation; (2) 1950, a period of relatively stable domestic fishing activity; (3) 1790, the late Māori phase just prior to the onset of European whaling and sealing; (4) 1500, the early to mid pre-European Māori phase; (5) 1000, before human settlement in New Zealand. Each model quantified the flow of organic matter through the marine food-web from primary producers to top predators over an annual period, and took into account centennial scale fluctuations in primary production. This approach allowed any differences in ecosystem structure between the time periods to be identified and quantified. Insufficient data were available to undertake similar modelling for the Otago-Catlins region. The key conclusions of this modelling were:

1. In the present day model, groups in the Greater Hauraki Gulf ecosystem with highest trophic importance (the degree to which changes in the abundance of one group are likely to affect other groups) were (in decreasing order): 1st phytoplankton; 2nd macrobenthos (mainly small benthic crustaceans and worms); 3rd mesozooplankton (mainly copepods); 4th bivalves; 5th snapper (which is the fish group with the highest trophic importance).
2. According to the model, carbon is estimated to be accumulating in the Greater Hauraki Gulf ecosystem at the rate of 0.3 $\mathrm{Mty^{-1}}$ which implies a value of ecosystem services in terms of carbon burial of about NZ$6.5 million per year (assuming a “carbon-tax” value of $25/t C).
3. Reductions over time in the biomass of upper trophic levels such as seals, cetaceans, sea birds, sharks, rock lobsters, and some fish, has led to substantial declines in their trophic importance.
4. The biomasses of many middle trophic level groups (such as small and large pelagic fishes, macrobenthos, squid, macrozooplankton, and gelatinous zooplankton) changed substantially (11–44%) over time in the models while others did not (especially benthic invertebrate epifauna). The groups that changed in biomass in the models were generally those that are important prey items for middle and upper level predators.
5. Despite changes to the biomass of many upper and middle trophic level groups, according to the trophic modelling, the rank trophic importance of about half the groups in the Greater

Hauraki Gulf did not change substantially over the period of human occupation; the rank trophic importance of 24 of 46 non-detrital groups changed by three places or less between AD 1000 and the present day. The groups with little change in their rank trophic importance include some commercially-important fish groups (snapper, gurnard, leatherjacket, tarakihi, flatfish, and barracouta), large and small pelagic fishes, small reef fish, many groups of benthic epifauna (urchins, bivalves, sponges, macrobenthos), squid, all groups of zooplankton, phytoplankton and macroalgae.

6. The biomasses of the lower food-web of the Greater Hauraki Gulf (primary producers, bacteria, detrital pathways, microbial function) were little affected in the ecosystem models by quite substantial changes over time to the biomass of fish and higher trophic levels. Our modelling suggests that the functioning of the lower food-web of the Greater Hauraki Gulf is somewhat decoupled from changes at higher trophic levels, probably by the "buffering" or stabilizing effect of middle trophic level organisms.

An ecosystem or population is likely to be perceived as stable or more or less pristine if the history of preceding changes is ignored, is unknown, or is unknowable, leading to "sliding baseline syndrome". The information contained in the reports and papers associated with this project help remedy this situation by detailing the changes to New Zealand marine ecosystems since first human settlement. Knowledge of human induced change to marine ecosystems over the full span of human settlement is rare from a global perspective. In most other localities sea level rise associated with the end of the last glacial period has obliterated most traces of first human exploitation of marine resources and the human population trajectory is poorly known. Because New Zealand was settled so recently, all this information is available to help inform marine policy development and management actions. Key implications for marine policy development and management, and directions for future research include:

(a) The analyses of midden derived otoliths has established that they can yield environmental data of similar quality to that obtained from freshly acquired otoliths. This suggests that a more extensive analysis of otoliths from middens over the entire pre-European Māori period could yield a detailed description of marine climate variation in New Zealand.
(b) The historical information indicates that for some fished species there were significant declines in abundance before the time series of fisheries landings information began in the early 1930s. Stock assessments of these species should attempt to use this information.
(c) Management of the Greater Hauraki Gulf should take into account the ecosystem effects that may result from further impacting the groups with high trophic importance such as macrobenthos, bivalves, and snapper, either directly (target species) or indirectly (impacts of bottom gear). Reducing direct and indirect human impacts on these groups may be required, as well as additional data collection to monitor their distribution and abundance, and further modelling undertaken to investigate how these groups affect ecosystem resilience.
(d) The biomass and composition of middle trophic level groups in the Greater Hauraki Gulf should be monitored due to their likely important role in maintaining ecosystem resilience.
(e) If the biomass of some higher predator groups, such as fur seals and baleen whales, recover towards pre-exploitation levels it is likely to change the pattern of trophic importance in the ecosystem. Management of the Greater Hauraki Gulf should take into account the potential for trophic and system-level effects of re-establishment/recovery of marine mammals towards historical levels.
(f) Other management challenges of recovered marine mammal populations include potential conflict with shore fishers and hikers for access to fur seal haul-out areas, perceived competition between fur seals and recreational and commercial fishers for food fish, and more frequent entanglement of cetaceans in long-lines and lobster trap-lines.

Knowledge of what happened to New Zealand's marine ecosystems over the course of human settlement is a required first step to informed ecosystem management. The important next step is to better understand and quantify the risks to the resilience of the marine ecosystem from these historical changes, present day pressures, and likely future scenarios.

# 1. INTRODUCTION

New Zealand was the last major land mass to be settled by humans, which occurred sometime in the period AD 1230 – 1280 (Wilmshurst et al. 2010, Matisoo-Smith & Daugherty 2012). Consequently, New Zealand has a short and reasonably complete and unbroken archaeological, historical and contemporary record of human exploitation of marine resources compared to most other places globally. Moreover, the human population trajectory for New Zealand is reasonably well known from first settlement (Pool 1991, Murray-McIntosh et al. 1998), a key parameter when estimating rates of resource exploitation. A large multi-disciplinary project (“Taking Stock” ZBD200505) was conducted to determine the effects of climate variation and human impact on the structure and functioning of New Zealand marine shelf ecosystems over the timescale of human occupation in New Zealand from about AD 1250 to the present day.

To achieve this overall objective the project has addressed five specific objectives.

1. To estimate changes in marine productivity via fluctuations in ocean climate and terrestrial nutrient input over the last 1000 years.
2. To assess and collate existing archaeological, historical and contemporary data (including catch records and stock assessments) on relevant components of the marine ecosystem to provide a detailed description of change in the shelf marine ecosystem in two areas of contrasting human occupation over last 1000 years.
3. To collect additional oral histories from Māori and non-Māori fishers and shellfish gatherers regarding the distribution, sizes and relative abundance (compared to present availability) of key fish and invertebrate stocks in both regions during the first half of the 20th century before the start of widespread modern industrial fishing.
4. To build a mass balance food web model of the coastal and shelf ecosystem for five critical time periods: present day, 1950 (before modern industrial fishing), 1790 (before European whaling and sealing), 1500 (mid Māori phase) and 1000 (before human settlement).
5. To use qualitative modeling techniques to determine the critical interactions amongst species and other ecosystem components in order to identify those that should be a priority for future research.

In all, 18 reports address these five objectives; two reports address Objective 1 (Lorrey et al. 2013b, Neil et al. 2014), 11 reports address Objective 2 (Smith 2011, MacDiarmid et al. 2015, Carroll et al. 2014, Jackson et al. 2016, Lalas & MacDiarmid 2014, Lalas et al. 2014 a & b, Paul 2012, 2014, McKenzie & MacDiarmid 2012, MacDiarmid et al. 2012), 2 reports address Objective 3 (Parsons et al. 2009, Maxwell & MacDiarmid 2015), 1 report addresses Objective 4 (Pinkerton et al. 2015), and 1 report addresses Objective 5 (MacDiarmid et al. in press). In this report we summarise and synthesise the major findings of the other reports and provide the overall implications for marine conservation and management.

Two regions, the Greater Hauraki Gulf and the Otago-Catlins shelf (Figure 1), were chosen as case studies of the broader New Zealand wide changes. Both regions were both settled by Māori at about the same time, but have since experienced contrasting trajectories in human population size and marine resource use (Smith 2013). While Māori rapidly explored and settled all the main islands, the Chatham Islands to the east, and as far south as the sub-Antarctic Auckland Islands, the main center of settlement and growth was the northern half of North Island (Te Ika a Māui), including the Greater Hauraki Gulf region, where a more benign climate allowed the cultivation of a greater range of tropically derived crops (King 2003). In 1769 only about 6000 Māori are thought to have lived in the whole of South Island (Te Wai Pounamu), including the Otago-Catlins region (Pool 1991). European settlement has followed a similar pattern with a densely populated North Island, particularly along the western shores of the Hauraki Gulf, and much lower population densities in South Island (King 2003). Importantly, both the Greater Hauraki Gulf and the Otago-Catlins regions have sufficient prehistoric, historic and modern information about marine resource use to demonstrate the pattern and magnitude of human impacts on the marine environment.

To determine the overall impacts of humans on a New Zealand shelf ecosystem this project aimed to build a mass balance model of the modern marine ecosystem in the Greater Hauraki Gulf, and then to estimate how this system operated at four earlier periods representing distinct phases of human marine resource exploitation over the last 1000 years (Pinkerton et al. 2015). These periods were *ca.* 1950, a period of a period of relatively stable domestic fishing activity; 1790, late Māori phase just prior to before the onset of European whaling and sealing; 1500, early to mid pre-European Māori phase; and 1000, before human settlement in New Zealand. There were insufficient detailed data to build similar models for the Otago-Catlins shelf. While all of the project reports contributed information to the mass balance modelling, individually they each provided details about particular trajectories of change for either the environment or specific groups of organisms and, as far as possible, explored the historical context of these changes.

In the sections below we summarise the main results of the project. In Section 2 we examine the evidence for climatological change in New Zealand during the period of human settlement and what that may have meant for the productivity and growth of marine organisms. In Section 3 we summarise archaeological, historical, and more recent information, including oral histories and fisheries landing histories, to construct narratives about the exploitation of shellfish, fish and sharks, seabirds, and marine mammals respectively. In Section 4 we summarise the findings from five mass balance models of the Greater Hauraki Gulf ecosystem spanning the last 1000 years. In Section 5 the overall results of the study are discussed. Then, in Section 6, we provide the overall implications of the study for marine conservation and management.

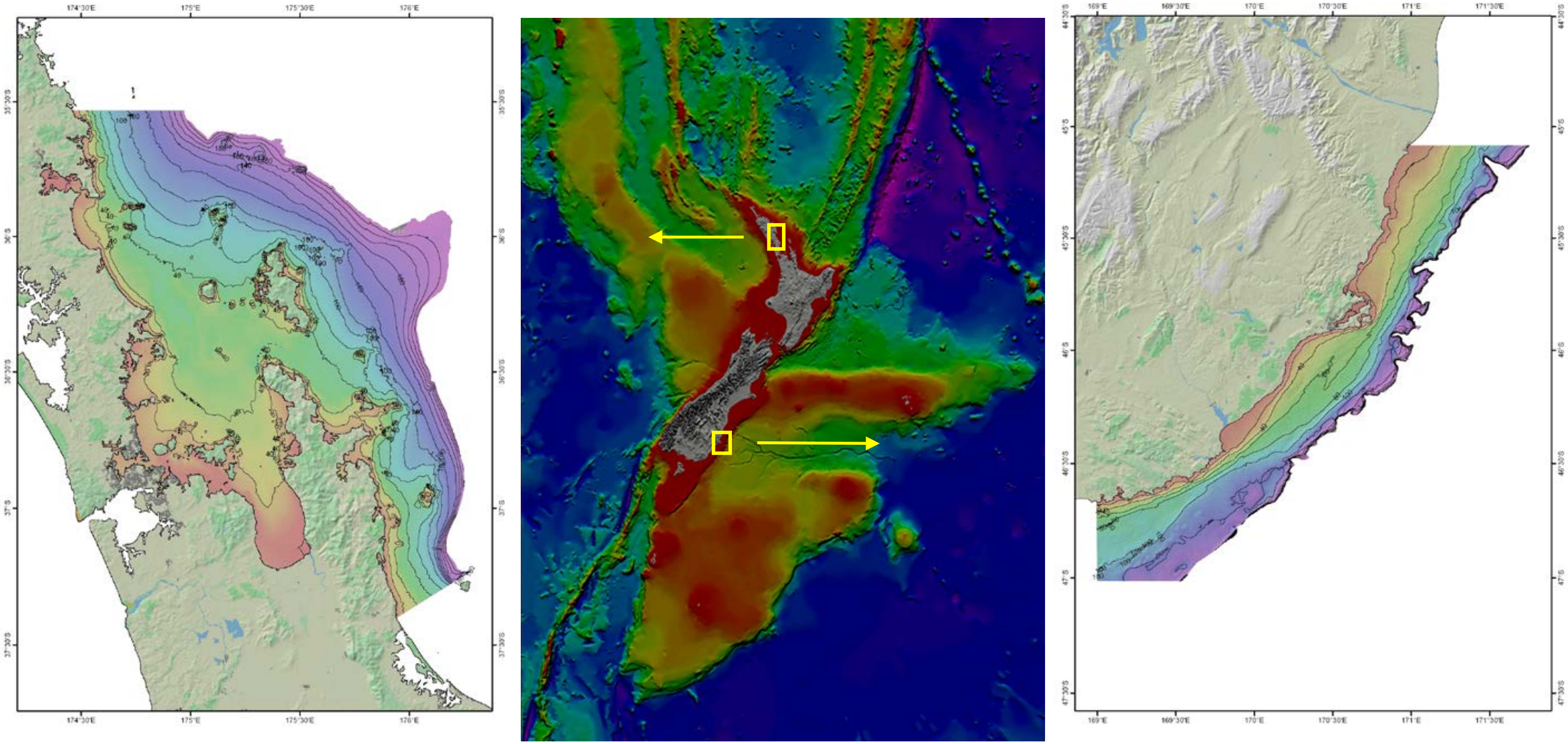

**Figure 1: Map of New Zealand (middle panel) indicating the location of the Greater Hauraki Gulf (left panel) and Otago-Catlins (right panel) study regions (coloured bathymetry). Contours (labelled by depth in m) representing bathymetry are drawn at 20 m intervals, with red/orange indicating shallow water (less than 40 m) and purple representing deep water (more than 200 m). The study area is constrained by the 250 m depth contour.**

## 2. BOTTOM-UP EFFECTS ON MARINE PRODUCTIVITY

Determining the historical impacts of humans on New Zealand shelf ecosystems depends in part on estimating the productivity of the ancient marine ecosystems compared to those of more recent times. Large scale naturally occurring variations in climatic processes and intermittent major geological events such as earthquakes and volcanic eruptions can influence the productivity of marine ecosystems (Behrenfeld et al. 2006, McFadgen, 2007). Climate variability can cause structural changes in water masses such as temperature, salinity, and nutrient gradients through upwelling or downwelling (Zeldis et al. 2005). Changes in dominant wind direction and/or strength may alter the depth of the mixed layer and promote or hinder the development of stratification (Sarmiento et al. 2004, Boyce et al. 2010). All these in turn may affect the timing and magnitude of primary production and the composition of the dominant primary producers, which has cascading effects up through the food chain and may cause changes in the patterns of growth, maturation and reproduction of marine organisms (Samiento et al. 2004, Zeldis et al. 2005, Powell & Xu 2011). Earthquake triggered tsunamis or sedimentation, and volcanic eruptions can disrupt, obliterate or reorganise nearshore habitats in particular (McFadgen 2007). So called bottom-up effects play an important role across a range of estuarine, rocky reef, coastal, shelf and deepwater marine ecosystems (Menge 2000, Seitz & Lipcius 2001, Philippart et al. 2007, Zeldis et al. 2008, 2010, Powell & Xu 2011, Zeldis et al. 2013)

While in the modern period extensive collection of biogeophysical data allows marine environmental variability to be measured and the cascading impacts of bottom up effects to be documented, other measures are required for the pre-instrumentation period. We used two approaches to describe large scale naturally occurring variations in New Zealand environmental processes.

### 2.1 Atmospheric climatic and coastal geologic event chronologies

Lorrey et al. (2013b) used multiple lines of proxy evidence covering the last millennium to generate parallel atmospheric climatic and coastal geologic event chronologies for New Zealand. The collection of palaeoclimate precipitation and temperature data were interpreted using regional climate regime classifications (Lorrey et al., 2007) to reconstruct atmospheric circulation patterns. The temporal reconstruction suggests that centennial-scale circulation anomalies during the last 1000 years can be divided into three basic eras. Conditions in the earlier half from 1000 to 1500, when New Zealand was first settled by Polynesians, were dominated by relatively settled warm weather characterised by ‘blocking’ regimes with anti-cyclonic high pressure systems over and to the west of New Zealand (Kidson 2000). During the latter half of the second millennium from about 1650 to the late 19th century wet conditions dominated the western South Island and drier conditions dominated in northern and eastern regions. The conditions reflect the prevalence of ‘zonal flow’ (Kidson 2000). The cool temperatures associated with this period suggest that polar circulation influences for New Zealand were prevalent. European discovery and colonisation occurred during this period.

The data presented by Lorrey et al. (2013b) strongly suggest that in the intervening period, from about 1500–1650, a climatic aberration occurred, characterised by a trough circulation regime (Kidson 2000) that produced disturbed regional flow across New Zealand with cold temperatures and increased precipitation in all regional climate districts (Lorrey et al. 2013a). Based on the holistic assessment of the environmental evidence, Lorrey et al. (2013b) considered that significant changes to the east coast nearshore habitats would have been likely as a result of both sedimentary and coastal geomorphic processes that were initiated in the middle of last millennium close to the onset of the 1500s. This coincided with changes in pre-historic Māori coastal activities, with the abandonment of some long-used sites which are documented in the New Zealand archaeological record (Leach 2006, McFadgen, 2007).

This increased input of sediments to the coastal environment was the second of three similar episodes over the last millennium. The first occurred within the first 200 years of Polynesian settlement around 1250 (± 30 years) (Wilmshurst et al. 2010) when 40% of New Zealand’s forests were rapidly removed, particularly on the east coasts of North and South islands (McGlone 1989, McWethy et al. 2009, 2010).

The third episode began with the removal of another 35% of the original forests over a period of 100 years by European settlers starting about 1840 (Campbell 1946, Gomez et al. 2007, Morrison et al. 2009, Marden 2011).

The influence of the millennial scale fluctuations in New Zealand's atmospheric climate described by Lorrey et al (2013b) on marine coastal climate over the same period are still to be determined. However, some of the underlying linkages are understood. For example, nutrient supply has been described in detail in the Hauraki Gulf and Nelson (Golden and Tasman) Bays where winds from the west, during the El Niño phase of the Southern Oscillation, strongly stimulate upwelling of slope-associated deep water, rich in nutrients, onto the shelf and into the coast, where nutrients are utilised within the photic zone to generate primary production (via photosynthesis) and secondary production (zooplankton, fish, etc.) (Shirtcliffe et al. 1990; Zeldis et al. 2004; Zeldis 2004; Bradford-Grieve et al. 2006; Zeldis 2008a; MacDiarmid et al. 2009; Bury et al. 2011, Gall & Zeldis 2011; Zeldis et al. 2013). In some places river inputs of nutrients are also critical sources of nutrients for coastal production. In the Firth of Thames, Zeldis (2008b) has shown that on average the rivers draining to the Firth contribute about 70% of the nitrogen supply to that coastal embayment in the Hauraki Gulf. Nelson Bays, in contrast, receive only about 15% of nutrient supply from rivers (Zeldis 2008b). The link between climate and secondary production levels is demonstrated in Pelorus Sound, Marlborough Sounds. Here, the biological yield of cultured green-lipped mussels can be predicted by large-scale environmental processes including the Southern Oscillation Index, along-shelf winds, sea surface temperature and river flow, which drive the supply of nitrogen to the Sounds from the ocean (via upwelling in northwest Cook Strait) and the Pelorus River (Zeldis et al. 2013).

## 2.2 Inferring the interaction of environmental drivers and ecological responses from fish otoliths

Another approach to assessment of environmental change in marine shelf ecosystems was taken by Neil et al. (2014). The hard parts of marine organisms may provide sufficient information to infer the interaction of environmental variables and ecological responses. For example, the shells of molluscs and fish ear stones (otoliths) are primarily constructed from calcium carbonate ($CaCO_3$) and the stable isotopes of oxygen and carbon have a well-established history of use as geological and biological tracers (e.g. Campana et al. 1995, Roelke & Cifuentes 1997, Thorrold et al. 1997, Campana & Thorrold 2001). Stable isotope analysis of otoliths has been used to provide information on the environmental variation (i.e. habitat, diet, temperature, depth, metabolic history and migration) that an organism has experienced throughout its life history (e.g. Radtke et al. 1987, Kalish 1991, Northcote et al. 1992, Thorrold et al. 1997, Schwarcz et al. 1998, Begg & Weidman 2001, Gao et al. 2001).

If fish otoliths or shellfish remains can be obtained from a known time in the past then the stable isotope and band increment evidence for environmental temperature and/or organismal growth and maturation for that period can be compared to the same measures from modern individuals. One source of ancient fish otoliths and shellfish in New Zealand is from the middens where Māori disposed of the remains of their food (see Smith & James-Lee 2010).

Neil et al. (2014) used otolith incremental growth analysis, and oxygen and carbon stable isotope analysis to infer the growth and environmental conditions experienced by snapper (*Pagrus auratus*) in the Greater Hauraki Gulf and by red cod (*Pseudophycis bachus*) along the Otago-Catlins shelf over two periods; around 1450 and during the 20th century. Lack of suitable otoliths from dated midden horizons prevented the comparison of the modern data to other time periods. The results of Neil et al. (2014) established that midden-derived otoliths yield environmental data of similar quality to that obtained from freshly acquired otoliths, suggesting that a more extensive analysis of otoliths from middens over the entire pre-European Māori period could yield a detailed description of marine climate variation. Neil et al. (2014) also established that for both species studied there was no difference between modern otoliths and otoliths from the 1450 period, at the geographic sites studied, with respect to growth (juvenile increment or total otolith), temperature at age, migration at age, diet or/and metabolic rate, age of maturity, and total change in metabolic rate over the lifetime. Neil et al.

(2014) concluded that there was no discernible oceanic climatic regime or productivity difference recorded by otoliths from the Greater Hauraki Gulf and Otago-Catlins regions between around 1450 and the 20th century. This correlates well with atmospheric proxy data collated and interpreted by Lorrey et al. (2013b) who suggest that the climate in the two periods was very similar although they were separated by a period of cool wet climate.

## 3. EXPLOITATION OF SHELLFISH, FISH AND SHARKS, SEABIRDS, AND MARINE MAMMALS

### 3.1 Approaches to the use of archaeological, historical and contemporary information sources

#### Estimating the magnitude of pre-European Māori marine harvest

Māori exploited marine resources around New Zealand for about 600 years before European colonisation and the establishment of commercial fisheries, leaving a rich archaeological record of more than 10 000 middens adjacent to the Greater Hauraki coast and 800 in Otago-Catlins, reflecting the marked concentration of pre-European Māori population in the northern third of the country (Leach 2006, Smith 2011). Estimation of the taxonomic composition and biomass of Māori harvests of seafood is essential if we are to understand the trajectory of human exploitation of marine resources over the entire period of human settlement, and how these removals affected the structure and functioning of coastal ecosystems. Smith (2011, 2013) used three broad approaches to generate this novel information for the Greater Hauraki and Otago-Catlins regions. First, an overview of marine resource use was constructed for each study area, based upon the presence/absence of marine taxa in 107 reliably dated archaeozoological assemblages and, where suitable data were available, their proportional abundance (Smith & James-Lee 2010, Smith 2013). Māori shifted residence to exploit seasonally available resources thus no one site can be considered to represent marine resource exploitation by an entire community (Leach 2006). Thus it was essential to aggregate data at a regional level (Smith & James-Lee 2010). Care was taken by Smith (2013) to interpret the archaeozoological assemblages taking into account the cultural and natural formation processes that shaped them, and the archaeological filters through which they have passed. These include the original harvesting, butchering and cooking processes, and patterns of consumption and discarding which together determine the composition of the deposited assemblage (Smith 2013). Subsequent differential weathering over hundreds of years, and archaeological recovery and identification thus produce the raw archaeological data from which to draw inferences about past harvests (Smith 2013).

The second approach involved estimating the magnitude of total marine energy removals through human exploitation in each study area. This was undertaken using estimates of the size of human populations, their energy requirements and the relative contributions of marine foods to their diet. In a third approach, the number of each marine animal species required to contribute the proportions derived in the first step to the total energy harvest from animals estimated in the second step was calculated using an estimate of the calorific value of the meat derived from an individual of the species concerned. Smith (2011) made three estimates for each species; a minimum estimate which used the lowest probable values for each variable in the second step of analysis, a maximum estimate using the highest probable values, and a best estimate based on the most realistic or well supported values. Smith (2011) applied cumulative calculation errors to each set of estimates.

#### Historical information

As pointed out by Tull & Polacheck (2001), New Zealand has a useful number of historical sources to draw upon with regard to the state and exploitation of marine resources in the years prior to the establishment of reliable landings histories in about 1931. The journals of Captain James Cook and Sir Joseph Banks from the voyage of the Endeavour in 1769 (Beaglehole 1955, 1963) are the first in a series of accounts by early European explorers and settlers which provide observations and anecdotes about Māori use of the marine environment, the abundance and availability of marine species, and the development of commercial and recreational fisheries. Some 78 early New Zealand books published between 1807 and 1932 have been digitized and are searchable on line (see www.enzb.auckland.ac.nz). In addition, there are archival and published sources including Waitangi Tribunal Reports and Evidence, Appendices to the Journals of the House of Representatives, and national archives of the Ministry of Transport, Department of Customs, Department of Trade and Industries, Department of Agriculture and Fisheries, Department of Industries and Commerce, Ministry of Works and Development, but especially the Marine Department. Johnson (2004) wrote a detailed history of the development of commercial fishing in New Zealand. MacDiarmid et al. (2015) searched all these sources for historical information relevant to the state and exploitation of marine fish and invertebrate resources in the Greater Hauraki Gulf and along the Otago-Catlins shelf for the period 1769 to 1950. They then organized this information by species by region and for each a summary narrative was produced.

## Oral histories

Oral histories can provide information that may not be available from official landings records. In the Gulf of California, oral histories have been used to help quantify the population decline of fish, sharks and marine mammals (Saenz-Arroyo et al. 2005, Lozano-Montes et al. 2008) over periods for which few other data exist. Similarly, Bunce et al. (2008) used fishers' perceptions to document the degradation of reef fisheries in the tropical Indian Ocean. These studies suggest that fishers can provide a very clear picture of where they formerly fished and where they currently fish, thereby providing an indication of spatial changes in availability of particular species. Moreover, fishers often have clear memories of when they caught their largest individual of a particular species, or made their largest haul of a particular species (e.g. Saenz-Arroyo et al. 2005, Lozano-Montes et al. 2008). If these accounts are collected from individuals with experience in different decades then a sequence of changes in distribution, abundance and size may emerge. These can be particularly valuable if the landings or biomass time series based on reliable quantitative data were initiated comparatively recently. Maxwell & MacDiarmid (2015) provide a detailed summary of the information about marine resource state and use by Māori and non-Māori in the Greater Hauraki Gulf and along the Otago-Catlins coast in the mid to late 20th century. This was gained through the analysis of existing oral histories of 22 individuals mainly from Great Barrier Island and of new oral histories systematically collected from 36 people from the Otago-Catlins area. Parsons et al. (2009) provided additional anecdotal information from 22 recreational fishers about the state of snapper populations in the Greater Hauraki Gulf.

## Landing histories and biomass estimates

Quantitative assessments of fish stocks usually incorporate a time series of landings (landing history) as a measure of fishing mortality in a statistical model. Ideally landing histories should extend back to the beginning of a fishery. Although many commercial fisheries in New Zealand began in the latter half of the 19th century, statistical data on landings by species were first recorded in 1931, with improvements in accuracy accumulating over subsequent decades. A change from reported landings by port to catches by area was made in 1983, in association with the introduction of the QMS in 1986. Catch data by area for the Greater Hauraki Gulf and Otago-Catlin regions for 1931–1982 were estimated from the landings data by Pinkerton et al. (2015) as part of this study, by procedures subsequently used in a compilation of all important New Zealand inshore finfish and shellfish species (Francis & Paul 2013). Paul (2014) subsequently used these data to compile the commercial fishery for finfish in the Greater Hauraki Gulf, from about 1850 to the early years of the 21st century.

As well as being valuable in their own right, fish biomass trajectories and biological parameters are critical as inputs to the present day and historical mass-balance models of the ecosystems in the two case-study regions reported by Pinkerton et al. (2015). Because of their abundance, commercial fish species comprise an important component of the biomass and flow of energy through shelf ecosystems and because of their economic value, better data are often available for these species than any other component of the ecosystem. McKenzie & MacDiarmid (2012) estimated combined sex biological parameters, total biomass trajectories since 1930, and proportions of individuals-at-age for 1930, 1946 and 2006 for 23 commercial species in the Greater Hauraki Gulf study region and 14 species in the Otago-Catlins study region. For many species the biological parameter values were not available for the study region, sometimes had multiple estimated values, or were available for the sexes separately. In these cases various approximations, such as choosing adjacent areas and averaging across sexes and multiple estimates, were used by McKenzie & MacDiarmid (2012) to generate the required values. For no species did a stock assessment exist that generated the total biomass and proportions-at-age estimates required for the study areas. Furthermore, for many species no stock assessments had been undertaken. Therefore, to obtain the required estimates of total biomass and proportions-at-age, existing stock assessments were modified and simplifying assumptions made for those species without assessments. These modifications and simplifying assumptions are explained in McKenzie & MacDiarmid (2012).

## 3.2 Fish and shellfish

### Archaeological reconstructions of pre-European Māori harvests

Three main results stem from Smith's (2011, 2013) archaeological reconstructions of pre-European Māori harvests. First, the reliance by Māori on dietary energy from terrestrial mammals (rats (*Rattus exulans*) and dogs) and terrestrial birds fell over time – from about 30% in 1400 to less than 10% in 1750 in the Greater Hauraki Gulf, and from about 35% to 16% over the same period in Otago-Catlins. Correspondingly, the reliance on marine dietary energy sources rose from about 70% to 90% in the Greater Hauraki Gulf and from 65% to 84% along the Otago-Catlins coast.

Second, from first settlement Māori harvested a very wide range of marine species in each of the study areas. In the Greater Hauraki study area 101 taxa (46 shellfish, 28 fish, 22 shore or seabirds and 5 marine mammals) were exploited, while in the Otago-Catlins study area 96 taxa (36 shellfish, 25 fish, 28 birds and 7 mammals) were harvested, although in both regions the number of taxa harvested fell over time. For example, in the Greater Hauraki Gulf, over the period from 1400 to 1750, the number of taxa harvested fell from 22 to 15 for fish, from 88 to 38 for shellfish, from 5 to 1 for marine mammals, and from 22 to 10 for seabirds. Over the same period in the Otago-Catlins the number of taxa harvested fell from 22 to 9 for fish, from 55 to 29 for shellfish, from 5 to 3 for marine mammals and from 25 to 18 for seabirds.

Third, while the range of taxa harvested fell, for fish and shellfish the best estimates all indicate increased total harvest over time (Figure 2), although just a few species were responsible for this increase. For example, in the Greater Hauraki Gulf, over the period from 1400 to 1750, the annual harvest of sharks and rays increased from about 5 ± 1.45 t to 1318 ± 396 t, the annual harvest of snapper increased from 72 ± 22 t to 997 ± 299 t, and the annual harvest of cockles (*Austrovenus stutchburyi*) increased from less than 1 t to 1358 ± 407 t (Smith 2011). Along the Otago-Catlins coast over the same period best estimates of annual harvests of groper (*Polyprion oxygenios* and *Polyprion americanus*) increased from 7.7 ± 3.3 t to 231 ± 69 t, annual harvests of barracouta (*Thyrsites atun*) increased from 43 ± 13 t to 363 ± 109 t, and annual harvests of paua (*Haliotis iris*) increased from 2.3 ± 0.7 t to 35 ± 10.5 t (Smith 2011).

Smith (2011) concluded that in the Greater Hauraki region, growth of the human population was one of two main reasons for the overall increase in harvests of marine species. In addition, the demand placed on fish and shellfish increased over time because seals, moa and some marine and coastal birds (see Sections 3.3 and 3.4) ceased to be available. This process of replacement of one food source by another was the single most important driver of change in Otago-Catlins, where the human population remained more or less stable throughout the pre-European period.

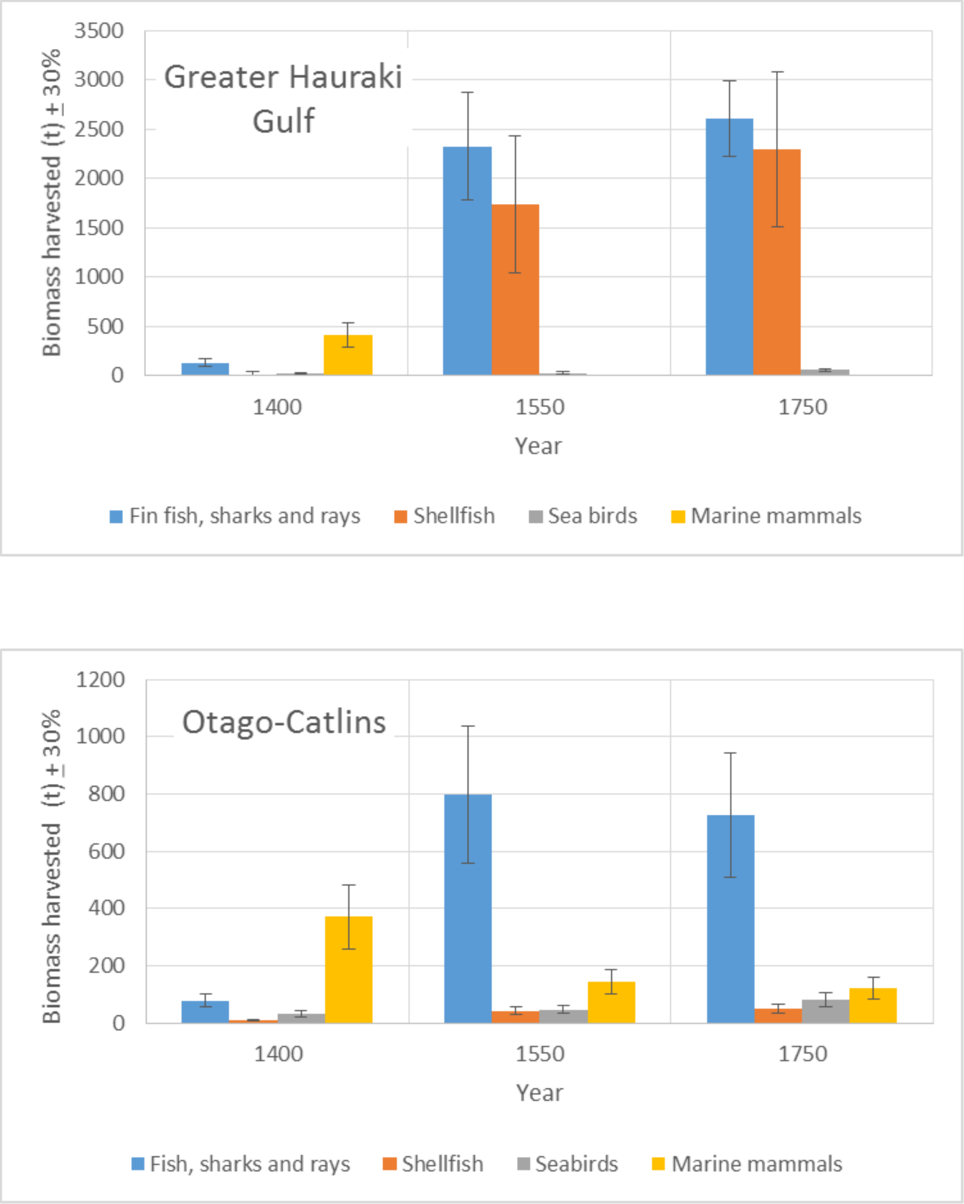

**Figure 2: Best estimates for biomass harvested annually from four classes of marine fauna in Greater Hauraki Gulf (top panel) and Otago-Catlins (lower panel). Note the change in scale on the y axis in the two panels. Redrawn from Smith (2011).**

## Historical evidence of marine resource state and use

The historical information indicates a decline in the state of coastal marine resources. It changed from one where the abundance of fish and invertebrates was remarkable to the earliest European visitors and explorers in the late 18th and early 19th centuries (Nicholas 1817, Earp 1853, Beaglehole 1955, 1963), to a situation, about 100 years later, when the rapid development of commercial fisheries prompted the introduction of laws restricting the most effective (but in many cases destructive) practices such as dynamiting (MacDiarmid et al. 2015).

### *Early European Impressions*

The early Europeans explorers and visitors were remarking on the abundance of fish and invertebrates from the perspective of their mostly British experience and observations of marine productivity and fisheries, as well as experiences gained on the long trip from Europe to New Zealand. In British seas at this time, despite seven centuries of exploitation through mainly hook and line, hand-seine and set-net fisheries, coastal fish were still relatively common (Barrett et al. 2004, Thurstan & Roberts 2010, Thurstan et al. 2013), so fish and invertebrates around New Zealand must have been very abundant to be worthy of mention in official journals and letters.

This abundance was despite a high reliance by Māori, in both the Greater Hauraki and Otago-Catlins regions around the time of early European contact, on marine fish and invertebrates (Leach 2006). Sir Joseph Banks and later European explorers and visitors were struck by the great size of the beach seines properly drawn by up to 500 Māori, as well as the numerous types of hooks, lures, and traps that were used to catch fish (Leach 2006). Smith (2011) estimated that in the Greater Hauraki region around 1769, 12 150 Māori were, each year, extracting approximately 2600 t (range 1464–3644 t) of fish (mainly comprising snapper 38%, and small sharks 37%), and 2295 t (range 1289–3207 t) of shellfish (comprised mainly of cockles 59%, and pipi (*Paphies australis*) 26%). In the Otago-Catlins region 1800 Māori were extracting approximately 725 t (range 540 – 939 t) of fish (mainly comprising barracouta 50%, and groper 31%), and 51 t (range 38–66 t) of shellfish (comprised mainly of paua 69%) annually at the time of Cook’s first voyage (Smith 2011). In both regions this equated to about 400 kg of fish and shellfish per person per year. To put into perspective the annual total catch of the fish species most heavily exploited by Māori around the time of Cook’s first voyage, for the Greater Hauraki region it was about 4.5% of the unfished biomass of snapper and about 11% of the unfished biomass of small sharks (McKenzie & MacDiarmid 2012). In the Otago-Catlins region, Māori annual catches around 1769 were about 1% of the unexploited biomass of barracouta and 0.5% of the unfished biomass of groper (McKenzie & MacDiarmid 2012). At these levels of exploitation Māori were probably having modest effects on small sharks, which because of a combination of late maturity, slow growth, and low fecundity overall have a low productivity (Ministry for Primary Industries 2013), and minor impacts on snapper in the Greater Hauraki Gulf, while effects on barracouta and groper stocks in the Otago-Catlins region were probably negligible. Thus, Cook and other early European explorers and visitors probably did experience almost pristine fish and shellfish populations, particularly in the sparsely settled southern parts of New Zealand.

### *Late 19th and early 20th century exploitation of some species*

The historical information compiled by MacDiarmid et al. (2015) indicates that commercial catches of some fish species were significant in the period prior to the establishment of regular and reasonably reliable landings time series in 1931. In the Greater Hauraki Gulf substantial fisheries for rock oysters (*Saccostrea commercialis*), dredge mussels (*Perna canaliculus*), rock lobster (*Jasus edwardsii*), grey mullet (*Mugil cephalus*), flatfish, groper, and particularly snapper had developed to supply the local domestic market, especially Auckland city (Parsons et al. 2009, Paul 2012, 2014). Along the Otago-Catlins coast substantial fisheries for blue cod (*Parapercis colias*), rock lobster, flatfish, and groper had developed to supply the growing cities of Dunedin and Oamaru in the period 1860–1930. Concern over the state of fisheries and of destructive fishing practices emerged quickly and as early as 1877 the Fish Protection Act was enacted. The following year the Fisheries (Dynamite) Act of 1878 was introduced to curb the very destructive practice of dynamiting of fish in the sea, lakes, and rivers.

The historical decline in fish stocks in New Zealand and the imposition of state regulations and controls was in two cases, grey mullet and rock oysters, rapid once a commercial fishery started (Paulin & Paul 2006, MacDiarmid et al. 2015). Both these species occurred in sheltered waters easily accessed by small row boats or sailing dories and required simple equipment to capture them. In the case of rock oysters, ongoing concerns about the dwindling state of stocks prompted the passing of the Sea Fisheries Amendment Act 1907 which saw the Marine Department take complete control of the North Island oyster beds. This involved the operation of picking and selling oysters to retailers,

periodic closure and opening of beds, building stone walls in the intertidal zone for oyster settlement, and removal of whelk predators. This state control was to last more than 50 years till in 1964 legislation was passed providing for the leasing of tidal lands and the harbour-bed by persons prepared to undertake the commercial production of rock oysters (MacDiarmid et al. 2015).
Similarly, continuing concern about the state of the grey mullet fishery prompted a government sponsored inquiry in 1895–96, led by one of New Zealand's leading scientists of the time, Sir James Hector. Although Hector's inquiry was comprehensive, his conclusions, and subsequent government actions, were limited by the lack of information about the biology of grey mullet (Paulin & Paul 2006). Marine Department reports for 1906 and 1907 noted the continuing scarcity of grey mullet and by 1914 Fisheries Inspector J.P. Bennett, in his Annual Report on Fishing Industry at Auckland, noted with some alarm that, '*Mullet are doomed to extinction if something is not done in the near future to conserve them'* (MacDiarmid et al. 2015). Though grey mullet did not become extinct the fishery remained very small through the 20th century with an average of only about 25 t landed each year from the Greater Hauraki Gulf until the mid-1970s. Annual landings in the Greater Hauraki Gulf study area increased in the 1980s and 1990s to over 100 t but have since dropped back to around 30 t (Paul 2014).

Other species were more resilient than rock oysters and grey mullet, having some parts of their populations inaccessible to the technology of the time, and problems only began to emerge after decades of commercial fishing and the development of new fishing technologies. For instance, by the early part of the 20th century, flatfish were among the most common fish landed by commercial fishermen in the Greater Hauraki Gulf (MacDiarmid et al. 2015). It was not until 1930, after about 70 years of fishing and the introduction of Danish seining in the 1920s, that Mr Hefford, the Chief Inspector of Fisheries, warned that '*This fishery is prosecuted at the expense of spawning aggregations of flounders and dabs, and therefore requires careful watching both from the economic and the biological aspect.*' Flatfish stocks along the Otago-Catlins coast came under earlier pressure, especially populations in Otago Harbour and other coastal inlets where small hand seines could be safely deployed in most weather (MacDiarmid et al. 2015). Continuing concern about flatfish and other stocks led to the establishment, in 1904, of the Portobello Marine Hatchery midway down the Otago Harbour.

Even a resilient species such as snapper showed early effects of fishing. In the Greater Hauraki Gulf study region, snapper was the principal target fish species by Māori during the prehistoric period, by the commercial fishery since the 1860s, and by a growing recreational fishery since European settlement (Parsons et al. 2009, MacDiarmid et al. 2012, Paul 2013, Smith 2011). Despite its continuing dominance in the modern Greater Hauraki Gulf ecosystem where it comprises over 40% of the biomass of all commercially fished species (McKenzie & MacDiarmid 2012), Parson et al. (2009) were surprised how early the effects of exploitation were noted in historical sources. They concluded that localised depletion of snapper in the inshore sheltered waters of the Gulf had begun before the end of the 19th century, and accelerated in the early decades of the 20th century after the introduction of steam trawlers and purse seiners. The success of trawling led to trawlers being banned from inner parts of the Gulf, not so much to preserve the species but to protect the livelihood of commercial long-liners and the enjoyment of recreational fishers (Paul 2014).

For other species the decline was quite gradual, especially for those species which had a deeper water refuge that was only exploited following changes in technology. A good example is the groper fishery. In 1928 a decline in the availability of groper was noted by the Chief Inspector of Fisheries Hefford in his report on the fisheries of the Auckland region. He further commented that '*It is the amount of fish that are extracted, not the method of fishing, which is the important factor*.' Along the Otago-Catlins coast, groper was the second most important fish species after barracouta for Māori (Smith 2011) and a commercial fishery for groper began in the 1860s. The written and oral historical evidence clearly indicates that groper were seasonally available close inshore in about 10 m of water around rocky headlands (MacDiarmid et al. in press, Maxwell & MacDiarmid 2015). This was the initial target of the commercial hand-lining fishery from small oar powered dories. Set and hand lines were used to capture groper within a short distance of Otago Heads. As the availability of groper nearshore inshore dwindled, exploitation of populations further offshore was enabled by new technologies, namely reliable benzene powered ‘oil’ engines, ‘long-lines’, and ‘dahn lines’. By the late 1920s Otago line fishermen were compelled to go well off the land to secure any quantity of groper with some of these boats steaming up to 25 miles to get on the fishing grounds. Regular commercial catches of groper near the coast was no longer possible but occasional specimens were caught nearshore by recreational fishers until about 1960 (Maxwell & MacDiarmid 2015). Gropers are now available only offshore on the outer half of the shelf and down the upper continental slope to depths of 300 m (Ministry for Primary Industries 2013).

## The statistical era

The nature of commercial fishing operations in the Greater Hauraki Gulf study region since the start of the fisheries statistical period in 1930 is described in detail by Paul (2014). Steam trawling which had commenced about 1900, and then quickly ceased when most of the inner Gulf was closed to this method, was revived in 1915, and continued until 1951 (apart from in the World War II years when these vessels were transferred to the Navy). Long-lining replaced hand-lining in 1912 and continues to the present day, now landing premium-grade export snapper. Danish seining commenced in 1923 and became the dominant method for catching snapper; it declined in the 1950s and again after the mid-1970s. Motor trawling began in the Greater Hauraki Gulf only in 1948 and alternated in importance with Danish seining apparently again due to changing economics. Vessels built from the late 1960s were capable of both seining and trawling. Purse seiners began fishing in the mid-1970s, initially for skipjack tuna (*Katsuwonus pelamis*) but later, intermittently, for other pelagic species (e.g. trevally (*Pseudocaranx georgianus*), mackerels (especially *Trachurus* spp.), kahawai (*Arripis trutta*) when skipjack were not available. Significant events occurred in the mid-1980s, centred on the introduction of the Quota Management System in 1986. Landings of many species rose sharply as fishers anticipated the need to establish a catch history, a new statistical reporting system took several years to become reliable, and there was a move to alternative fisheries as quotas of several of the main species were reduced. The greater variety of species reported post-1983, and the reduction in landings of several species post-1986, is attributed to a combination of these factors, particularly the requirement to report catches, in addition to landings, more reliably. A broadly similar sequence of developments occurred in the Otago-Catlins region except that Danish seining was prohibited in the South Island in 1948 and purse seining was not common (MacDiarmid et al. 2015, McKenzie & MacDiarmid 2012).

McKenzie & MacDiarmid (2012) estimate that the total regional biomass of all commercially fished finfish and lobster species in the Greater Hauraki Gulf combined has declined by about 60% since the modern fisheries time series started in 1930 (Figure 3a) although the modeling undertaken relied on reported landings rather than catches adjusted for underreporting, discarding, and additional fishing mortality. Alhough all 23 species declined to an extent, several species stand out. Snapper, contributed to half of the overall decline and the biomass of seven species including rock lobsters, groper and school shark (*Galeorhinus australis*), have each decreased by over 70%. The decline in the total combined regional biomass of commercially fished species along the Otago-Catlins shelf is much less severe, falling by only 16% over the same period with only one species, rock lobster, declining by more than 70%. McKenzie& MacDiarmid (in press) estimate that the biomass density (t $km^{-2}$) of commercial fish species in the Greater Hauraki Gulf and along the Otago-Catlin’s shelf at the start of the modern time series in 1930 was very similar at about 21 t $km^{-2}$ indicating similar carrying capacities (Figure 3b). While the biomass density of commercial fish along the Otago-Catlins shelf dropped only slightly over the subsequent 76 years, that in the Greater Hauraki Gulf decreased by 60%; a result of higher exploitation.

The recorded changes in biomass are reflected in the personal narratives and anecdotes of customary, and recreational fishers from the period 1940–2008 (Parsons et al. 2009, Maxwell & MacDiarmid 2015). These narratives indicate that sixty to seventy years ago fishing and gathering was a regular, sometimes daily occurrence by customary and recreational fishers in both study regions. Fish and shellfish were very abundant and could be reliably caught with little effort, often from the shore with simple equipment. It is more difficult to fish or gather most species today. Often interviewees reported that these days they have to go into deeper water, to more distant locations or use more specialised equipment (off-shore capable boats, snorkel, and scuba) to obtain their catch. This extends the observations of Graham (1957) who wrote about trends in the Otago region prior to the 1930s.

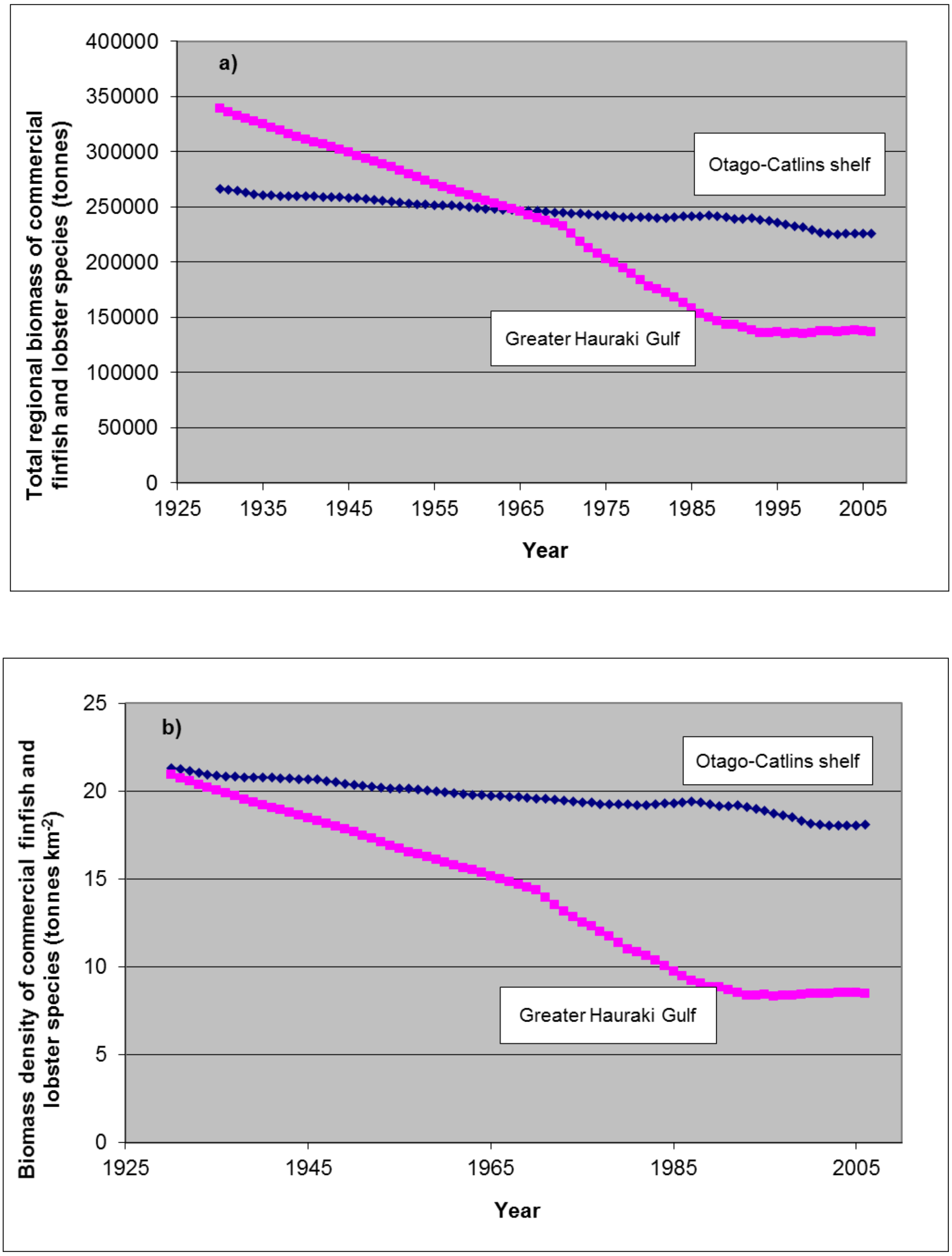

**Figure 3: Decline in commercial finfish and lobster species in the Greater Hauraki Gulf and Otago-Catlin study areas in terms of a) total regional biomass and b) biomass per unit area, 1930–2006. From McKenzie & MacDiarmid (2012).**

## 3.3 A history of the Firth of Thames dredge fishery for green-lipped mussels

Green-lipped mussels form biogenic habitat on both soft and hard substrates. Historically, extensive beds occurred in the Hauraki Gulf, Kaipara Harbour, and Tasman Bay (McLeod 2009, Paul 2012, Morrison et al. 2014). They were important as a fishery (Paul 2012) and ecologically (McLeod et al. (2014) and their disappearance, largely through the actions of the fishery itself, during the modern statistical period when landing statistics were adequately recorded, provides a good example of the need for evaluation of the ecological characteristics of specific fisheries alongside the assessment of stock sustainability.

Green-lipped mussels were taken by pre-European Māori, particularly at locations close to rocky shores or to shallow reefs and banks in embayments and harbours (Smith 2013, Paul 2012). They occur within middens at numerous archaeological sites around New Zealand, but their thin shells are usually so fragmented that even the characteristic hinge portions are difficult to quantify in order to establish relative abundance[1]. In a study of 77 Greater Hauraki Gulf middens Smith (2013) found that green-lipped mussels steadily decreased in percentage occurrence from 88% to 15% over the period from first Māori settlement to about 1800. This was accompanied by an increase in the percentage occurrence of pipi and cockles in middens reflecting a change in Māori habitation from rocky to sheltered coastlines more conducive to adjacent land crop cultivation (Smith 2013). Smith (2011) estimated that around the time of Cook's first voyage to New Zealand in 1769 three to seven tonnes of green-lipped mussels were harvested annually by Māori from the Greater Hauraki Gulf study area, indicating that exploitation rates were very low.

The exploitation of green-lipped mussels in the Firth of Thames and adjacent embayments has been described by Paul (2012) and much of the information below comes from this source. The green-lipped mussel supported a dredge fishery on dense sub-tidal beds on soft sediments in the Firth of Thames and inner Hauraki Gulf from about 1910 to the mid-1960s (Figure 4). Landings were modest to 1920 and under-reported to 1930 but probably reached 500 t annually. After a dip during the Depression, landings increased to 1400 t by 1940 (Figure 5). Wartime events decreased landings, although canned mussels were a permitted export to prisoners of war. A three-year closure of some Coromandel beds kept landings low through the late 1940s. In the 1950s there was a rapid rise in landings, to peak at about 2800 t in 1961. Landings then crashed to 180 t in 1965, and zero in 1969. Underwater video and grab surveys in 2002 showed no sign of recovery of the natural beds (McLeod 2009). The dredge fishery's failure appears to have been caused by progressive fishing-out of beds, with sedimentation perhaps being a minor and localised influence. The failure of beds to recover during the subsequent 40 years is generally attributed to the loss of the most suitable substrate for larval settlement, the beds of existing adult mussels.

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[1] Dr B.F. Leach, pers. com.

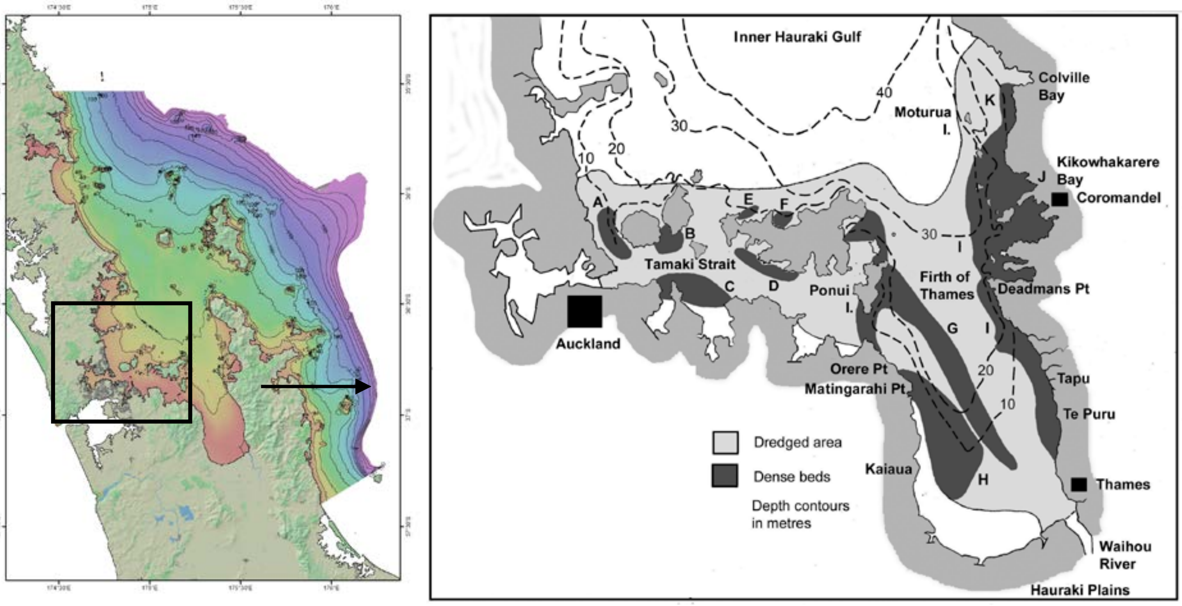

**Figure 4: Left panel: Map of the Greater Hauraki Gulf study area showing inset the location of the detailed map on right. Right panel: Map of the inner Hauraki Gulf and the Firth of Thames, showing the area worked by the green-lipped mussel dredge fishery and the position of the main mussel beds. The letters cross-refer to the beds listed in table 1 in Paul (2012). Islands and the edge of the mainland are shaded mid grey. From Paul (2012).**

Paul’s (2012) review of the mussel fishery illustrates the impact of human activity, over a relatively short time-scale, on an important resource in one of New Zealand’s most productive shallow water ecosystems. McLeod (2009) calculated that the potential annual loss of macrofaunal invertebrate productivity due to the destruction of the Hauraki Gulf mussel beds was between 39 000 and 3.1 million t (wet weight) per year. Morrison et al. (2014) noted that these estimates were probably conservative as they did not include sessile invertebrates or larger invertebrates such as sponges, tunicates, and sea cucumbers. McLeod et al. (2014) examined remnant mussel beds and estimated that they support 3.5 times higher densities of invertebrates and 13.7 times higher densities of small fishes than surrounding areas with no mussels. Morrison et al. (2014) calculated that prior to dredging, the inner Hauraki Gulf mussel beds could have supported a biomass of between 200 and 16 000 t $y^{-1}$ of predatory fish above those able to be supported by ‘bare’ sediment areas, which replaced the beds from the late 1960s onwards. They also note that as well as providing direct habitat structure and food foraging, the beds could have potentially filtered the entire water volume of the Firth of Thames in less than a day, compared to over a year on the basis of current mussel biomass (McLeod 2009).

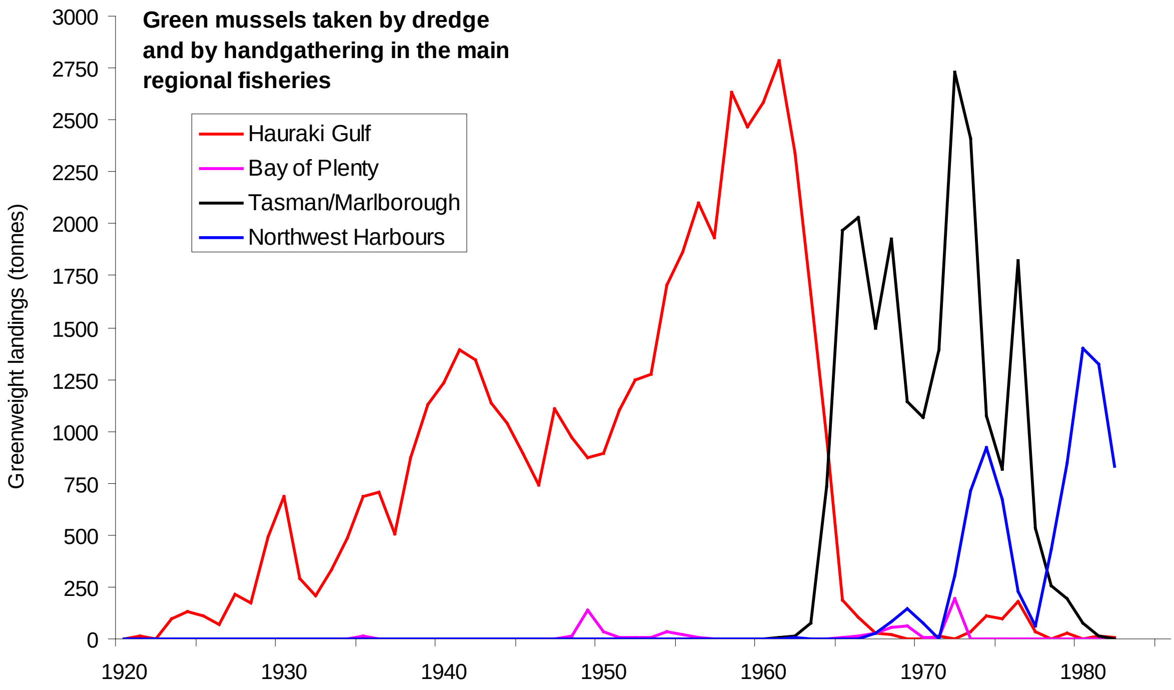

**Figure 5: Recorded landings from natural populations of green-lipped mussel, *Perna canaliculus*, in the main New Zealand fisheries, based on data in Annual Reports on Fisheries. Most were taken by dredge, with some collected by shoreline handpicking. Hauraki Gulf landings are into the ports of Thames, Coromandel, and Auckland; dredge vessels usually landed into the ports where their owners' factories were situated, rather than the nearest port to the fishing grounds. Very small (to 6 t) and infrequent handpicked quantities were landed at Whangarei. The Bay of Plenty landings are from Tauranga and Whakatane, outside the Greater Hauraki Gulf study area. Northwest Harbours are Kaipara, Manukau, and Raglan. Small (to 200 t) and/or intermittent fisheries are not shown: east Northland from 1968, Napier from 1928, the Wellington coast from 1963, and in the South Island Kaikoura, Lyttelton, and Bluff from about 1970. Figure from Paul (2012).**

### 3.4 A complete history of the exploitation of snapper

The availability of more or less contiguous archaeological, historical, and contemporary information on marine resource use in New Zealand (Smith 2011, 2013, Paul 2012, 2014, MacDiarmid et al. 2015, McKenzie and MacDiarmid in press) enables the catch history of selected fish species from first human settlement to be estimated. This catch history provides a time series of fishing mortality that can potentially be incorporated into the statistical models used in current stock assessment (Francis & Paul 2013). In this project, the catch history for snapper was assembled for the Greater Hauraki Gulf study area as a proof of concept to determine what can be achieved when archaeological and historical information are used in combination with official catch data (MacDiarmid et al. 2012).

A combination of estimates of the marine component of the human diet, Māori population size, daily human energy needs, and midden composition enabled Smith (2011) to calculate that the annual human take of snapper from the Greater Hauraki Gulf grew from a modest 72 t (range 12–107) in 1400 to a significant 997 t (range 560–1394) towards the close of the 18th century (Figure 6a). This growth was due to an increase both in Māori population size and an increasing reliance on snapper as a food source. Historical sources indicate that Māori fishermen supplied European settlers with snapper until the 1860s when commercial fisheries began to develop in the sheltered south-western Hauraki Gulf (MacDiarmid et al. 2012, 2015). In 1899, the first small steam powered beam-trawler began fishing in Greater Hauraki Gulf and over the next 20 years there was serial depletion of the fishing grounds closest to Auckland city until most of the commercial catch was taken from the outer part of the Gulf. Fisheries landings data are available from 1931 and subsequent landing fluctuations resulted from a complex combination of ground closures, gear developments, economic and social events and variable recruitment linked to climate (Paul 2014). Annual combined commercial and recreational catch from the Greater Hauraki Gulf study area peaked in 1971 before the introduction of the Quota Management System in 1986 eventually reduced effort and catch and allowed some stock rebuilding in the period since 1995 (Ministry for Primary Industries 2013).

Over the 700 years of the fishery about 880 000 tonnes of snapper has been fished from the Greater Hauraki Gulf, 50% of this in the last 100 years (Figure 6b), and the stock is currently at about 14% of the estimated pre-human stock size (MacDiarmid et al. 2012). Despite this decline in biomass, snapper is still the most important fish in the modern Greater Hauraki Gulf, both commercially and ecologically (see Section 4). Commercial catches of snapper in the Gulf comprise about 42% of the biomass of all commercially fished species combined (McKenzie & MacDiarmid 2012).

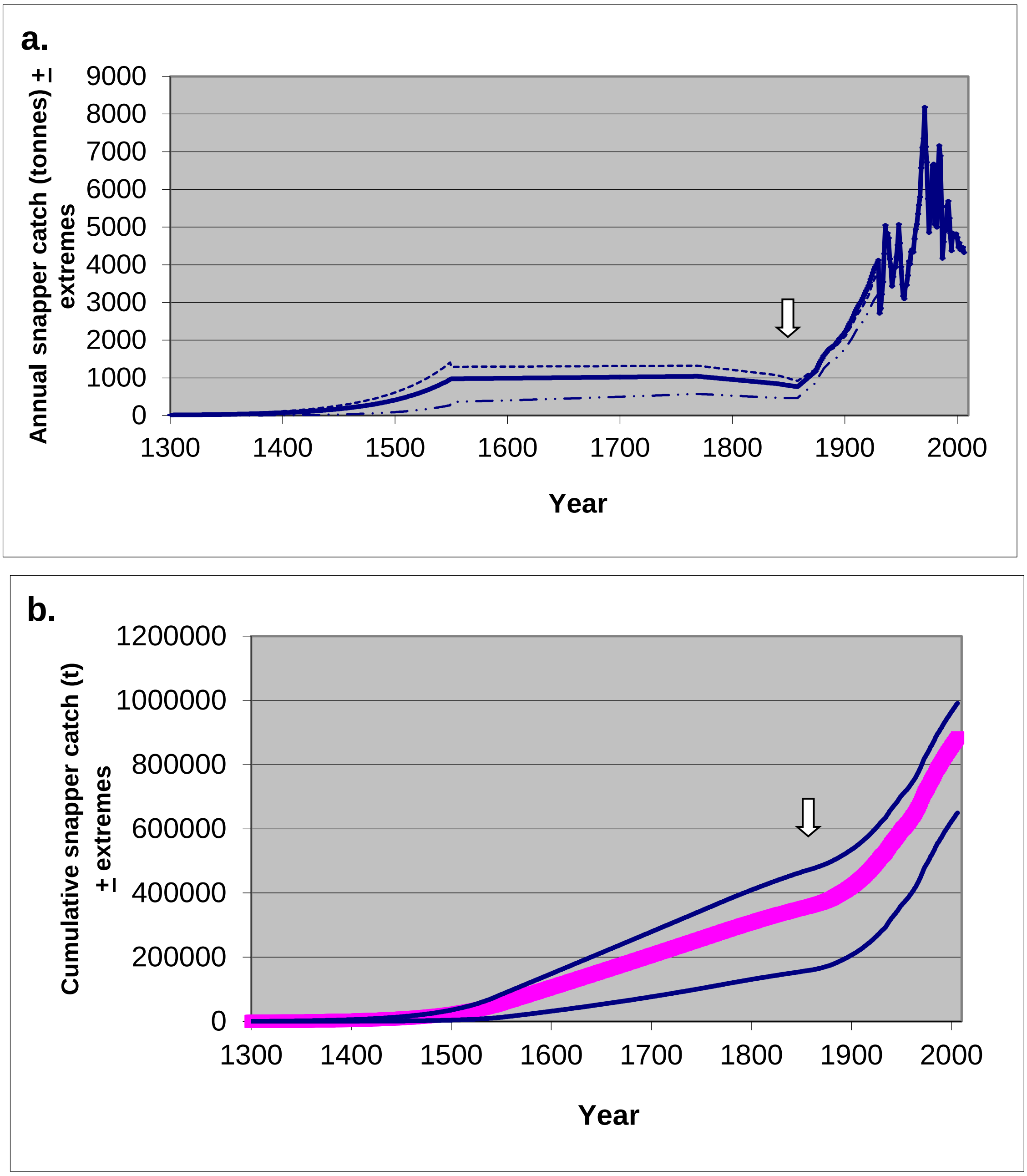

**Figure 6: Catch history of snapper from the Greater Hauraki Gulf 1300 – 2006: a) annual catch; b) cumulative annual catch. The three lines on each graph represent the maximum, best and minimum estimates. The start of the commercial fishery is indicated by the arrow.**

## 3.5 New Zealand fur seals and sea lions

The earliest European explorers in New Zealand observed populations of New Zealand fur seals (*Arctocephalus forsteri*) and sea lions (*Phocarctos hookeri*) that had already undergone substantial exploitation. Smith (2011) showed a high reliance by Māori on seals which contributed to about 61% of the marine diet in Greater Hauraki Gulf region and to about 74% of the marine diet along the Otago-Catlins coast in the period from 1250–1450. This equated to an annual removal of about 4000 fur seals and 560 sea lions in the Greater Hauraki Gulf and 5300 fur seals and 1121 sea lions along the Otago-Catlins coast (Smith 2011). This level of exploitation gradually eliminated seal populations southwards from North Cape to the southern shores of the South Island over a period of 500 years (Smith 2005). European sealers in the late 18th century and early 19th century completed the local extinction of seals from the New Zealand mainland and their near elimination from the sub-Antarctic Islands by the 1830s (Lalas & Bradshaw 2001; Ling 2002).

### New Zealand fur seals

Closed seasons and hunting permits for New Zealand fur seals were introduced from 1875 (Lalas & Bradshaw 2001). Fur seals were last hunted commercially in New Zealand in 1946 (Crawley 1990) and were finally protected with the passing of the Marine Mammals Protection Act 1978. Since then fur seal populations have started to rebound in southern New Zealand (Watson et al. 2015). The best information comes from the Otago-Catlins region along a 250 km stretch of coastline in south-eastern South Island, New Zealand, from Oamaru to Slope Point. The nearest breeding location to this study area was 80 km off the southern boundary at Ruapuke Island in Foveaux Strait and at Banks Peninsula, 240 km north-east of Moeraki (Harcourt 2005). The first reported sighting of a New Zealand fur seal ashore within the study area following the decimation of the species in the early 19th century was at Otago Peninsula in 1913, and the earliest indicators for breeding were reports of solitary pups in 1976 and 1978 (Wilson 1981). Breeding began further south in 1979 or 1980 at Nugget Point (Lalas & Murphy 1998) and further north at Moeraki in 1989 (Lalas & Harcourt 1995). Annual direct counts of pups throughout the study area began in 1983 (Lalas & Harcourt 1995; Lalas & Murphy 1998; Watson et al. 2009) where trends in pup counts indicated increases of about 30% annually through the 1990s (Lalas & Bradshaw 2001; Lalas 2008) (Figure 7). Estimates of the size of this recovering population were generated by Lalas & MacDiarmid (2014) from population demography created from Leslie matrix simulations for stationary age distributions. They deduced population size (excluding pups) from simulations by using the ratio for the number of pups to the number of older individuals. Their best estimate for this pup multiplier was 4.8 (plausible lower and upper estimates 4.2–5.3). A logistic growth model applied by Lalas & MacDiarmid (2014) to 13 years of estimates for annual pup production indicated that this population in 2009 was at 95% of the asymptote of 19 600 individuals (plausible range 13 000–28 800).

The recent and rapid increase in abundance and northward spread of New Zealand fur seals has raised the spectre of seals as a threat to New Zealand fisheries (Lalas & Bradshaw 2001; Lalas 2008). The best estimate for average daily consumption per individual New Zealand fur seals is 6.4 kg (15% of mean body mass 41.3 kg), similar to the higher of two previously published deterministic estimates (Lalas et al. 2014 a). For the New Zealand fur seal population along the Otago-Catlins coast this daily rate per individual sums to a total annual consumption of 45 500 t (23 400–87 100 t). In comparison, the annual commercial catch of fish along the Otago-Catlins shelf is about 226 000 t (McKenzie & MacDiarmid 2012). The concern that fur seals threaten local fisheries appears unfounded, at least for south-eastern South Island where the size of the New Zealand fur seal population has almost reached its predicted maximum without any reports of detrimental effects on squid or finfish fisheries (Lalas & MacDiarmid 2014).

The recent increase in the Otago-Catlins population of New Zealand fur seals indicates the capacity of this species to quickly recover once breeding is re-established. Long absent from the Greater Hauraki Gulf, New Zealand fur seals are now being regularly observed there too, albeit in very small numbers (Clemens et al. 2011, Department of Conservation 2011, 2012).

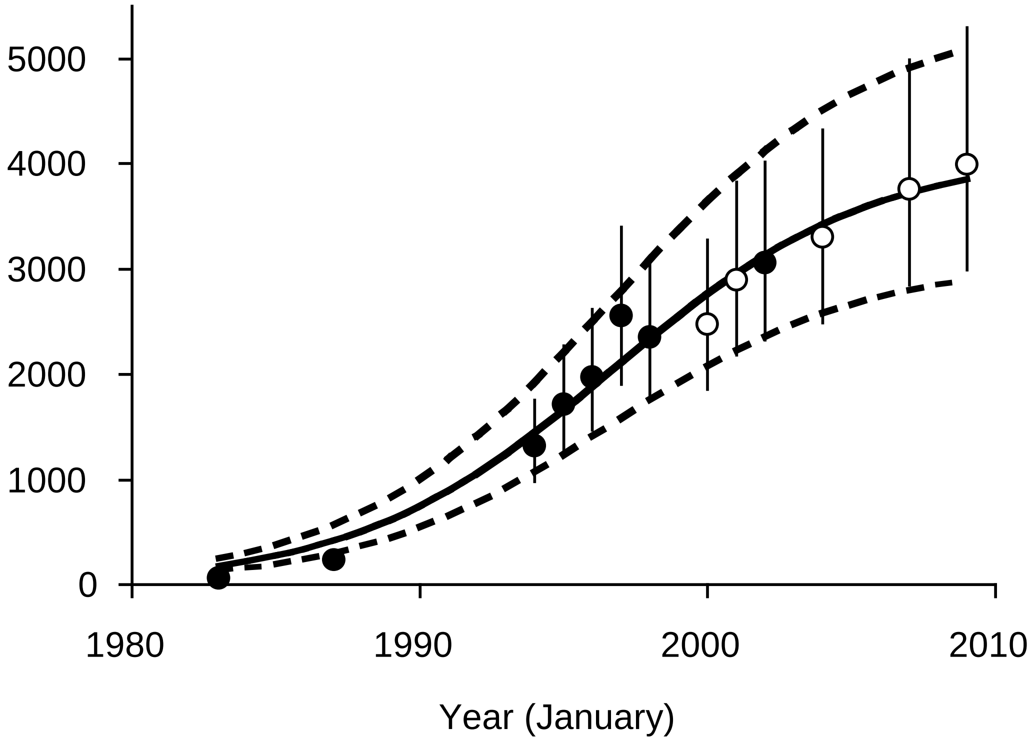

**Figure 7: Trend in estimates of annual pup production by New Zealand fur seals for south-eastern South Island, New Zealand (from Lalas & MacDiarmid in press). Symbols indicate best estimates (vertical bars delineate lower and upper estimates) from 13 years with comprehensive surveys; all breeding sites were surveyed for eight years (solid circles) but some sites were missed in five years (open circles). Logistic model curve for best estimate (solid line) is flanked by lower and upper estimates (dotted lines).**

### New Zealand sea lion

In contrast to New Zealand fur seals which is classified ‘Least Concern’, the New Zealand sea lion is listed as ‘Nationally Critical’ under the New Zealand Threat Classification System (Baker et al. 2010). The main extant populations are at the sub-Antarctic Auckland and Campbell islands on the southern margin of its historical distribution. The production of pups at breeding colonies in the Auckland Islands has decreased by over 30% since the mid-1990s (Chilvers et al. 2007). Augé et al. (2011) used comparative foraging information to argue that, compared to the Otago coastline, the Auckland Islands is a marginal habitat for this species.

Knowledge of the consumption rates by New Zealand sea lions is critical because it assists in estimating the energy requirements of the threatened Auckland Island population and the recovering Campbell Island and Otago populations. In turn this estimate of energy requirements informs any adjustment in fisheries quota necessary to accommodate the present and future dietary needs of this species. New estimates of consumption rates for New Zealand sea lions, were applied to the present Auckland Islands population, indicating an annual consumption of 41 000 t (Lalas et al. 2014b). This is more than 1.5 times the recorded catch of 25 000 t of commercial fish and squid in the Auckland Islands region (Statistical Area 602) during the 2011–12 fishing year but the potential for competition between New Zealand sea lion and fisheries is difficult to judge from existing information. More data are required to establish where sea lions are foraging and to quantify their diet by mass.

Female New Zealand sea lions have a strong tendency to return to their beach of birth to reproduce (Chilvers & Wilkinson 2008, Gales 2009). Consequently, new breeding colonies are slow to establish. New Zealand sea lions have been regularly sighted on the Otago-Catlins coastline since the 1980s and a new breeding colony was established on the Otago Peninsular in 1992 by a single female (McConkey et al. 2002a and b, Chilvers & Wilkinson 2008). Since then to 2010, 45 pups were born in this new population with the surviving mature females also breeding (Augé et al. 2011). New genetic research on ancient sea lion DNA extracted from midden derived bones indicates that the sea lions that once inhabited mainland New Zealand were distinct (possibly a separate species) from the surviving populations of sea lions in the sub-Antarctic Islands (Collins et al. 2014). This suggests that repopulation of northern New Zealand may be slow or not occur.

### 3.6 Cetaceans

There is not much evidence for hunting of larger whales by pre-European Māori (Smith 2011). The evidence of carved whale bone and teeth indicate the use of stranded whales, however. The remains of small dolphins in middens allowed Smith (2011) to estimate that in the pre-European period between 21 and 47 individuals were taken each year in the Greater Hauraki Gulf study area and between 11 and 32 individuals were taken each year along the Otago-Catlins coast. Few of the dolphin remains have been identified to species so the impact on target populations is unclear. Nonetheless, Captain James Cook commented on the abundance of whales and dolphins around the New Zealand coast in the journal from his first voyage to New Zealand (Beaglehole 1955). Jackson et al. (2016) estimated that about 27 500–31 500 (95% confidence interval of 22 000 and 38 000) southern right whales (*Eubalaena australis*) occurred in New Zealand waters at this time. Carroll et al. (2014) have estimated that about 35 860 to 40 650 southern right whales were removed from the waters surrounding New Zealand during the 19th century by the combined efforts of pelagic whalers, bay whalers and shore-based whaling stations. About 80 percent were taken between 1830 and 1849, indicating a brief and intensive harvest that resulted in the commercial extinction of southern right whales in New Zealand within two decades. Few were taken from the Greater Hauraki Gulf study region, but at least 1141 were taken by shore stations and bay-whalers along the Otago-Catlins coast (McNab 1913). In the New Zealand region the majority of the pelagic catch of southern right whales came from off the Otago and Southland coasts, the southern flank of the Chatham Rise, and along the Louisville Ridge (Smith et al. 2012). The combined shore whaling, bay-whaling and pelagic catches had a devastating effect on the New Zealand population of southern right whales which Jackson et al. (2016) have calculated came close to extinction with perhaps less than 100 individuals surviving into the early 20th century. Recovery of the New Zealand population has been slower than reported for some other southern right whale breeding stocks (Jackson et al. 2016).

During the 19th and 20th centuries sperm whales (*Physeter macrocephalus*) and humpback (*Megaptera novaeangliae*) whales were also taken from New Zealand waters (Jackson et al. 2016, Smith et al. 2012), and pelagic whaling in the Southern Ocean and the Antarctic removed vast numbers of humpback, blue (*Balaenoptera musculus*) and fin (*Balaenoptera physalus*) whales (Baker & Clapman 2004, Clapman & Ivashchenko 2009, Clapman et al. 2009), some of which would have migrated through New Zealand waters on their way to and from winter calving and breeding grounds in the tropics. Pinkerton et al. (2015) has estimated that in combination these historic whaling activities reduced present day whale biomass in the Greater Hauraki Gulf study region by about 70%.

The greatly reduced biomass of marine mammals around New Zealand, with the consequent reduction in the annual production of pups, calves and placentas, and more modest declines in fish stocks described above may have had important consequences for top predators such as white sharks (*Carcharodon carcharias*) and killer whales (*Orcinus orca*) which prey upon a variety of fish, seals and cetaceans (Cortes 1999, Visser 1999a and b, 2000, Heithaus 2001, Estrada et al. 2006, Mehta et al. 2007, Carlisle et al. 2012). Marine mammals are an energy rich food source for white sharks (Fallows et al. 2013, Semmens 2013). Depletion of prey species has been identified as a threat to white shark populations worldwide (Wildlife Conservation Society 2004) and some populations of killer whales (Ainley & Ballard 2012, Ayres et al. 2012).

### 3.7 Seabirds

Seabirds are high trophic level predators of a broad range of fish and invertebrate prey. There is increasing evidence that seabirds were previously important in transferring nitrogen from the ocean to New Zealand's terrestrial and freshwater ecosystems at mainland breeding colonies (Hawke & Holdaway 2003, 2005, Harrow et al. 2006, Holdaway et al. 2007, Hawke & Holdaway 2009). Seabirds are sensitive to changes in prey availability which makes them an ideal indicator of ecosystem status and change (Piatt et al. 2007). However, because they are generally long-lived and have low fecundity, seabirds are also sensitive to predation, and in New Zealand they experienced a marked change in the range of predators over the last 800 years (Tennyson & Martinson 2006). According to Worthy & Holdaway (2002), prior to the arrival of Māori, hills and mountain ranges on mainland New Zealand were densely populated with seabird breeding colonies. Before human contact, small burrowing seabirds (especially petrels) probably occurred on the hills and ranges fringing both study areas. These would have been quickly depleted by the arrival of the Polynesian rat (*Rattus exulans*), which probably arrived with the first Māori settlers (Wilmshurst et al. 2010). Early Māori also directly consumed many seabirds. Smith (2011) has constructed best estimates of consumption of seabirds in the two study regions.

Around 1400 about 19 t of seabirds comprising 22 species were harvested annually by Māori in the Greater Hauraki Gulf (Smith 2011). This equates to about almost 18 000 individual seabirds harvested each year. The key species were little penguin (*Eudyptula minor*), spotted shag (*Stictocarbo punctatus*), pied shag (*Phalacrocorax varius*), and albatrosses, that together made up 70.1% of the total biomass harvested from marine and coastal birds. Around 1550 about 28 t, equating to 16 000 individual seabirds, were harvested annually by Māori from the Greater Hauraki Gulf with three taxa (albatrosses, little penguin, and spotted shag) yielding 90.2% of the harvested biomass. By 1750 the total annual harvest of seabirds in the Greater Hauraki Gulf had risen to 56 t, equivalent to 62 500 individuals, with the same three taxa (albatrosses, little penguin, and spotted shag) providing 71.6% of the harvested biomass.

Smith's (2011) best estimate of the total annual harvest of seabirds along the Otago-Catlins coast at around 1400 is 32 t or 15 600 individuals. Four species, white-capped albatross (*Thalassarche cauta*), *Megadyptes* sp. (at this time almost certainly the waitaha penguin), Fiordland crested penguin (*Eudyptes pachyrhynchus*), and little penguin, made up 76% of the total biomass harvested. Around 1550 about 47 t equating to about 47 500 individual seabirds were harvested annually by Māori from along the Otago-Catlins coast, with four taxa (white-capped albatross, *Megadyptes* sp. penguin, Fiordland crested penguin, little penguin, and spotted shag) yielding 74% of the harvested biomass. By 1750 the best estimate of the total annual harvest of seabirds in the Otago-Catlins study region had risen to 80 ± 24 t, equivalent to 32 366 individuals, with the four taxa (white capped albatross, Stewart Island shag (*Leucocarbo chalconotus*), spotted shag, and *Megadyptes* – by this time probably yellow-eyed penguin) providing 67.9% of the harvested biomass (Smith 2011).

While this level of harvesting of seabirds in the two study areas would have depressed the populations of the main target species, seabirds comprised only between 1.5% and 4% of the energy Māori derived from animal sources in the Greater Hauraki Gulf and between 6.5% and 16.2% in Otago-Catlins (Smith 2011) over this period. The harvest of marine and coastal birds by Māori expanded at less than half the rate of human population growth, indicating an overall diminution of their part in the human diet, which is likely to reflect reduced availability through both hunting pressure and the impact of introduced mammalian predators (Holdaway 1999, Smith 2013).

European settlement introduced a host of additional mammalian predators to mainland New Zealand and some of its offshore islands (Towns et al. 1997, Holdaway 1999, Nogales et al. 2004). While few New Zealand seabirds species became extinct (Tennyson & Martinson 2006), the combined effects of predation, harvesting (Smith 2011), and fisheries by-catch (Richard & Abraham 2013) has undoubtedly depressed numbers of many seabird species. Of the 70 seabird species that breed in the New Zealand region six species have recently been assessed as being at "Very high risk" from unsustainable levels of mortality due to interactions with fishing gear (Richard & Abraham 2013). Four species were considered at ‘High risk’, nine at ‘Medium risk’, seven at ‘Low risk’, and the risk for the remaining 45 species was assessed as negligible. The black petrel (*Procellaria parkinsoni*) was found to be the species most at risk, with most observed deaths occurring close to its breeding grounds in the Greater Hauraki Gulf. This endemic species is classified as ‘Nationally Vulnerable” by the Department of Conservation (Robertson et al. 2013). The other species assessed as high risk from fisheries interactions were Salvin’s albatross (*Thalassarche salvini*), flesh-footed shearwater (*Puffinus carneipes*), southern Buller’s albatross (*Thalassarche bulleri bulleri*), Chatham Island albatross (*Thalassarche eremita*), and New Zealand white-capped albatross (*Thalassarche cauta steadi*) (Richard & Abraham 2013). The magnitudes of the declines in seabird numbers from the combined effects of predation, harvesting, and fisheries by-catch are not well known. Pinkerton et al. (2015) use the best available sources to estimate numbers of each species of seabird for each period modelled, and then combined these to estimate seabird biomass in the Greater Hauraki Gulf study area. They estimated seabird biomass as a proportion of the present day biomass to be 0.67 (1950), 1.76 (1790), 2.37 (1500) and 3.62 (1000). Pinkerton et al. (2015) noted that that the biomass of petrels in the pre-human model is probably conservative as the numbers of these burrow breeding species could have been 2–3 times higher because of the huge breeding areas available on the mainland before Pacific rats and dogs arrived. He estimated that seabird biomass was lowest in the 1950 model before modern predator control and conservation programmes were initiated.

## 4. ECOSYSTEM MODELLING

### 4.1 Top-down effects on rocky reef ecosystems in north-eastern New Zealand: a historic and qualitative modelling approach

Since New Zealand was first settled, humans have had a profound impact on the abundance of many of the larger predatory marine species. Over the last 700 years the populations of sea lions, groper, white sharks, killer whales, and small and medium sized sharks, such as school sharks and bronze whaler sharks (*Carcharhinus brachyurus*), have been sequentially depressed either directly through exploitation or indirectly through reductions in their prey species (Wildlife Conservation Society 2004, Smith 2011, Ainley & Ballard 2012, Ayres et al. 2012, McKenzie & MacDiarmid 2012, Pinkerton et al. 2015).

A previously developed qualitative model of a rocky reef ecosystem in the Hauraki Gulf (Beaumont et al. 2011) was used by MacDiarmid et al. (in press) to explore the effect of successively including these mega-predators until the full complement were present, simulating the pre-human situation. Each mega-predator was included in the model by applying a positive or negative perturbation to the abundance of one or more of the existing groups in the model. The model was used to ascertain the critical interactions amongst species and identify which of these should be a priority for future research.

The inclusion of small and medium sized sharks in the model had the most predictable effects, with highly certain decreases in the abundance of lobsters and highly certain positive increases in the abundance of large predatory invertebrates, such as sea-stars and ophiuroids, and macro-invertebrate predatory fish, such as snapper. In the model none of these groups are directly preyed upon by small and medium sized reef sharks, indicating that shark predation propagates through the food web indirectly via linkages of prey groups to the affected groups in a complex manner. Subsequent and sequential inclusion of white sharks and orca, groper, and sea lions to the model system had uncertain effects on the abundance of other groups in the model. This uncertainty indicates that if a better understanding of the influence of these predators on reef ecosystems in northern New Zealand is required, then it will be necessary to include more information than the direction of the first order interactions. Such additional information may be about the intensity of interactions which are likely to be density or encounter rate dependent as these larger predators range over very large distances revisiting the same area only once or a few times a year.

The qualitative modelling undertaken in this study suggests that historically higher school shark and bronze whaler populations in the Greater Hauraki Gulf were very likely to increase the abundance of reef fish, such as snapper, that prey upon macro-invertebrates, but depress rock lobster abundance. In order to apply these findings to the present day situation it would be necessary to undertake a field sampling programme to examine changes in reef community structure across a gradient of small and medium shark population abundance in northern New Zealand, investigate the diet of these sharks in greater detail, and remodel the relationships between these predators and other components of the reef ecosystem once further data are available.

### 4.2 Trophic modelling of the Greater Hauraki Gulf shelf ecosystem since AD 1000

Pinkerton et al. (2015) developed food-web models of the Greater Hauraki Gulf region for five periods representing distinct phases of human marine resource exploitation over the last 1000 years: (1) present day, a period of controlled commercial catches of fish and shellfish, and seabird and cetacean conservation; (2) 1950, a period of a period of relatively stable domestic fishing activity; (3) 1790, late Māori phase just prior to the onset of European whaling and sealing; (4) 1500, early to mid pre-European Māori phase; (5) 1000, before human settlement in New Zealand. Each model represents all the major biota of the Greater Hauraki Gulf, from bacteria to whales and was developed using information provided by 10 teams of experts. Each model quantifies the flow of organic matter through the marine food-web from primary producers to top predators over an annual period. This approach allowed any differences in ecosystem structure between the time periods to be identified and quantified. Insufficient data were available to undertake similar modelling for the Otago-Catlins region.

The first model to be developed was that representing the present day ecosystem of the Greater Hauraki Gulf, as there is much more data to inform this model than the others. Stable isotope measurements were successfully used to validate that the trophic levels of organisms in the model were plausible. Sensitivity analysis showed that the food-web structure in the present-day model was robust to uncertainties in the initial parameter estimates of up to a factor of three. Historical models were then developed in turn, working backwards in time from the present day. Biomass and catch parameters were altered using information from historical reconstructions of landing histories (Paul 2012, 2014, Carroll et al. 2014, MacDiarmid et al. 2012, in press), population modelling (McKenzie & MacDiarmid 2012, Jackson et al. 2016), historical evidence (MacDiarmid et al. 2015), archaeological information (Smith 2011), reconstructions of past climate (Lorrey et al. 2013b, Neil et al. 2014), and evidence from narratives (Maxwell & MacDiarmid 2015, Parsons et al. 2009). Changes to the structure of the food-web was determined by estimating “trophic importance”. Trophic importance describes the degree to which changes in the abundance of one group are likely to affect other groups. Groups with high trophic importance are considered as more likely to be keystone groups i.e. ones with higher importance in maintaining the structure and function of the food-web as a whole. Key conclusions of the modeling are given below.

- In the present day model, groups in the Greater Hauraki Gulf ecosystem with highest trophic importance were (in decreasing order): 1st phytoplankton; 2nd macrobenthos (mainly small benthic crustaceans and worms); 3rd mesozooplankton (mainly copepods); 4th bivalves; 5th snapper (which is the fish group with the highest trophic importance). Management of the Hauraki Gulf should take into account the larger ecosystem effects that may result from further impacting these groups either directly (target species) or indirectly (impacts of bottom gear). Management action which may be considered appropriate could include additional data collection to understand or monitor these groups, further modelling to investigate how these groups affect resilience, or reducing direct and indirect human impacts on these groups.

- According to the model, carbon is estimated to be accumulating in the Greater Hauraki Gulf ecosystem at the rate of 0.3 $Mty^{-1}$ which implies a value of ecosystem services in terms of carbon burial of about NZ$6.5 million per year (assuming a “carbon-tax” value of $25/t C).

- Some higher trophic level parts of the ecosystem of the Greater Hauraki Gulf have changed substantially since human arrival, largely as a result of harvesting and introduced land-based predators. Fur seals and sea-lions were eliminated from the Greater Hauraki Gulf ecosystem before 1790 as a result of hunting by Māori. The abundance of cetaceans is estimated to have declined by 97% since 1000. The abundance of seabirds was estimated to have declined by 69% since 1000, largely due to the introduction of rats and other mammalian predators of eggs and chicks. Reductions in the biomass of fish groups over the period of human occupation due to fishing were estimated to be: sharks, 86%; snapper, 83%; rock lobster, 76%; other key fish stocks (jack mackerels, blue mackerel, gurnard, leatherjacket, tarakihi, kahawai, rig, flatfish, trevally, barracouta, skipjack tuna), average of 57%; “other demersal fish”, 59%.

- Reductions in the biomass of upper trophic levels over time led to substantial declines in their trophic importances. Cetaceans and seals had some of the highest trophic importances (3rd and 5th respectively out of 46 groups) in the Greater Hauraki Gulf system in the pre-human model. Seals declined to zero in the 1790 and subsequent models and in the present day model cetaceans are now 21st. Sharks and rock lobster also had much higher trophic importance in the pre-human model than in the present day due to reductions in their biomasses over time.

- The biomasses of many middle trophic level groups (such as small and large pelagic fishes, macrobenthos, squid, macrozooplankton, and gelatinous zooplankton) changed substantially (11–44%) over time in the models while others did not (especially benthic invertebrate epifauna). The groups that changed in biomass in the models were generally those that are important prey items for middle and upper level predators. We recommend establishing monitoring for changes in these middle trophic level groups in the Greater Hauraki Gulf due to their likely important role in maintaining ecosystem resilience.

- Despite changes to biomasses of many upper and middle trophic level groups, according to the trophic modelling, the rank trophic importance of about half the groups in the Greater Hauraki Gulf did not change substantially over the period of human occupation; the rank trophic importance of 24 of 46 non-detrital groups changed by three places or less between AD 1000 and the present day. The groups with little change in their rank trophic importance include some commercially-important fish groups (snapper, gurnard, leatherjacket, tarakihi, flatfish, and barracouta), large and small pelagic fishes, small reef fish, many groups of benthic epifauna (urchins, bivalves, sponges, macrobenthos), squid, all groups of zooplankton, phytoplankton and macroalgae.

- The biomasses of the lower food-web of the Greater Hauraki Gulf (primary producers, bacteria, detrital pathways, microbial function) were little affected in the ecosystem models by quite substantial changes over time to the biomass of fish and higher trophic levels. Our modelling suggests that the functioning of the lower food-web of the Greater Hauraki Gulf is somewhat decoupled from changes at higher trophic levels, probably by the “buffering” or stabilizing effect of middle trophic level organisms.

- If the biomass of some higher predator groups recover towards former levels it is likely to change the pattern of trophic importance in the region. For example, after an absence of nearly 500 years New Zealand fur seals have reappeared in the Greater Hauraki Gulf although their biomass is still negligible. Management of the region should take into account the potential for trophic and system-level effects of re-establishment/recovery of marine mammals towards historical levels.

## 5. DISCUSSION

### 5.1 Bridging the gap between the present and past

An ecosystem or population is likely to be perceived as stable or more or less pristine if the history of preceding changes is ignored, is unknown, or is unknowable (Hughes et al. 2005) leading to "sliding baseline syndrome" (Pauly 1995, Dayton et al. 1998). However, over the last 20 years what is knowable and acceptable as information that can usefully compliment quantitative fisheries catch and research survey data has expanded globally as the new disciplines of historical marine ecology and marine environmental history have emerged (Holm et al. 2001, 2010, Bolster 2006, Gertwagen 2011, Poulsen 2010). These new disciplines provide methodological approaches to accessing and interpreting information and data that help to bridge the gap between the modern statistical era, when information about marine resource use and state is routinely collected in a deliberate and organized manner, and previous periods for which the available information is that which has fortuitously survived (Holm et al. 2010, Gertwagen 2011, Poulsen 2010). This expansion of knowable information includes the oral histories of participants in marine resource exploitation (e.g., Saenz-Arroyo et al. 2005, Maxwell & MacDiarmid 2015), and it has extended back in time to include notes and journals of earlier explorers and observers (e.g., Saenz-Arroyo et al. 2006, Fortibuoni et al. 2010), as well as information that survives from company records, government archives, newspapers, photographs, and unofficial private correspondence (Paul 2014, MacDiarmid et al. 2015). Moreover, Smith (2011) has demonstrated that archaeological data can also be used to extend estimates of harvests of particular species into the pre-historical period.

### 5.2 Changes to New Zealand marine ecosystems since first human settlement

The information collated, reviewed, and interpreted for this study, using the methods established by the new disciplines of historical marine ecology and marine environmental history, indicates that since first human settlement marine environments in the Greater Hauraki Gulf and Otago-Catlins study sites underwent a profound change (summarised in Table 1 below). Seabird populations were affected by the arrival of the Pacific rat as well as by sustained human harvesting. Fur seals and sea lions were eliminated from much of the New Zealand coast within a few hundred years of Māori arrival by a small human population.

Following European arrival fur seals were largely eliminated from their remaining foothold around the southern coasts of the South Island, Stewart Island and the sub-Antarctic Islands, and southern right whales were driven almost to extinction by the late 1840s. This was followed by increasing exploitation of a range of fish and invertebrates once commercial fisheries were established in the 1860s. For some of the exploited species in both study regions, noticeable declines in abundance occurred in the late 19th century and early 20th century prior to the organised collection of fishery statistics. The declines were first evident in species such as oysters, grey mullet, and flatfishes in sheltered, shallow, readily accessible areas, but later progressed to species with a wider distribution such as snapper and blue cod, or with a deep water refuge such as groper. Laws and regulations to control fishing practices were introduced as early as 1866 and continued to be modified throughout the period.

Declines in most commercial fish species continued from the mid-1930s onwards during the 'statistical era' when fisheries landings data started to be comprehensively gathered nationwide. The most dramatic example during this period was the dredge fishery for green-lipped mussels in the inner Hauraki Gulf which completely collapsed in the 1960s, with significant ecological consequences, and has not recovered since. Marine habitats in the Greater Hauraki Gulf and probably elsewhere have been modified where the bottom trawling footprint is intense (Jones 1992, Thrush et al. 1998, Baird et al. 2015). By drawing upon archaeological, historical, and contemporary information the catch records of species over the whole span of human settlement can be estimated. Use of archaeological and historical information in combination with modern catch data has extended the estimated catch-history for some species by over 600 years to the beginning of human exploitation. From a global perspective, it is rare to have an estimate of the entire catch history of a species (Holm et al. 2010).

**Table 1. Time line of key events affecting the Hauraki Gulf and/or the Otago-Catlins coast from 1000 to the present day.**

| Year | Hauraki Gulf | Otago-Catlins coast |
|---|---|---|
| ~1250 | Māori arrive in NZ from eastern Polynesia and quickly settle NZ mainland. Introduce Pacific rat and dog. | |
| 1500 | 150 year period of unusually cold and wet climate conditions starts | |
| ~1550 | Fur seals and sea lions hunted to local extinction. | |
| 1650 | 150 year period of unusually cold and wet climate conditions ends | |
| 1769 | | Breeding colonies of fur seals and sea lions eliminated. Vagrant non-breeders persist. |
| 1769 | Captain James Cook, Sir Joseph Banks and crew explore NZ and introduce steel and iron | |
| 1792 | European sealers and whales arrive in New Zealand | |
| 1830s | NZ fur seal eliminated around mainland and almost extinct at sub-Antarctic Islands | |
| 1830 | Whaling for southern right whale begins in earnest at shore stations and offshore | |
| 1840 | Treaty of Waitangi is signed | |
| 1840 | Auckland city founded | |
| 1841 | Māori supply European settler community with fresh fish | |
| 1848 | | Dunedin city founded |
| 1849 | 90% of southern right whale population in NZ waters removed through whaling | |
| 1850 | Commercial fisheries established to supply a rapidly growing population in both regions | |
| 1868 | | First trawling in NZ undertaken in Otago Harbour by the *Redcliffe*. Lasts less than a year. |
| 1869 | | Report by the Commissioners for Otago into state of fisheries |
| Early 1870s | Export of fresh rock oysters to Sydney and canning of grey mullet commence | |
| 1877 | Fish Protection Act establishes regulations for New Zealand's fisheries, such as closed areas and seasons and gear restrictions. Marine Department established. | |
| 1878 | Fisheries Dynamite Act 1878, prohibits dynamiting fish in the sea and fresh water | |
| 1882 | | New Zealand Deep Sea Fishing Company, operating out of Port Chalmers, briefly trawled with a steamer before winding up. |
| 1884 | Fisheries Conservation Act 1884. Consolidates previous legislation and introduces more specific regulations on minimum sizes, closed seasons, and fishing methods. | |
| 1885 | Fisheries Encouragement Act. 1885. Provides for the establishment of fishing towns and villages, and promotes (via a financial bonus) the export of canned and cured fish. | |
| 1888 | Regulations define mesh size for general seine nets, garfish nets and herring [yellow-eyed mullet] nets. Defines minimum weight or size (length) for 21 fish species. | |
| 1897 | J. Hector report on the protection of grey mullet published | |
| 1899 | *Minnie Casey* begins trawling in the Hauraki Gulf | Otago Trawling Company begins bottom trawling using the chartered *Napier*. |
| 1900 | Government trawler *Doto* begins exploratory bottom trawling around NZ | |
| 1902 | Trawling prohibited in the inner and much of the central Hauraki Gulf | Report of Inspector of Fisheries on Trawling at Port Chalmers |
| 1903 | Regulations under the Sea-fisheries Act 1894 revises size limit for sand flounder, and closes season for this species in Auckland waters. Trawl net mesh size defined. | |
| 1904 | Owners of *Minnie Casey* prosecuted for trawling in closed area and trawling in the Gulf ceases until 1915. | Portobello Marine Hatchery established to boost local production of flounder and sole |
| 1906 | Regulations under the Sea-fisheries Act 1894 | |

| Year | Hauraki Gulf | Otago-Catlins coast |
|---|---|---|
| | defines an area of the inner and central Hauraki Gulf closed to trawling. | |
| 1907 | Regulations under the Sea-fisheries Act 1894 revise the area of Hauraki Gulf closed to trawling | |
| 1907 | Government trawler *Nora Niven* surveys fishing grounds from Stewart Island to Bay of Plenty and Chatham Islands | |
| 1907 | NZ government takes control of the rock oyster beds in the entire country | |
| 1908 | Fisheries Act 1908 consolidates previous legislation, establishes administrative framework that survives in broad form until 1983, and more formally claims jurisdiction over a Territorial Sea to 3 miles offshore. | |
| 1912 | Long-lining replaces hand-lining | Blue Cod Commission sits to decide on regulations for this fishery |
| 1915 | Trawling in Hauraki Gulf recommences | |
| 1919 | Royal Fisheries Commission focussed on fisheries in the Auckland region, especially on restricted areas for trawlers, trawl mesh size, industry-imposed limits on fish landings, and public price of fish. | |
| 1929 | Report on the fisheries of the Hauraki Gulf by AE Hefford, with special reference to the snapper fishery and to the effects of trawling and Danish seining | |
| 1930 | Catch log books issued to the skippers of fishing boats working the Hauraki Gulf. | |
| 1932 | Export fishery for rock lobster to London starts in both regions | |
| 1934 | Export cray-fishery in Hauraki Gulf ceases | |
| 1935 | Monthly returns of fish landed from every licensed fishing-boat becomes mandatory | |
| 1937 | Report by the Sea Fisheries Investigation Commission inquired generally into New Zealand’s fisheries, but with specific reference to the Hauraki Gulf. | |
| 1937 | | Export fishery for rock lobster along Otago coast collapses |
| 1939-1944 | Trawling in Hauraki Gulf ceases during WWII as trawlers seconded to Navy | |
| 1945 | Trawling resumed in Hauraki Gulf | |
| 1948 | Motor trawling starts in Hauraki Gulf | |
| 1951 | Steam trawling in Hauraki Gulf ceases | |
| 1953 | Most coastal and seabirds protected with the passing of the Wildlife Act 1953 | |
| 1964 | State control of rock oyster beds ceases throughout NZ and individual leases offered | |
| 1965 | Dredge mussel fishery in inner Hauraki Gulf collapses due to overfishing | |
| 1978 | Marine Mammals Protection Act 1978 protects seals and cetaceans in NZ waters | |
| 1985 | IWC commercial whaling moratorium comes into effect internationally | |
| 1986 | Quota Management System introduced throughout territorial sea and EEZ | |
| 2013 | Six seabird species assessed as being at "Very high risk" from unsustainable levels of mortality due to interactions with fishing gear. | |

Not until protection of most seabirds in the 1950s and marine mammals in the 1970s, and the introduction of the fisheries Quota Management System in the mid-1980s, were removals of marine species finally brought under control, allowing some stocks and populations to rebuild. The New Zealand fur seal, in particular, is quickly recolonizing its former range. However, recovery of New Zealand sea lion populations significantly north of their current southern New Zealand distribution appears unlikely over the next century as the northern genetic lineage was driven to extinction at some stage since human settlement (Collins et al. 2014). Some seabird species are still at risk from unsustainable levels of mortality due to interactions with fishing gear (Richard & Abraham 2013). Whaling by some nations has continued to affect whales migrating through New Zealand waters until very recently. The felling and clearing of 35% of New Zealand’s forests over a period of 100 years by European settlers starting about 1840 led to increased rates of sedimentation in harbours and sheltered coastal waters with long-lasting legacy effects on benthic communities (Campbell 1946, Thrush et al. 2004, Lohrer et al. 2004, 2006, Hayward et al. 2006, Gomez et al. 2007, Morrison et al. 2009, Marden 2011). Changes to land-use since human settlement have also affected riverine input of dissolved nutrients to coastal seas. For example, the once forested Hauraki Plains now support intensive dairy farming. Rivers draining this catchment contribute 70% of the nitrogen supply to the Firth of Thames (Zeldis 2008b).

### 5.3 Mass balance modelling

The mass-balance modelling undertaken in this study (Pinkerton et al. 2015; Section 4.2) provides insights into how the changes to New Zealand marine ecosystems described above affected the structure and aspects of the functioning of the Greater Hauraki Gulf ecosystem now, and in four historical periods. Compilation of the present day and historical models of the Greater Hauraki Gulf ecosystem has been a long and involved undertaking which has drawn on decades of research experience across diverse areas of marine science in New Zealand and from around the world. Uniting this knowledge and coercing the disparate data into comparable forms has taken a number of years but has been critical, as knowledge of how species interrelate through feeding is an important step in understanding how an ecosystem is structured and functions.

The Hauraki Gulf region has been intensively studied for decades, and is probably the best studied large coastal ecosystem in New Zealand. There was sufficient information on the ecology of the Greater Hauraki Gulf to obtain a reasonable estimate of most parameters to develop an end-to-end mass balance of the ecosystem in its present day state. In historical models, changes to parameters estimated from archaeological, historical, and climatological data could be accommodated and the models balanced with relatively small changes in other parameters. Obtaining a balanced present-day model from field measurements and other data required more adjustments to parameters than moving from one historical period to the next.

It is recognised that a balanced model is but one solution of many possible solutions given that the conceptual model framework is highly under-constrained, and that there are significant uncertainties in many parameters. Hence, outputs from this modelling should be considered as working hypotheses in that they provide the best available, self-consistent, quantitative description of the structure of the Greater Hauraki Gulf ecosystem through the period of human occupation. In other words, the models represent plausible scenarios of how the ecosystem could have been structured historically in a way that is consistent with all we know of organisms now and based on historical, archaeological, narrative, and climatological evidence from the study region. It is recognised that there are other scenarios that also fit the available evidence and these could be explored in future work. Nonetheless, the potential value of these models and supporting datasets is high and has allowed examination of historical change, but would equally allow the exploration of future scenarios to investigate the ecological impact of changes in any model component.

The biomasses of most benthic invertebrates through the Greater Hauraki Gulf seem to be relatively poorly known in that changes to these parameters during model balancing tended to be greater than average. Benthic invertebrates are difficult to represent appropriately in models because they are functionally and taxonomically diverse, often cryptic and/or hard to identify, have a very patchy spatial distribution, and have inconsistent energetic parameters (e.g. many vary their consumption and growth rates in response to local conditions). The amount of sampling of basic properties of benthic invertebrates (abundance, mean size, diet) is low even for a well-studied and accessible area like the Greater Hauraki Gulf. To improve modelling such as this in the future, a habitat-stratified survey of benthic invertebrates in the study region is recommended. This kind of basic, baseline survey information is extremely valuable for developing models to understand ecosystem structure.

The modelling undertaken indicates that the trophic levels of almost all consumer organisms in the Greater Hauraki Gulf have increased from the pre-human period to the present, despite harvesting or the introduction of land-based mammalian predators reducing the biomass of fish, invertebrates, cetaceans, seals, and seabirds. The Greater Hauraki Gulf models suggested that there was a similar total amount of food available in all model periods, but because there were substantially more consumers in the past (especially air breathing predators and fish), most predators were likely to feed at a slightly lower trophic level historically than at the present-day. Between 1000 and the present day, the net primary production becomes spread round progressively fewer high trophic level predators so that each predator can feed on slightly higher trophic level prey.

There were substantial changes to the biomass of some important middle trophic level groups (small fish, cephalopods, benthic and pelagic invertebrates) in the historical models and it is notable that these changes arose from food-web rebalancings rather than being forced from historical data. For example, decreases in biomass between 1000 to the present day were estimated to have occurred for small and large pelagic fishes (32% and 33% respectively), macrobenthos (44%), squid (11%), macrozooplankton (22%), and gelatinous zooplankton (11%).

The historical ecosystem models of the Greater Hauraki Gulf reveal substantial changes in the pattern of trophic importance (TI) during human occupation. The TI of cetaceans was the 3rd highest in the system in 1000, 7th highest in 1950 and declined to 21st (present day). Fur seals/sea lions had the 5th highest TI in 1000, but were extirpated from the Greater Hauraki Gulf ecosystem before 1790. The reduction and losses of these apex predators in conjunction with their high historical trophic importances suggests that the pattern of ecosystem control in the Greater Hauraki Gulf ecosystem may have substantially changed during the period of human occupation, at least in the middle and upper trophic levels.

In the trophic models, sharks and snapper were the most trophically important fish in the Greater Hauraki Gulf ecosystem between 1000 and 1950. Between 1950 and the present day the TI of sharks decreased substantially (from 5th to 15th in the system) due to reductions in their biomass. At the same time, the TI of snapper stayed approximately constant. In the present day model, snapper are the most trophically important fish (5th overall). Changes to the patterns of trophic importance in the models suggests that the “fishing-down” period between 1950 and the present day (when the total biomass of targeted fish species were reduced by 55% on average) led to a reorganisation of the relative trophic roles of many species of fish, but did not have major effects on the pattern of trophic interactions at lower trophic levels. The overall high importance of snapper in the food web was maintained and even slightly increased during the fish-down period between 1950 and the present day.

Rock lobster (crayfish) was a reasonably important benthic invertebrate group in the Greater Hauraki Gulf before human arrival (6th out of 12 benthic groups) but with decreases in the biomass of rock lobster between 1000 and 1950 (76% decline), its TI declined to the least trophically important benthic invertebrate group and almost the lowest in the whole system (42nd out of 45).

### 5.4 Changes in human society and technology

Changes to New Zealand marine ecosystems over the 750 years since first human settlement have been accompanied by changes in human society and technology as profound as that experienced in most other parts of the world over many millennia (Erlandson & Rick 2010, Narchi et al. 2014). In the New Zealand case, the sequence has been very compressed in time, and the change between technologies based on bones, feathers, stone, wood, and fibre from flax, to a metal based technology was abrupt. The Polynesian ancestors of Māori arrived in New Zealand with a well-developed tropical fishing culture and quickly adapted these to exploit local marine species (Leach 2006, Paulin 2007, Wehi et al. 2013). Although impacts on vulnerable species such as fur seals, sea lions and seabirds from the small founding population were immediate, the following 400 years was a period of gradual change and technological adaptation with modest impacts on the marine environment. The analysis by Smith (2011, 2013) indicates a change from exploitation of species occurring on exposed open coasts to fish and bivalve species commonly occurring on more sheltered coasts. This transition occurred more swiftly and more thoroughly in northern regions, such as the Greater Hauraki Gulf, where human population growth, sustained by horticultural production, is likely to have been more rapid and continuous (Smith 2013). In southern regions, such as the Otago-Catlins, the opportunities for horticulture were fewer because of the harsher climate, and settlements remained clustered near rocky headlands (Smith 2013). Technologies for the capture and storage of large numbers of fish developed in both areas; focused on snapper in Greater Hauraki Gulf and on barracouta along the Otago-Catlins coast. For example, at the time of Captain Cook's arrival in the Hauraki Gulf in 1769 the technology for making beach seines up to 1 km long from flax fibre was well developed and was a major enterprise of coastal villages (Beaglehole 1963). Deployment required the coordinated efforts of up to 500 people to draw them properly (Thomson 1859). Drying bony fish and sharks without the use of salt for winter consumption was a widespread practice (Leach 2006, MacDiarmid et al. 2015).

Cook's arrival in New Zealand also saw the introduction of iron and steel which was quickly adopted by Māori in both fishing and horticulture. For example, Māori quickly adopted metals to make fish hooks for their own use, although there was considerable manufacture of replica traditional hooks for sale to curio hunters in the late nineteenth and early twentieth centuries (Paulin 2007). Similarly, in the lures used by Māori to capture barracoota along the Otago-Catlin's coast, steel nails replaced the single bone point, often made from the jaw-bone of a dog (Leach 2006). Māori quickly became heavily involved in trade and supplied fish and shellfish to European sealers and whalers, missionaries, explorers and the early settlers. Establishment of commercial fisheries later in the 19th century saw the involvement of Māori in fisheries for rock oysters, groper, and snapper.

The period between the arrival of Captain James Cook in New Zealand and the beginning of the 20th century was a time of profound societal transformation in New Zealand. In the late Māori period European visitors were few and Māori kawanatanga, culture, values, and trade dominated life. Within less than 130 years European governance, culture, values, law, commerce, and technologies were preeminent (see King 2003). The prevailing societal perceptions of the marine environment, use of its resources, and the laws that governed this use reflected this change from a Māori (Anon 1993, Walter et al. 2006, Leach 2006, Smith 2011, 2013) to a European (Arnold 2004, Hughey et al. 2010, McKenzie & MacDiarmid 2012, MacDiarmid et al. 2015) dominated society.

### 5.5 Conclusions

The information contained in the reports and papers associated with this project detail the changes to New Zealand marine ecosystems since first human settlement. Only three marine species have become extinct over this period but the populations of many groups harvested by humans have been greatly depressed, some from very soon after human arrival. The legacy of habitat loss or modification through sedimentation and/or bottom trawling and dredging may prevent some populations from recovering. However, capacity exists to rebuild some populations and the models of the Greater Hauraki Gulf ecosystem provide a means to examine the ecological consequences of various rebuilding scenarios.

Knowledge of human induced change to marine ecosystems over the full span of human settlement is rare from a global perspective. In most other localities sea level rise associated with the end of the last glacial period has obliterated most traces of first human exploitation of marine resources and the human population trajectory is poorly known. Because New Zealand was settled so recently, all this information is available to help inform marine policy development and management actions.

## 6. MANAGEMENT IMPLICATIONS

Policy development and management, including key research implications of this work are numbered for clarity (order does not imply importance):

*Atmospheric climatic and coastal geologic event chronologies*

1. Consideration should be given to modelling the effects of historic rainfall, vegetation patterns, and geological events on sediment delivery to coastal environments by New Zealand river systems. This will help indicate historic levels of sedimentation against which present rates can be judged and assist in understanding how past climates, geological processes, and human actions interacted to affect New Zealand's harbours and coastal seas.

*Inferring the interaction of environmental drivers and ecological responses from the hard part of marine organisms*

2. The analyses of midden derived otoliths has established that they can yield environmental data of similar quality to that obtained from freshly acquired otoliths. This suggests that a more extensive analysis of otoliths from middens over the entire pre-European Māori period could yield a detailed description of marine climate variation.

*Fish and shellfish*

3. The methodologies developed and applied by Smith (2011, 2013) to two regions could be applied to the rest of the New Zealand coast to yield similar time series of estimates of annual harvest by pre-European Māori.
4. It is apparent that from both a marine historical environmental and a marine resource management perspective that the middens and collections of material derived from them are nationally important and need to be managed and conserved appropriately to safeguard their future.
5. It is clear that New Zealand has a rich history of marine exploitation in the period before detailed fisheries landings records began, although the information is largely in a form of written observations and anecdotes. This study examined historical information from only two regions in any detail. Other regions would benefit from an examination of historical source material and collation of the information along the lines undertaken for this study.
6. Oral histories provide a source of information about present and past fishing and gathering practices that complements the collection of official landings statistics. The number of people with direct experiences of customary, recreational and commercial fishing in the middle of the 20th century is steadily decreasing and will approach zero by about 2030. If their experiences and observations are to be recorded, there is some urgency to systematically interview those now in their 70s and older. While analysis of the data can be delayed, the interviews cannot.
7. The approach taken by Maxwell & MacDiarmid (2015), using semi-structured interviews to elucidate relevant information within the context of a personal narrative, appears to be efficient and enjoyable for participants and interviewer alike. Any future interviews should focus on just a few key species to gain the maximum benefit.
8. The historical information indicates that for some species there were significant declines in abundance before the time series of fisheries landings information began in the early 1930s. Stock assessments of these species (blue cod, flatfish, grey mullet, groper, rock oysters, and snapper) should attempt to take this information into account.

*History of the Firth of Thames dredge fishery*

9. The loss of the habitat forming and water filtering aspect of approximately 500 km$^2$ of mussel beds represents a substantive ecological change in the inner Hauraki Gulf. The effects on secondary annual production of invertebrates and fish, and on water quality is likely to be substantial and could be modelled in more detail.
10. Consideration should be given to the suggestions of Morrison et al. (2014) that the feasibility of restoring the beds in the inner Greater Hauraki Gulf be investigated and research undertaken to determine where soft sediment mussel reefs may still exist in New Zealand, the likely relative importance of mussel beds as finfish habitat, and whether habitat restoration might result in improvements to fin fisheries and water quality.

*A complete history of the exploitation of snapper*

11. It is clear that archaeological, historical and modern time series information can be assembled to form estimates of the annual landings of snapper in New Zealand back to the earliest phases of

the fishery. The same approach could be applied to other species. These landing histories provide time series of fishing mortality that can potentially be incorporated into the statistical models used in current stock assessment.

12. The catch series for snapper in the Greater Hauraki Gulf study area can be characterised as three distinct periods: a long period of low and stable Māori and early European explorer landings, a 100 year period of rapidly increasing and fluctuating exploitation to meet expanding settler then export markets, followed by a quarter of a century of stable commercial catch under a Quota Management System (although the less well documented recreational catch is increasing). This catch history may broadly reflect trends experienced by other inshore fisheries in other parts of the world, where the earliest parts of the catch history may be difficult or impossible to estimate because archaeological data and /or human population estimates are not available. The applicability of this catch history to other long-exploited species in other parts of the world should be explored.

*New Zealand fur seals and sea lions*

13. The recovery of populations of New Zealand fur seals around much of New Zealand's coast line, where they have been absent for hundreds of years, will pose management challenges. For example, New Zealand fur seals prefer rocky shores as rookeries and haul-outs and thus there is potential conflict with shore fishers and hikers for access to these areas. Fur seals are likely to be perceived by recreational and commercial fishers as competitors for food fish.
14. Recovery of New Zealand sea lion populations significantly north of their current distribution appears unlikely over the next century.

*Cetaceans*

15. The populations of great whales exploited in the 19th and 20th centuries are slowly rebuilding and are likely to recolonise former ranges over coming decades. The presence of southern right whales close inshore on winter calving grounds such as in Blueskin Bay, north of the Otago Harbour entrance, and off the Kapiti coast, is likely to lead to tourism opportunities as well as potential conflicts with fishing and shipping operations for use of these areas. More frequent entanglement of cetaceans, especially humpback and southern right whales, in lobster trap-lines and long-lines is highly probable and mitigation methods will need to be considered.
16. Rebuilding populations of marine mammals around the New Zealand coastline may have positive consequences for top predators such as killer whales and white sharks, which may in turn pose difficulties for surfers and swimmers wishing to share the same environment.

*Seabirds*

17. The estimates by Smith (2011) suggest a high and sustained harvest of seabirds from two regions in New Zealand by pre-European Māori. These could be used to back calculate the seabird population size necessary to sustain the observed harvest, particularly those species such as the shags and penguins that probably bred within the study areas. This was beyond the scope of this study but would assist in providing the prehuman context for seabird numbers observed today.

*Qualitative modelling of reef top-predators*

18. Qualitative modelling of the effects of mega-predators on rocky reef ecosystems in the Greater Hauraki Gulf indicated the existence of a hitherto overlooked important historical interaction between small and medium size reef associated sharks with rock lobsters, large predatory invertebrates such as sea-stars and ophiuroids, and macro-invertebrate predatory fish, such as snapper.
19. In order to apply these findings to the present day situation it would be necessary to undertake a field sampling programme to examine changes in reef community structure across a gradient of small and medium shark population abundance in northern New Zealand, investigate the diet of these sharks in greater detail, and remodel the relationships between these predators and other components of the reef ecosystem once further data are available.

*Trophic modelling of the Greater Hauraki Gulf shelf ecosystem since 1000*

20. The compilation of data and subsequent food-web modelling suggest that the relative trophic importance of upper trophic level organisms (fish, seabirds, marine mammals) in the Greater Hauraki Gulf have changed over the period of human occupation, largely as a result of human harvesting (fishing, birding, whaling, sealing) and the introduction of land-based predators. Patterns of trophic importance are indicative of the types of dynamics that may be expected in an ecosystem. Changes to trophic importance of upper trophic levels in the Greater Hauraki Gulf hence suggest that ecosystem dynamics we see in the present day may be different to those that operated in the past. Further work on what effect this may have on emergent properties of ecosystems which are of relevance to management (for example, ecosystem resilience) is required.
21. If the biomass of some groups recover towards former levels it is likely to change the balance of trophic importance in the region. For example, after an absence of nearly 500 years New Zealand fur seals have reappeared in the Greater Hauraki Gulf although biomass is still negligible. Management and policy actions should take into account the effects of possible restablishment and recovery of marine mammals towards historical levels, and trophic modelling of future scenarios is recommended.
22. Over the period of human occupation of the Greater Hauraki Gulf the models predict that there have been quite large changes (11–44%) to the biomasses of middle trophic level groups such as small and large pelagic fishes, macrobenthos, squid, macrozooplankton, and gelatinous zooplankton. These are important prey items for a range of middle and upper level predators, especially fishes, and are likely to be affected by both top-down and bottom-up effects in ecosystems. Monitoring long-term trends in abundance of these middle trophic level groups in the Greater Hauraki Gulf is likely to yield useful data for understanding the dynamics of this ecosystem.
23. The present day food-web model suggests that snapper, benthic macrofauna (mainly small benthic crustaceans and worms) and mesozooplankton have high trophic importance (potentially a keystone role) in the ecosystem of the Greater Hauraki Gulf. Fisheries management should take into account the larger ecosystem effects that may result from further impacting these groups either directly (target species) or indirectly (impacts of bottom gear). Management action which may be considered could include additional data collection to understand or monitor these groups, further modelling to investigate how these groups affect resilience, or reducing direct and indirect human impacts on these groups.
24. Recent changes in phytoplankton production resulting from agrarian and wastewater nutrient input to the Greater Hauraki Gulf study region did not have a substantial effect on lower food web structure in the models. Given that mass-balance modelling such as that used here is functionally simplistic and does not include biogeochemical mechanisms, this result should be treated with caution. A biogeochemical model of the Greater Hauraki Gulf would be useful to investigate this further.
25. Food-web and ecosystem modelling such as the present study can help to quantify the value of ecosystem services (for example, long-term burial rates of carbon; provision of food for fish targeted by commercial fisheries). Quantifying the value of ecosystem goods and services using food-web modelling may be useful to management in balancing economic and ecological use of marine ecosystems.
26. The ecosystem modelling highlighted that the biomass of most benthic invertebrates throughout the Greater Hauraki Gulf study area was relatively poorly known. To further improve the usefulness of this modelling approach to ecosystem management, habitat-stratified survey(s) of benthic invertebrates in the study region are recommended to improve the quality of this information. Within each habitat strata (which should be more detailed than used in the present study), randomly-located transects should measure key information including identification of taxa (not necessarily to species level), abundance (number individuals per $m^2$) and mean weight of individuals (blotted wet weight). There is a particular paucity of data in deep strata (i.e. soft sediments between 40 and 250 m in depth) and a lack of large-scale systematic mapping of invertebrates in shallow strata (intertidal zone).

*Next steps*

27. Knowledge of what happened to New Zealand’s marine ecosystems over the course of human settlement is a required first step to informed ecosystem management. The important next step is to better understand and quantify the risks to the resilience of the marine ecosystem from these historical changes, present day pressures, and likely future scenarios.

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