Changes to *Austrovenus stutchburyi* growth rate since early human settlement in New Zealand: an indication of the extent of human impact on estuarine health

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Abstract

When humans first arrived in New Zealand around 1250AD they started making changes to the environment to make it more habitable. Coastal marine ecosystems such as estuaries are an important link between the land and the sea and are sensitive to changes in environmental conditions such as sediment load and fluxes in nutrients. The New Zealand cockle (*Austrovenus stutchburyi*; tuaki, tuangi), is a filter-feeding bivalve species that is common in estuaries throughout New Zealand. The growth rate of *A. stutchburyi* is recorded as growth bands in the shell and is affected by many factors, including nutrient concentrations and sediment load within the water column. *A. stutchburyi* is consequently well-suited as an indicator species for studying temporal changes in environmental conditions. *A. stutchburyi* was an important food source for early Maori and shells are abundant in middens nationwide. In this study, the growth rates of modern and archaeological *A. stutchburyi* shells were measured to determine how the growth rate has changed through time. By using cockle growth rate as an indicator of estuarine health, we can determine the impact that anthropogenic changes have been having on the health of estuarine environments since the early arrival of humans in New Zealand.

This research analysed growth parameters of *A. stutchburyi* shells from midden sites across a range of environments throughout New Zealand and compared them to modern shells collected from the same localities. Thin sections of shells were prepared, and the width of summer, winter, and annual growth bands were measured between years five and twelve for each shell to determine an average growth rate. Growth rates of shells from different time periods ranging from the 1300’s AD to present were studied.

This study found that there was an overall trend of declining growth rate in shells over time, with no sites showing an increase in growth rate. Shells from sites with the most highly modified catchment areas showed the greatest change in growth rate over time.
(up to a 50% reduction in growth per year), and shells from sites with the least modified catchment areas did not show significant changes in growth rate over time.

*A. stutchburyi* is a culturally important species and is recreationally and commercially harvested within New Zealand. The information gained in this study provides a baseline for the health of estuaries, as indicated by growth rate of cockles, prior to major anthropogenic impacts to the surrounding environment. These baselines can be used to inform future management of *A. stutchburyi* stocks and to aid in the conservation and restoration of estuarine areas.
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Chapter 1 Introduction

New Zealand was Earth’s last major landmass to be colonised only ~800 years ago (Wilmshurst, et al., 2011). When people settled in New Zealand they made changes to the environment to make it more suitable for habitation (McGlone & Wilmshurst, 1999; Schallenberg et al., 2012). For example, approximately three-quarters of native forests were cleared for easier travelling and, later, for agriculture (McWethy et al., 2010). A reduction of habitat and the introduction of predators, such as the Pacific rat (Kiore, Rattus exulans), led to many extinctions in the native flora and fauna (Anderson and McGlone, 1989). Over 30 species of birds were driven to extinction and other species were greatly reduced in number or range (Anderson & McGlone, 1992; Nagaoka, 2001).

Archaeological records for the time period since the first arrival of humans in New Zealand are relatively intact and archaeological sites are easily accessible and have been well studied (Máñez et al., 2014). There is also a good record of climatic conditions from this time period, which makes it possible to distinguish any recent ecosystem changes made by humans from natural changes due to variability in climate (Jackson et al., 2009). Other countries were colonised by humans earlier and therefore have a longer history of anthropogenic changes. Over these longer time periods, it can become more difficult to distinguish human impacts from those of natural changes in climate. Thus, New Zealand provides a unique opportunity to study the long-term impacts of human exploitation of natural resources on ecological processes (McGlone & Wilmshurst, 1999).

Early Maori settlements tended to be located close to the coast. Sheltered environments, such as estuaries, were popular locations for settlements as they provided some protection from the elements and often provided easy access to abundant food supplies (Smith, 2013; Smith & James-Lee, 2010). Marine resources played an important role in supporting early settlers in New Zealand, and an analysis of midden contents excavated from a site at Shag River mouth, an estuarine site in
southern New Zealand indicated that a large proportion of protein consumed by early Maori settlers came from marine sources (Nagaoka, 2001). Initially, there was a reliance on large species, such as fur seals (*Arctocephalus forsteri*) and Moa (e.g., *Dinornis* spp.), but as these resources became more scarce, a reliance on fish and shellfish developed (Kirk, 1989; Nagaoka, 2001). Archaeological middens throughout the country contain remains from shellfish eaten by Maori settlers; analysis of these shells can provide information about the health of estuaries at the time of Maori settlement.

This study used cockle (*Austrovenus stutchburyi*) shells, which are abundant in middens and in estuaries today, as bioindicators to identify the extent to which anthropogenic changes to environmental conditions have affected the health of estuaries (as indicated by cockle growth) since the early settlement of New Zealand.

1.1 Bioindicators

Changes in environmental conditions can elicit a response in the organisms living in that environment. These responses can be measured to provide information about the nature of the change and the effect that the change has had on populations in the area. This is known as using organisms as bioindicators. There are three main applications of bioindicators: to monitor the environment, to monitor ecological processes or to monitor biodiversity. Environmental indicators are species, or groups of species, that respond in a predictable way to environmental disturbance or change (Kennedy & Jacoby, 1999). Ecological indicators are species that are known for being sensitive to stressors, such as pollution or habitat fragmentation, and respond in a fashion that is representative of the community (Holt & Miller, 2011). Biodiversity indicators are taxa that can be used to indicate the species richness of a community (Gerhardt, 2002). Other parameters of biodiversity can also be measured by biodiversity indicators, such as species richness, endemism, genetic parameters and population-specific parameters (Thomas, 1993; Bongers & Ferris, 1999; Gerhardt, 2002; Dzikowski et al., 2003). Bioindicators are commonly used in studies of estuarine health, with a range of species being used including zooplankton, shellfish and echinoderms, as well looking
at community structuring (Wilson, 1994). The growth rate of *A. stutchburyi* is affected by many factors, including nutrient concentrations and sediment load within the water column (Marsden, 2004; Norkko et al., 2006). *A. stutchburyi* is consequently well-suited as an indicator species for studying temporal changes in environmental conditions.

1.2 Drivers of environmental change

Prior to human arrival in New Zealand (ca. 800 yr BP), forest covered approximately 90% of the entire land area (McGlone, 1989). There is substantial evidence for rapid deforestation from anthropogenic burning for 400 years after the first arrival of humans (McWethy et al., 2010; Ogden, et al., 2003). Dry coastal lowland sites were the first to be cleared extensively by burning (McWethy et al., 2010). Tracts of forest were cleared in order to grow edible vegetation such as bracken, to aid in the hunting of Moa, and to make travel easier (Ewers et al., 2006). Before human settlement, fires were a natural occurrence in New Zealand, caused by factors such as lightning strikes (McGlone, 1989). These naturally-occurring fires left evidence to be seen as sporadic charcoal influxes in sediment cores pre-dating human arrival. Naturally-occurring fires can be differentiated from anthropogenically-caused fires, which are manifested as larger continuous deposits of charcoal in sediment cores. The spread of edible plants such as kumara and bracken can also be traced through sediment cores and followed the burning off of lowland forest (McGlone, 1989). Climatic variation over this time was not significant enough to cause such changes to the fire regime (McGlone, 1989; McWethy et al., 2010). By the time the early European settlers arrived in New Zealand, at about 180 y BP, approximately half of the lowland forest had already been cleared (McGlone, 1989). Further deforestation occurred when European settlers converted land for agricultural use (McWethy et al., 2010). As of 2006, the amount of New Zealand land covered in natural forest had declined to only 23% (Ewers et al., 2006).

Following deforestation, soils become less stable and more susceptible to erosion (McGlone & Wilmshurst, 1999). Intentional clearing of land by burning has been linked to subsequent sediment loading of adjacent waterways (Ogden et al., 2003). For
example, sediment cores taken from around Wellington Harbour showed that anthropogenic activities since the arrival of European settlers in 1839 had significantly increased the deposition rate of sediment from watercourses in the area (Goff, 1997). Sedimentation rates in the harbour remained relatively constant from around 5000 y BP until the middle of the 19th century when rates increased to up to six times pre-European rates. The increased rate of sedimentation correlates with the timing of extensive forest clearing around Wellington by European settlers (Goff, 1997). Similarly, a roughly 30-fold increase in sedimentation rate has been documented at Lake Waihola, a coastal lake in southern New Zealand, after its catchment area was converted from forest to agricultural land in the 1850’s (Schallenberg et al., 2012).

Sediment load can have negative effects on the functioning of sensitive environments such as estuaries (Ellis, et al., 2000; Norkko, et al., 2006). Due to their direct connection to river systems, estuaries can be especially at risk of contamination from sedimentation and depleted river water-quality. Increased suspended sediment load in estuaries has been shown to decrease the feeding rate of filter feeders such as the North American clam Mercenaria mercenaria (Bricelj & Malouf, 1989), and the New Zealand horse mussel Atrina zealandica (Ellis, et al., 2002). Increased concentrations of suspended sediment particles may decrease the amount of algal food ingested by filter-feeders, may damage bivalve gills and may cause pseudofaeces production to increase, thus increasing energy expenditure (Ellis et al., 2002), which in turn limits the organism’s growth rate (Ellis et al., 2000). Increased sedimentation coming into estuaries can negatively impact the organisms living in the estuary; it can also cause a shift in the community structure in estuaries due to turbidity modifying microphytobenthos abundances (Pratt et al., 2015). The decline of species that are intolerant to increased sediment (such as Macamona and Austrovenus) may be accompanied by increased abundance of other species such as annelids (Halliday & Cummings, 2012).

Sediment suspended in the water column decreases both the clarity of the water and the depth to which light can penetrate to (Wilber & Clarke, 2001). When less light is
available for the autotrophs in a system, their photosynthetic capacity is reduced, leading to a decrease in the primary productivity of that area (Cloern, 1987). This decrease in productivity can in turn influence the distribution and abundance of phytoplankton (Cloern, 1987) and macroalgae (Tait & Schiel, 2011). Decreasing the depth of the photic zone can also change the stratification of heat in the water column (Wilber & Clarke, 2001). Filter feeders have the ability to remove suspended sediments from the water column; they do so by filtering the sediment and depositing the organic material as faeces and pseudofaeces (Jones, 2011). High concentrations of sediment can be harmful to filter feeders, such as cockles, as sediments clog and damage the organism’s gills (Jones, 2011).

In events such as storms, a higher than usual amount of sediment is deposited into estuaries and coastal ecosystems which can result in a layer of sediment building up that smothers the underlying sediments. In such cases, the underlying sediment turns anaerobic and organisms living in the sediment can be suffocated (Peterson, 1985; Norkko et al., 2002; Norkko et al., 2006). Sediment deposits thicker than 2cm have been observed to completely defaunate intertidal sandflats. Norkko et al. (2006) carried out field and laboratory experiments to test the effect of increased sedimentation on the health of *A. stutchburyi* and *Paphies australis* (Norkko et al., 2006). The results of this study showed that *A. stutchburyi* were tolerant to temporary increases in turbidity and sedimentation. This tolerance is possibly because *A. stutchburyi* occur in a wide range of habitats and have thus adapted to a wide range of environmental conditions (Norkko et al., 2006; Thrush et al., 2003)). However, Norkko et al. found that continued long-term sediment input negatively affected their physiology (Norkko et al., 2006).

Changes to land use in the areas surrounding estuaries can increase the nutrients flowing into the estuary. Increases in nitrogen and phosphorus from agricultural run-off can also affect the ecological processes of estuaries. The species composition of phytoplankton and macroalgae can change when excess nutrients are added to estuaries (Munkes, 2005; Paerl, 2006; Smith et al., 1999), resulting in a shift of species
composition to taxa that may be harmful or inedible. Nitrogen and phosphorus are often limiting nutrients in estuaries and are common components of agricultural fertilisers. Runoff from surrounding agricultural land can carry increased amounts of nitrogen and phosphorous into estuaries and under the right conditions can lead to toxic algal blooms (Smith et al., 1999). Some algal blooms can be deadly to fish and shellfish species. Excessive concentrations of nutrients can lead to a rapid increase in the growth of phytoplankton. If this phytoplankton is not taken up into the food web it can settle to the estuary bed where it is then decomposed by bacteria; an hypoxic state can form as the result of the process of the bacterial decomposition (Paerl, 2006; Rick & Lockwood, 2013). The Greifswalder Bodden, a 510km² estuary on the German Baltic coast, has been affected by increased inorganic nutrients coming into the estuary (Munkes, 2005). Nutrient levels increased significantly between 1950 and 1990 because of increased urban and agricultural development in the catchment of the estuary (Munkes, 2005). Increased nutrients enhanced the pelagic productivity of the estuary, which in turn increased the turbidity of the water thus decreasing the depth that light could penetrate to (Munkes, 2005). The increase in turbidity led to a phase shift from a macrophyte dominated system to a phytoplankton dominated system (Munkes, 2005). Similar effects can be seen with increased nutrient inputs to freshwater lakes. Nutrient loading into previously pristine lakes causes previously clear water to become turbid once a nutrient concentration threshold is passed (Scheffer et al., 2001). Increased turbidity of the water leads to a disappearance of submerged plants and an associated loss of animal biomass (Scheffer et al., 2001).

Metal contaminants can also be major pollutants of estuarine systems. Abrahim and Parker (2008) investigated the concentrations of the pollutants Cu, Pb, Zn and Cd, in the Tamaki Estuary, Auckland, New Zealand. They analysed sediment cores taken from the estuary and compared modern and pre-human metal concentrations in the sediment core and found that the current metal concentration has increased four-fold in the upper layers of the sediment core when compared to pre-human levels of metal accumulation in sediment (Abrahim & Parker, 2008).
1.3 **Shifting baselines**

Deforestation, sedimentation, pollution and eutrophication can combine to cause synergistic changes to the coastal ecosystem. These changes occur over a long period of time and sometimes the effects cannot be seen until well after the impacts started. Before we can fully understand the magnitude of anthropogenic change, however, we must first be able to provide a natural baseline for what an ecosystem was like prior to any anthropogenic changes (Dayton et al., 1998). The current baseline that we have for an area based on historical records or from past accounts, may not fully represent the state of that area before human impacts; it may represent a less modified state but not the natural, unmodified state (Duarte et al., 2009). Fisheries provide a good example of such shifting baselines. Each generation of fisheries scientists and fishermen have a baseline of what the condition of the fishery was like at the start of their career and any changes away from this state are perceived over the course of their career (Klein & Thurstan, 2016; Pauly, 1995). The initial baseline they have is not necessarily the natural baseline for the fish population but instead may represent an already degraded ecosystem (Klein & Thurstan, 2016). Knowledge about the historic state of marine ecosystems is often based on anecdotal accounts from previous generations and over time, knowledge of the true state of past ecosystems is lost (Pauly, 1995).

Coastal systems are naturally highly variable in both space and time at an ever-increasing hierarchy of scales. Subject to daily, seasonal and inter-annual fluxes in the processes that define them, it is still useful however to define baselines that, to the best of our knowledge, quantify the state of a virgin ecological system, within the bounds of its ever-present natural variability. These baselines enable a birds-eye view of an ecosystems trajectory over time, to understand past changes to ecosystem processes and to provide a target for future ecosystem restoration (Klein & Thurstan, 2016; Lotze et al., 2006). Due to the relatively short history of human settlement in New Zealand, we have an opportunity to be able to determine natural, close to pre-
human baselines of ecosystems, something that is difficult in other parts of the world with longer settlement histories (Orton, 2016). Archaeological material from deposits from early human settlement in New Zealand can be used to inform ecosystem baselines as close to pre-human conditions as possible. Studying changes in growth rates of the key estuarine species, *Austrovenus stutchburyi*, over time, using modern and archaeological material allows us to make inferences about the natural state of estuaries throughout New Zealand, before widespread human settlement, and how they have changed as humans arrived, and until now.

**1.4 Study species**

The New Zealand cockle (*Austrovenus stutchburyi*), also known as tuaki, tuangi, or the littleneck clam, is a filter-feeding bivalve species, commonly found in soft sediment estuaries throughout New Zealand. *A. stutchburyi* are often found in beds of high densities; >4000 individuals per square meter have been recorded (Larcombe, 1971). They make up a large proportion of the biomass of an estuary and are therefore a key species in estuaries throughout New Zealand. Along with other filter feeders, they play an important role in linking primary producers with higher trophic level species. Their growth rate is highly variable, driven by environmental conditions such as temperature, salinity and food availability (Marsden, 2004). The plastic nature of their growth rate makes cockles an ideal species for studying the health of the estuarine environments in which they live. Furthermore, cockles were an important food source for early Maori and their shells are abundant in middens nationwide (Smith & James-Lee, 2010); this makes it possible to compare modern and archaeological cockle shells to investigate how growth rate, and thus estuarine health, has changed over time.

The shell of *A. stutchburyi* consists of calcareous and organic elements arranged in a highly organised fashion (McKinnon, 1996; Sheppard, 1985). Shell growth is controlled by the mantle. Calcium, calcium carbonate and carbon dioxide pass through the mantle into the extrapallial fluid. Crystals of calcium carbonate are formed in the extrapallial fluid between the inner shell surface and the mantle. These crystals orient and grow on an organic matrix excreted by the mantle
The shell of *A. stutchburyi* is made up of three layers: the outer periostracum which is uncalcified, and the middle and inner layers which are calcified.

Growth increments are visible on the shell of *A. stutchburyi* as ridges that traverse the width of the shell. Each growth increment is made up of two layers, a layer of calcium carbonate and a lamina of conchiolin. Conchiolin is an organic material and a layer of it corresponds to an interruption in calcification. The increment boundary is created by the onset of calcium carbonate deposition (Sheppard, 1985). Studies have shown that calcification ceases when the shell’s valves are closed. Valve closure is controlled by environmental factors such as temperature and shell exposure (McKinnon, 1996; Sheppard, 1985). *A. stutchburyi* shows two types of growth increments: macroincrements and microincrements. Macroincrements are associated with annual growth and consist of a wide band of opaque shell that corresponds to a period of rapid growth (summer), followed by a thin translucent band that corresponds with a period of slower growth (winter) (Figure 1.1). Each translucent band is associated with a notch at the outer surface of the shell (McKinnon, 1996). Microincrements are increments within the macroincrements that in *A. stutchburyi* are associated with daily tidal patterns (McKinnon, 1996). This study will focus on the macroincrements of *A. stutchburyi* to determine whether there has been change in the annual, summer or winter growth rate over time.
Transplantation experiments have shown that cockle growth rate is highly variable and is correlated with the distance from the mouth of the estuary and the distance from the low tide line (Dobbinson et al., 1989). A gradient in growth can be found along an estuary with the mean size of *A. stutchburyi* increasing from high to low tide levels and the mean size and growth rate decreasing as the distance from the entrance to the inlet increases (Irwin, 2004; Larcombe, 1971). This growth gradient is thought to be due to variable salinities throughout the estuary. Closest to the entrance of the estuary, salinity levels are greatest but they decline along the estuary as freshwater mixes with the saline water and exposure decreases (Tanabe, 1988). Growth rates can also be variable between different estuaries (Tanabe, 1988), and can vary depending on the temperature (Green, 1973) and thus latitude (McKinnon, 1996). Weather patterns can also influence growth of the shell. House and Farrow (1968) found that storms and gales could cause a cessation of growth of the European cockle, *Cerastoderma edule*, for the duration of the bad weather. The most likely reason for the
cessation in growth during storm events is high concentrations of sediment becoming resuspended when water conditions are rough. Also, storm events are often associated with a period of decreased temperatures. If water temperatures drop below the species’ minimum growth temperature then growth will (temporarily) cease.

1.5 Objectives of study

In this study, archaeological and modern shells of *Austrovenus stutchburyi* were compared to measure whether cockle growth rates have changed since humans arrived in New Zealand. Thin sections of cockle shells were analysed to compare rates of summer, winter and annual growth for the time since early human settlement in New Zealand to present day. A range of sites were chosen throughout New Zealand that cover a range of environmental conditions and form a scale from highly anthropogenically modified areas to areas with little anthropogenic impact. Modern shells were collected from each site for comparison with archaeological material. Understanding if and when cockle growth rate has changed since people arrived in New Zealand will help to develop a baseline for the original ecological condition of New Zealand estuaries and provide valuable information on the current scale of human impact on estuarine health.
Chapter 2 Study locations

2.1 Overview of New Zealand occupation

The first Polynesian settlers in New Zealand (ca. 1250AD) initially exploited large bird species, such as Moa, which were abundant at the time of early settlement. As these food sources became scarce or extinct, settlement patterns changed (Wilmshurst et al., 2011). In the subtropical/warm temperate north, horticulture became important and kumara and taro were cultivated, allowing for permanent settlement (Belich, 1996). However, in the cool temperate south, conditions were too harsh for these plants to flourish and wild plants such as bracken and cabbage tree were readily-available carbohydrate-rich food sources. In the South Island, in the Early Maori period (ca. 1250-1450AD), small villages were established and occupied briefly close to abundant resources of food (Anderson & Smith, 1996). As these resources ran out due to overexploitation a period of transience, the Middle Maori period (ca. 1450-1650AD), began. However, by the Late Maori period (ca. 1650-1850AD), more permanent settlements appeared again (Anderson & Smith, 1996).

New Zealand was first discovered by Europeans in 1642 by Abel Tasman, but it wasn’t until James Cook’s expedition in 1769 that it was explored in detail. The first European visitors to arrive were whalers and sealers, who made New Zealand a regular part of their routes in the early 1800’s, starting with small numbers of whalers and traders. In the 1830’s the number of European settlers living in New Zealand increased rapidly to approximately 2000 and farming became increasingly popular. Gold discoveries in Otago and Westland in the 1860’s led to a further rapid increase in the population (Hawke, 1985). By 1881 the European population in New Zealand had grown to 500,000 (Belich, 1996). Today the NZ population stands at 4.7 million, with 15% of Maori extraction (Stats NZ, 2013).

During the course of human arrival and consequent settlement in New Zealand, many changes were made to the environment to make it more suitable for habitation,
including burning, planting, construction, and roading (McGlone & Wilmshurst, 1999; McWethy et al., 2010; Perry et al., 2012; Schallenberg et al., 2012). Land-use practices such as forestry, farming, and urban development have also resulted in significant environmental change.

### 2.2 Study Site Selection

Six locations around New Zealand were chosen for this study. The study locations are spread throughout the country, representing areas with differing historical settlement patterns and covering a range of current environmental conditions, in part related to the different latitudes/climates of the sites. Also, some parts of New Zealand have been more heavily impacted by human settlement and development than others. The sites chosen for this study reflect a range from highly impacted and modified areas (Opoutere, Shag River Mouth) to those that have been subject to little human impact (Chalky Inlet).

In order to be suitable for this study, each site met all of these criteria: 1. archaeological material available from confidently radiocarbon dated midden deposits containing cockle (*Austrovenus stutchburyi*) shells; 2. archaeological collections with large numbers of intact cockle shells (because the study is destructive); 3. Living cockle population accessible for collection. The six locations chosen for this study are described below along with a brief history of the area.

Radiocarbon dating information for archaeological material was scrutinised and selected using protocols outlined by Smith (2010) and particular attention was given to sample suitability criteria, with those not meeting these criteria excluded from consideration. Multiple dates for a stratigraphic context were tested for significance of difference and, if indistinguishable, a pooled mean age was calculated (Ward and Wilson, 1978). Dates were calibrated with Calib 7.1, using the SHCal3 calibration curve for terrestrial samples, and the Marine13 calibration curve for marine samples with Reservoir correction set at -7±45 (Smith, 2010). Periodisation of sites follows dates set out in Smith (2010).
2.3 Study Locations

2.3.1 Opoutere

Opoutere (-37.109°, 175.879°) is a small community located on the eastern side of the Coromandel Peninsula, adjacent to the Wharekawa Harbour (Figure 2.1). The Wharekawa Harbour is a tidal inlet where the Wharekawa River flows into the Pacific Ocean. A sand spit at the mouth of the harbour partially blocks the inlet from the open ocean.

Figure 2.1 Map of Opoutere showing location within New Zealand

a. Prior to human occupation

Prior to human occupation of the area, the land directly adjacent to the Wharekawa Harbour was covered in coastal forests composed of pohutukawa, puriri, and kohekohe, typical of the Coromandel Peninsula (King & Morrison, 1993). Dense tracts of Kauri forest covered most of the rest of the catchment area as well as patches of
Rimu-Tawa-Kamahi forest in the upland areas (Landcare Research, 2016) (Figure 2.2A). Within the Harbour, cockles and flatfish were abundant, whereas outside of the harbour crayfish, pipi and mussels were present. Kingfish, kahawai and snapper were numerous in the open waters just beyond the harbour (King & Morrison, 1993).

b. **Maori Occupation**

The earliest known settlers in the Opoutere area were in the tribe Ngati Hei of the Arawa waka (canoe). There is evidence that there were a number of settlements around the shores of the Wharekawa Harbour (King & Morrison, 1993; Green, 1959). Defendable pa (fort) sites were located on the southern headland of the harbour at Ruahiihihiwi and on the high volcanic bluff Maungaruawahine (King & Morrison, 1993). Middens around the estuary indicate that the main attraction to the area was the abundant seafood (King & Morrison, 1993). Analysis of midden remains excavated by Furey in 2008 show a reliance on cockle, pipi and tuatua (Furey, pers. comm., May 2016). The area was periodically settled from the 1400’s to the 1900’s by Maori (Furey, pers., comm., May 2016). During the years before European contact, Maori used the area for fishing, collecting shellfish, and hunting birds, but also, they would have cleared patches of bush, extending only as far as 1km inland from the harbour, to make way for gardens (O’Donnell, 2009).

c. **European Occupation**

European settlement of the Wharekawa area began in the 1870’s and by this time only one Maori family lived in the area (King & Morrison, 1993). The earliest European settlers in the area were prospectors in the 1870’s and 1880’s. A number of major gold strikes were made around Wharekawa which prompted the opening of several mines in the 1890’s (King & Morrison, 1993). In the 1890’s fires in the district burnt tracts of forest in the area and shortly after this timber merchants started felling trees in the catchment area. The trunks of the felled trees, mainly Kauri, were floated down rivers to the Wharekawa Harbour (King & Morrison, 1993). By the 1900’s there was a community of around 50 people living in the area. The felling of the forests and later the decline of the Kauri gum industry in the 1920’s caused the Opoutere village to
decline in size (King & Morrison, 1993). With the native forest cleared, land in the area was converted for agriculture and in some areas, exotic pine plantations were started (King & Morrison, 1993; O’Donnell, 2009).

**Figure 2.2** Catchment area of the Wharekawa Harbour. A inferred vegetation cover prior to human arrival in the area and B current vegetation in the area (adapted from Landcare Research, 2016).

d. **Current Setting**

The Wharekawa River catchment drains a total area of 100 km². The sides of the catchment are steep, and the terrain is rugged in areas. Plantation forests cover 52% of the total catchment area, with indigenous forest and scrubs covering 35% of the area (O’Donnell, 2009). A further 12% of the catchment is covered in grassland and used for farming (Figure 2.2B) (O’Donnell, 2009). The catchment of the Wharekawa Harbour is part of the Hauraki volcanic area and the geology is dominated by Whitianga group, late Miocene to Pliocene-aged (11-1.8 million years ago), lithic and pumice-rich ignimbrite and local rhyolitic and obsidian-rich pumice and breccia deposits (Edbrooke, 2001) with Jurassic Greywacke as a basement rock (O’Donnell, 2009). Observed erosion in the catchment is mainly negligible (<0.5% by area) but patches in
the headlands of the Wharekawa River are classified as having slight (0.5-2% by area) or moderate (2-5% by area) erosion severity (Landcare Research, 2016).

Opoutere has a warm-temperate climate with an average annual temperature of 14.8°C. The area has an average annual rainfall of 1850 mm.

The Wharekawa estuary is a shallow subtidal estuary covering an area of approximately 2.5 km² with 90% of the area being intertidal. Vegetation covers between 40-60% of the intertidal area including seagrass and mangroves and exotic invasive species (O‘Donnell, 2009). The Wharekawa Harbour and environs support a wide range of animal life: flounder live in the estuary and parore, kahawai and mullet come into the estuary at high tide. Shellfish, especially cockles, are still abundant in the intertidal area (King & Morrison, 1993; O‘Donnell, 2009). The sandspit at the mouth of the harbour is an important breeding ground for the banded dotterel and the variable oystercatcher (Dowding, 2013).

Currently, the Wharekawa Harbour is used recreationally for fishing, boating and kayaking and the surrounding area is used for tramping and camping. At Opoutere there is a camping ground and a primary school with a roll of approximately 100 students. There are important cultural and historic sites in the Wharekawa area. People in the Opoutere community are conscious of the impacts that various land uses in the catchment area have on the health of the harbour and have been working with Environment Waikato to monitor and manage the health of the harbour (O‘Donnell, 2009). The community has a strong environmental focus and have actively fought against plans to develop the Wharekawa area further.

In this study, the Opoutere site provides a warm-temperate location with a moderately modified catchment area that has historically been subjected to much environmental degradation.
e. Cockle collection sites

In May 2016, 60 live cockles were collected from the Wharekawa Harbour, near Opoutere with 20 cockles from each of three sites (Figure 2.3). Sites were chosen along a gradient according to decreasing proximity to the mouth of the inlet and were chosen to reflect differing growing conditions for the cockles. Cockles collected at the outer site were collected adjacent to where the midden is located.

Figure 2.3 Satellite image showing modern sampling locations in the Wharekawa Harbour and the location of the archaeological site.

f. Archaeological material

Archaeological material for this site was provided by Louise Furey, curator of archaeology at Auckland Museum. The archaeological site at Opoutere (T12/20) is located on the sand spit at the mouth of the Wharekawa Harbour. Four column-samples of the site were excavated in 2008 which revealed ten layers of shell midden (Figure 2.3), which date from the 1400’s to 1900’s (Mason, 2009). The midden remains indicate that the site was used as a shellfish processing factory which people returned to summer after summer (Furey, pers. comm., December 2015). There were three radiocarbon dates taken from marine shells from this site. Radiocarbon dating for layer two gave an age of 780 ±35 yBP (Furey, pers. comm., May 2016), when calibrated using
the Marine13 calibration curve with Reservoir correction set at -7 ±45 y (Smith, 2010) gives a mean date of 1528 AD. Radiocarbon dating was also carried out on shells from layers three and eight. The dates were statistically indistinguishable from each other and gave a pooled mean age of 883 ±24 \text{yBP} (Furey, pers. comm., May 2016), which when calibrated gave a mean date of 1445 AD. The shells used in this study came from layers three, six and ten of the midden. Based on the three radiocarbon dates for this site, we can infer that samples from layer three and layer six are both from around the boundary of the Early and Middle Maori periods (ca. 1400-1500AD) (Smith, 2010). Layer six is older than layer three but is from the same time period. Layer 10 is older by an unknown amount but can be assigned to the Early Maori period (Smith, pers. comm., April 2017).
2.3.2 Shag River Mouth

The Shag River mouth (-45.474°, 170.811°) is located approximately 70km north of Dunedin City along the east coast of the South Island of New Zealand (Figure 2.4). The Shag (Waihemo) River, which has its catchment in the Kakanui range, flows into the Pacific Ocean through a valley constrained by Shag Point in the north and the Palmerston hills to the South. At the mouth, the river widens out into a large open estuary which is partially blocked off from the ocean by a sand dune system.

![Map of Shag River mouth showing location within New Zealand](image)

**Figure 2.4** Map of Shag River mouth showing location within New Zealand

a. Prior to human occupation

Prior to human occupation in the area, the land surrounding the Shag River and its estuary (Figure 2.5A) were covered mainly in large dense tracts of podocarp forest (Allen, 2015). Immediately surrounding the river mouth was an area of scrub and fernland (Boyd et al., 1996). The forest and scrubland supported now-extinct birds such as moa and the New Zealand quail (Allen, 2015). The inlet itself supported abundant populations of shellfish such as cockles, blue mussel, and pipi. The estuary
was a feeding and nesting ground for shorebirds and water birds of many kinds (Smith and James-Lee, 2010). There was a large seal rookery at Shag Point (Allen, 2015).

b. Maori occupation

The sand dune area at the mouth of the Shag River was settled by Maori in the 1380’s and occupied for a period of up to 50 years according to radiocarbon dating of archaeological material excavated from the dunes. The site supported a village of around 100 to 200 people which may have been used as a base camp for a more extensive settlement system in the surrounding area (Allen, 2015). Analyses of the faunal remains found within the middens show an early reliance on high-protein, large, hunted species such as fur seals and moa. This diet was later replaced by a reliance on fish and shellfish (Kirk, 1989; Nagaoka, 2001). The change of food source indicates the decline of large resources (such as moa and fur seals) and is a possible reason that the site was abandoned after about 50 years of occupation (Anderson & Smith, 1996).

During the course of Maori occupation of this site some of the surrounding Podocarp forest was cleared, perhaps to make way for carbohydrate-rich plants such as bracken and ferns. An increasing saltmarsh area has also been noted (Allen, 2015) so that this area had become a partially deforested landscape by the time of European arrival.

c. European occupation

After European arrival in New Zealand in the 1840s, a small settlement was established at Shag Point which included a school, a hotel and a general store (Cyclopedia Company Limited, 1905). A coal mining operation began in 1863; it was the first coal mining operation in New Zealand. The mine peaked in 1880 producing 36,000 tonnes of coal annually with approximately 170 workers before closing down in 1934 (Cyclopedia Company Limited, 1905; Churchman and Hurst, 1991). Currently, only a small number of holiday houses remain at the site.
Figure 2.5 Catchment of the Shag River mouth estuary (indicated by black oval). A inferred vegetation prior to human arrival in the area and B current vegetation cover in the area (Adapted from Landcare Research, 2016).

*d. Current setting*

The Shag River catchment drains a total area of 550 km² (Otago Regional Council, 2014). The catchment area includes steep mountain ranges, gently rolling hills and valley flats (Goldsmith & Ryder, 2005). The geology of the upper catchment consists of sandstone with areas of igneous rock and the lower catchment consists of alluvial deposits and marine and non-marine sandstone and siltstone (Forsyth, 2001). For most of the catchment observed erosion severity has been recorded as slight (0.5-2% by area) (Landcare Research, 2016).

Most of the catchment for the Shag river is classified as a cool-dry climate, with a mean annual temperature of less than 12 °C and mean annual rainfall of less than 500 mm. The open ocean temperature at Shag Point ranges between a low of 7 °C and a high of 15 °C with the highest temperatures seen in mid-February (late summer) and the lowest temperatures usually seen at the start of August (mid-winter). The Shag River water temperature is similar; on average, the water temperature in the river ranges between 5 °C and 16 °C but has been recorded as high as 25 °C (Olsen, 2014).
The Shag River estuary covers an area of approximately 1.3 km², mostly very shallow mudflats exposed at low tide, incised by a 1 m-deep (at low tide) channel that narrows around the sand spit. There are cockle beds in sandy sediments throughout the estuary, with the highest densities found alongside the channel (pers. obs., 2016).

The majority of the land in the Shag River catchment is now used for agriculture with small sections of exotic forestry (Figure 2.5B). Additionally, Oceana Gold operates an extensive open cast and underground gold mining operation in part of the catchment area. There are a few holiday homes at Shag Point.

For this study, the Shag River site provides a cool-temperate location with modified catchment land use.

*e. Cockle collection sites*

In March 2016, 60 live cockles were collected from Shag River Mouth. The cockles were collected from three sites on the estuary (Figure 2.6) along a gradient of distance from the mouth of the inlet. Sites were chosen to reflect differing growing conditions for the cockles.
The midden site at Shag River Mouth (J42/3; Figure 2.6) was excavated between 1987-1989 (Anderson et al., 1996). This site is one of the most extensively dated archaeological sites in New Zealand; 35 admissible radiocarbon dates were reported by Anderson et al. (1996). These dates show that all areas and layers of the site were occupied during a relatively short period of time in the 14th century. The best estimate of age for this site is based on 14 admissible charcoal dates which were statistically indistinguishable and give a pooled mean age of 620 ±13 yBP. When calibrated this gives a mean date of 1389 AD indicating that the site belongs in the Early Maori period (Anderson et al., 1996).
2.3.3 Warrington

Warrington (-45.714°, 170.589°) is a small township located approximately 16km north of Dunedin (Figure 2.7). It is situated on the north-east corner of Blueskin Bay, a tidal estuary with an area of approximately 6.9km². The townships of Doctors Point, Waitati and Warrington are located around the bay and Waitati River and Carey’s Creek both flow into the bay.

![Map of Warrington and Blueskin Bay showing location within New Zealand](image)

Figure 2.7 Map of Warrington and Blueskin Bay showing location within New Zealand

a. Prior to human occupation

Prior to human occupation, the land surrounding Warrington and Blueskin Bay was covered mainly in large dense tracts of podocarp-broadleaf forest (Landcare Research, 2016). Wetlands covered the area adjacent to Carey’s Creek (Figure 2.8A) (Landcare Research, 2016). The inlet and surrounding environs supported abundant shellfish,
such as cockles, oysters, and pipi, also eels, flounder and whitebait (Church et al., 2007).

b. Maori Occupation

Over the course of Maori occupation in Otago, there were a number of semi-permanent settlements in the Blueskin Bay area (Church et al., 2007), as evidenced by archaeological sites found at numerous places around the bay, including the Warrington sand spit, Evansdale, Waitati, Doctors Point and Rabbit Island (Church et al., 2007).

The archaeological site on the Warrington Spit is the most extensive of the sites in the area, covering at least two hectares (Church et al., 2007). There are multiple layers to the archaeological site which provides evidence that the site was occupied intermittently over a sustained period of time (Allingham, 1988). Radiocarbon dating of shells from different layers reveal that the site was occupied between 1329 AD and 1745 AD (Allingham, 1988). There is evidence that, during the early occupation of the site, a wide range of moa species were hunted locally and butchered onsite. Sea mammals, fish and shellfish were also important food sources (Church et al., 2007). Further along the spit, erosion has exposed evidence of ovens and shell middens.

c. European Occupation

By the time European settlers arrived in Otago, Blueskin Bay was no longer occupied. Instead, there was a major settlement nearby at Purakaunui (Church et al., 2007). With the increasing settlement of Dunedin in the mid 1800’s, Blueskin Bay was one of the last remaining areas that was still covered with intact native forest (Church et al., 2007). Rimu, matai, miro and broadleaves made up the dense tracts of forest surrounding the bay. Cedar (Libocedrus bidwillii) and Hall’s totara grew on the upper slopes of the surrounding hills and manuka, kanuka and flax grew on the lower slopes (Church et al., 2007). In the 1860’s and 1870’s tracts of land in the lowland areas around Blueskin Bay were cleared for growing crops and farming (Church et al., 2007). Most of the early Europeans living in the area around Blueskin Bay relied on farming and clearing of
forest land for timber as their main sources of income (Church et al., 2007). Fishing in Blueskin Bay was popular, especially for oysters in the channel on the Warrington side of the estuary (Church et al., 2007). In 1868 a tsunami, caused by an earthquake near Chile, shifted sediments and caused the oyster beds to be almost completely buried (De Lange & Healy, 1986; Church et al., 2007). Abundant fish, especially flounder, were fished in the bay. From the 1860’s to the 1880’s a flax mill operated at Blueskin Bay (Church et al., 2007). The Blueskin Bay area became increasingly popular for Dunedin residents for fishing, shooting and holidays.

Figure 2.8 Catchment area of Blueskin Bay. A inferred vegetation cover prior to human arrival in the area and B current vegetation cover in the area (adapted from Landcare Research, 2016).
d. Current Setting

The Waitati River and Carey’s Creek both flow into Blueskin Bay. Carey’s Creek results from a confluence approximately 3.5 km upstream from Blueskin Bay. The north branch flows through sheep and beef farmland and pine plantations (Otago Regional Council, 2008) for 8.5km. The south branch of Carey’s Creek flows through areas of indigenous forest starting 6.5 km upstream. The combined total catchment area of Carey’s Creek is 33 km$^2$ (Otago Regional Council, 2008), constrained by the Silverpeaks range to the west and by Kilmog Hill to the east. The Waitati River flows 5.5km from Swampy Summit to Blueskin Bay, constrained to the east and south by Mount Cargill and to the west by Swampy Summit and Double Hill. The Waitati catchment covers a total area of 46 km$^2$, consisting of steep river valleys. The upper catchment is dominated by native podocarp-broadleaf forest as well as pine plantations (Otago Regional Council, 2008). The lower catchment is predominantly used for farmland; mainly sheep and beef farming (Figure 2.8B) (Otago Regional Council, 2008).

The observed erosion in most of the catchment is slight (0.5-2% by area). The sandspit at Warrington and an area on the Kilmog Hill have moderate (2-5% by area) observed erosion severity (Landcare Research, 2016).

Warrington and the Blueskin Bay area have a temperate climate with an average year-round temperature of 10.9 °C. The temperatures are highest in January (mid-summer), with an average temperature of 15.4 °C and lowest in July (mid-winter), with an average temperature of 5.7 °C (Climate-Data, 2017). The area has an average annual rainfall of 710 mm.

The area immediately surrounding Blueskin Bay has been modified by human activities. There are residential settlements around the bay at Warrington, Waitati, Evansdale and Doctors Point, with additional houses scattered in between these settlements. The settlements of Warrington and Waitati have a combined total population of approximately 1000 people (Statistics NZ, 2013). Recently there has been
a move away from dairy farming in the Blueskin Bay area to smaller lifestyle blocks instead (Church et al., 2007). Currently, Blueskin Bay is used for commercial collecting of cockles, called “littleneck clams” for export, by Southern Clams Ltd. People also recreationally collect shellfish in the inlet. Blueskin Bay falls within the East Otago Taiapūre, which means that the area is under customary management. Within the Taiapūre the recreational limit on shellfish collection (previously 150 cockles per person per day) is reduced to 50 cockles per person per day. The East Otago Taiapūre was set up with the goals of maintaining and enhancing local fisheries for future generations (East Otago Taiāpure Management Committee, 2008). Within the Taiapūre area, recreational fishing is important with cockles being the most harvested shellfish among fishers (McCarthy et al., 2013).

For this study, the Warrington site provides a cool-temperate location with a moderately modified catchment area.

e. Cockle Collection Sites

In October 2016, a sample of 60 cockles were collected from Blueskin Bay, near Warrington. 20 live cockles were collected from each of three sites within the bay (Figure 2.9). Sites were chosen along a gradient according to decreasing proximity to the mouth of the inlet and were chosen to reflect differing growing conditions for the cockles.
f. Archaeological Material

Archaeological material for this site was provided by the University of Otago Department of Anthropology and Archaeology. The archaeological complex at Warrington is located on the sand spit on the Warrington side of Blueskin Bay. Excavations in six different parts of the site were carried out at various times between 1983 and 1989. Material used for this study came from Area A (Allingham, 1986; Allingham, 1988) and Area B (I.W.G. Smith, pers. comm., 2017). Intact material was limited for this site so material was selected from a combination of layers from the same time period, as determined by radiocarbon dates. The combinations of layers are as follows:

Early Maori period – Area B, layers 1b, 1c and 3

Mid Maori Period – Area A, layers 5 and 7; Area B layer 1a
Late Maori Period – Area A layers 1 and 2.

Radiocarbon dating for material from the Early phase involved three dates on marine shells. These shells gave statistically indistinguishable ages and give a pooled mean age of 1047 ±29 yBP. When calibrated using the Marine13 calibration curve for marine samples with Reservoir correction set at -7 ±45 y (Smith, 2010) a mean date of 1329 AD was given, placing these samples in the Early Maori time period (Smith, 2010). Two dates were taken on marine shells from material from the Mid Maori phase. The shells gave statistically indistinguishable ages with a pooled mean age of 920 ±31 yBP, which when calibrated gives a mean age of 1415 AD placing these specimen on the cusp between the Early Maori and Mid Maori time periods (Smith, 2010). Radiocarbon dating was carried out on one shell from the material from the Late phase giving an age of 570 ±45 yBP. When calibrated this gives a probable age of 1745 AD, placing these layers in the Late Maori time period. However, the samples used in this study for the late time period (from Area A layers 1 and 2) were from layers stratigraphically higher than the dated layer so these shells may be younger than the indicated date and therefore they belong to either the Late or Historic time period (I.W.G Smith, pers. comm., 2017).
2.3.4 Purakaunui Inlet

Purakaunui Inlet (Figure 2.10) is a tidal inlet located approximately 8 km north of the Otago Harbour entrance (−45.753°, 170.626°). It covers an area of about 2 km² and is mostly made up of intertidal fine sand flats. The inlet is surrounded by hills on three sides; a sandspit extends across the northern mouth of the inlet. The Purakaunui creek, a small stream, flows into the southern end of the inlet. The stream has its catchment in the hills to the south of the inlet, originating near Mihiwaka. The stream passes through pastoral lands and native bush before flowing into the inlet. After periods of high rainfall, other small streams drain water into the inlet from hills on the east and west sides.

Figure 2.10 Map of Purakaunui Inlet showing location within New Zealand.
a. **Prior to human occupation**

Prior to human occupation in the area, the land surrounding Purakaunui inlet was covered in large dense tracts of forest (Figure 2.11A). (Landcare Research, 2016). Wetlands were present along the western edge of the inlet (Landcare Research, 2016).

b. **Maori Occupation**

Located within the sand dune system at the mouth of the Purakaunui inlet (Figure 2.12) are midden sites from Maori settlement of the area. Excavations in this area were undertaken in 1978 (Anderson, 1981) and once again from 2001-2003 (Barber and Walter, 2001; Barber and Walter 2002). Analysis of midden remains indicate that this site was occupied around 1416 AD (Smith & James-Lee, 2010) and the people occupying the site were reliant on estuarine and hard shore shell fisheries as well as finfish such as red cod and barracouta (Anderson, 1981; Barber and Walter, 2002). Mammal and bird remains were relatively minor components of the middens, suggesting that this site was used as a specialised fishing village (Anderson, 1981; Barber and Walter, 2002).

Palynological studies of charcoal excavated from the midden site at Purakaunui indicate a well-established matai and totara forest surrounded the inlet with understory species such as *Coprosma spp.*, manuka and *Hebe spp.* also being abundant (Allen, 2015). Allen (2015) looked at charcoal from multiple layers of the midden to compare the relative abundance of plant species used as fuel for fires and found that there was little difference in the abundances of different species between the layers. The species burnt as fuel can provide an indication of the types of vegetation surrounding the midden site and changes in fuel type can indicate vegetation changes in the area. Allen (2015) found only small changes to the composition of species used as fuel, indicating that over the time of settlement at Purakaunui there was little change to the vegetation in the surrounding area.

At the northern end of Purakaunui inlet, there is a small peninsula, known as Mapoutahi, that is an important site in Maori history. In the mid 1700’s a fortified pa
(fort) was located at Mapoutahi which was home to approximately 250 Maori settlers (Potts, 2013). The pa was reportedly attacked during inter-tribal Ngai Tahu hapu warfare during this time and most of its occupants were killed. Following this attack, Mapoutahi and Purakaunui were declared as tapu (sacred) areas and were not occupied further until the tapu was lifted in the 1820’s (Anderson, 1981; Potts, 2013).

c. European occupation

After the tapu was lifted in the 1820’s Purakaunui was settled by approximately 20 families from a number of Ngai Tahu hapu (groups) and became the main settlement of the area immediately north of Otago Harbour. The population of the area increased and in the 1830’s there was around 500 Maori living in the area (Church et al., 2007). This village was continuously settled until approximately 1875.

In the late 1830’s a whaling station was set up in the area by the Weller brothers (Anderson, 1981). The station was used for two seasons before being closed down as operations were moved north due to the declining whale numbers in the Otago area (Church et al., 2007). In the 1870’s the area was starting to be settled by Europeans. Manuka bush surrounding the inlet was burned to clear the area for grazing of cattle (Church et al., 2007).
The geology of the area surrounding Purakaunui Inlet consists of strong, volcanic basalt. The western side of the inlet is made up of marine-derived loose sands. The erosion severity of the area ranges from negligible (<0.5% by area) to slight (0.5-2% by area). Purakaunui Inlet is located adjacent to Blueskin Bay, therefore the climate in and around Purakaunui Inlet is much the same as described previously for the Warrington site. The area receives an average of 650 mm of rain per year. Sea water temperatures in the area range between 6° C and 16° C and the mean annual air temperature is 10.9° C.

The Purakaunui Inlet covers an area of approximately 2 km², the majority of which is intertidal sand flats. The Purakaunui stream flows into the estuary. At low tide, water almost completely drains from the inlet, with the exception of a channel that flows from the stream input across the tidal flats to the mouth of the estuary. There are
extensive cockle beds where sandy sediments are located in the estuary.

The hills surrounding the Purakaunui Inlet are covered by a range of vegetation. The majority of the area is grazed farmland but there are corridors of indigenous vegetation that remain (Figure 2.11B). The sand dune system at the northern entrance of the inlet is partially covered by a pine plantation (*Pinus radiata*) and small parts of the catchment also contain forestry blocks. On the eastern margin of the inlet is a small settlement, which is home to approximately 66 permanent residents (Stats NZ, 2013).

For this study, Purakaunui Inlet provides a cool-temperate location with a slight to moderately impacted catchment area.

e. Cockle collection sites

In March 2016, a sample of 60 cockles were collected from Purakaunui Inlet. 20 live cockles were collected from each of three sites within the inlet (Figure 2.12). Sites were chosen along a gradient according to decreasing proximity to the mouth of the inlet and were chosen to reflect differing growing conditions for the cockles.

![Figure 2.12 Satellite image of Purakaunui inlet showing the locations of the modern sampling sites (outer, middle and inner) and the location of the archaeological midden site.](image)
f. *Archaeological material*

The midden site at Purakaunui (I44/21) was excavated on two occasions; first by Anderson in 1978 (Anderson, 1981) and again from 2001-2002 (Barber and Walter, 2002). Archaeological material used in this study were from the later excavations and was provided by the University of Otago Department of Anthropology and Archaeology. Shell samples were taken from material excavated from provenance S-J5-4 Northern baulk. Six marine shell radiocarbon dates were made from this excavation (Smith & James-Lee, 2010). The six dates give statistically indistinguishable ages with a pooled mean age of 920 ±23 yBP. When calibrated using the Marine13 calibration curve for marine samples with the reservoir correction set at -7±45 y this gives a mean date of 1416 AD, placing occupation of the site on the cusp between the Early and Middle Maori periods (Smith, 2010).
2.3.5 Tiwai Point

Tiwai Point (−46.582°, 168.409°) is located near Bluff in Southland, New Zealand. It is an approximately 13 km long peninsula that stretches between Awarua Bay to the north and Foveaux Strait to the south and is separated from Bluff by an approximately 1 km wide channel (Figure 2.13). Awarua Bay, a large tidal estuary, branches off to the east of Bluff Harbour. The bay is 12 km long and covers an area of approximately 20 km².

Figure 2.13 Map of Tiwai Point showing location within New Zealand

a. Prior to human occupation

Prior to human occupation in the area, the land surrounding Awarua Bay was predominantly covered in wetlands (Figure 2.14A and C). Sand dunes covered the entire Tiwai Peninsula and small areas of dunelands existed at the northern end of the Bluff Harbour (Landcare Research, 2016). Parts of the peninsula would have had light podocarp forest cover (Gillies, 1981). To the north of Awarua Bay are the Awarua Plains, covered in extensive areas of wetlands, mostly bogs (Figure 2.14B and D), areas
of fen were also present. The Awarua estuary and its environs supported shellfish such as pipi and cockle, flatfish and abundant bird species.

b. *Maori Occupation*

Located at the end of the Tiwai Peninsula is the Tiwai Point archaeological site (Figure 2.15), excavated in 1968 (Park, 1969). The Tiwai Point settlement was primarily a sealing and stone working camp (Jacomb et al., 2010). Radiocarbon dating of charcoal from the site revealed that the site was occupied around 1344 ±29 AD; thus placing the site in the Early Maori time period (Anderson, 1991). Sutton and Marshall (1980) analysed the faunal assemblage from Tiwai Point and found that seal meat made up over 70% of the meat weight of the diet at the time. Moa contributed to the rest of the meat weight along with other forest and seabirds and a small reliance on shellfish (Sutton and Marshall, 1980). Through analysing the faunal remains from the midden, Sutton and Marshall (1980) also suggested that although the site was small it was intensively occupied and was occupied over a number of seasons.

c. *European Occupation*

European peoples visited Bluff (across the harbour from Tiwai Point) earlier than many other parts of New Zealand. There are reports of whaling and sealing around the Foveaux Strait as early as 1792. A fishing station was set up in Bluff in the 1820s and soon after more settlers arrived and a town was established. Bluff was a popular place for whalers and sealers to settle (Bluff History, 1999).

After the 1840’s, Bluff became an important settlement in the Southland region and a shift occurred from a whaling based economy to a largely agricultural one (Ngai Tahu, 2014). From 1883 until the early 1990’s frozen mutton and lamb were exported overseas from Bluff (Ngai Tahu, 2014). By the 1960’s, the largest exports of frozen mutton and lamb in New Zealand were coming from Bluff port (Ngai Tahu, 2014).
**Figure 2.14** Change in vegetation type (A and B) and wetland coverage (C and D) throughout the Awarua Bay catchment area. Figures adapted from Landcare Research (2016).

*d. Current Setting*

At the 2013 census, the population of Bluff was 1800 people, with 44% identified of Maori descent (Stats NZ, 2013). Bluff and the wider Southland district are reliant on primary production and industries such as dairying, meat processing and the New Zealand Aluminium Smelter (NZAS) at Tiwai Point (Southland, 2017). Fishing is also an important industry in Bluff, with Bluff oysters being a delicacy throughout the country.

The aluminium smelter located at Tiwai Point was established in 1971 and produces aluminium which is then exported internationally (NZAS, 2017). The smelter employs approximately 800 people. The area surrounding the smelter on the Tiwai Peninsula is managed by the Department of Conservation as part of New Zealand’s Conservation Estate and is leased to NZAS (Cromarty, 1996; NZAS, 2017). Public access to the peninsula is restricted and recreational users can only gain access by applying for an
access permit (NZAS, 2017). The Tiwai Peninsula is covered mainly in silver tussock (*Poa cita*) and red tussock (*Chionochloa rubra*) communities as well as areas of flax (*Phormium tenax*) (Cromarty, 1996). To the north of Awarua Bay are the Awarua Plains, an area of extensive peat wetlands (Cromarty, 1996; Clarkson et al., 2011). The peatlands cover an area of approximately 180 km² and are fed by direct rainfall with no major river inputs (Cromarty, 1996). The Awarua Plains wetlands complex is part of the Waituna Wetland Scientific Reserve and is recognised as an area of international importance by the Ramsar Convention (Ramsar, 2014) supporting a high diversity of wildlife. There is private land to the north of Awarua Bay used for agriculture (Cromarty, 1996).

Awarua Bay has extensive areas of seagrass (*Zostera muelleri*) beds (6 km²) and at low tide, 30% of the tidal flats are vegetated (Robertson and Stevens, 2006). Freshwater feeds into the bay via small streams, the largest of which is Muddy Creek flowing into the northeast side of the bay. The bay is mostly shallow with 80% of the bay area being uncovered at low tide (Robertson and Stevens, 2006). Awarua Bay and the surrounding wetlands are popular for bird watching as well as walking, recreational fishing, whitebaiting, and boating and swimming (Robertson and Stevens, 2006).

The area surrounding Awarua Bay and Bluff is classified as having a temperate climate with the highest average temperatures of 13.9 °C in January (mid-summer) and lowest average temperatures of 5.0 °C occurring in July (mid-winter). The area has high annual rainfall with the wettest month (January) receiving an average of 112 mm of precipitation. The driest month is August (late-winter) with an average of 65 mm of rainfall (Climate-Data, 2017). The average sea surface temperature of Bluff is 12.1 °C (Statistics NZ, 2016).

The geology of the area surrounding Awarua Bay is mainly comprised of Holocene to Pleistocene-age (126,000 - <10,000 yBP) marine and non-marine sands and gravels underlain by Neogene-age (23-2.5 Ma) sedimentary rock and lignite beds of the East Southland Group (Turnbull and Allibone, 2003). To the south of Awarua Bay is a series
of quartz gravel dunes which are interpreted to be a historically prograding shoreline of what is now Tiwai Peninsula (Orpin, 1994; Cromarty, 1996). The surficial beach deposits along the Tiwai Peninsula are composed of well-graded sands intermixed with iron stained quartz gravels. The observed erosion severity on the Tiwai Peninsula is slight (0.5-2% by area) and observed erosion on the Awarua Plains in negligible (<0.5% by area) (Landcare Research, 2016).

e. Cockle collection sites

In April 2016, a sample of 60 cockles were collected from Awarua Bay. 20 live cockles were collected from each of three sites within the bay (Figure 2.15). Sites were chosen along a gradient according to decreasing proximity to the mouth of the inlet and were chosen to reflect differing growing conditions for the cockles.

Figure 2.15 Satellite image showing modern sampling locations within Awarua Bay and the location of the archaeological site at Tiwai Point.
Archaeological material for this site was provided by the Southland Museum. The archaeological site at Tiwai Point (Figure 2.15; E47/13) was excavated by Park in 1969 (Park, 1969). Six radiocarbon dates from charcoal from this site have been reported, however, only one meets sample suitability criteria for this study (Anderson, 1991). The admissible radiocarbon dating gives an age of $656\pm 29\text{yBP}$, when calibrated using the SHCal13 calibration curve for terrestrial samples this gives a mean date of 1344 AD, indicating that the site was settled during the Early Maori period (Smith, 2010).
2.3.6 Chalky Inlet

Chalky Inlet (Figure 2.16; -46.039°, 166.599°), located in the south west of New Zealand, is part of Fiordland National Park. The inlet lies between Dusky Sound to the north and Preservation Inlet to the south. Chalky Island is a 5 km² island that shelters the mouth of the inlet. The inlet is approximately 24 km long and halfway towards the head, it branches into two arms, Edwardson Sound and Cunaris Sound. The mouth of the inlet is approximately 10 km wide with Chalky Island situated in the middle of the mouth; the inlet narrows to a width of approximately 3 km by halfway towards the head.

Figure 2.16 Map of Chalky Inlet showing the location within New Zealand
a. Prior to human occupation

Prior to any human occupation in the area, the environment in Fiordland was mainly covered by beech forests with tussock grasslands and herbfields above the treeline (Coutts, 1977; McLintock, 1959; Wardle, 1962) (Figure 2.17A; Landcare Research, 2016). A rich and diverse marine ecosystem was present in Fiordland (Coutts, 1977). Beds of cockles and pipi were found in the estuarine areas of Fiordland (Coutts, 1977).

b. Maori occupation

In general, Maori occupation in Fiordland was seasonal, with Maori coming to Fiordland in late summer and autumn for fishing and sealing expeditions (Begg and Begg, 1973). Maori also travelled to Fiordland to hunt kakapo and for the pounamu (greenstone) which they used to make ornaments (including hei-tiki), tools and weapons (Begg and Begg, 1973). While they were in the area, travellers used mainly marine resources for food. Chalky Inlet was known to Maori as Taiari and within the inlet, there is evidence of multiple groups occupying the area, with 61 archaeological sites having been recorded in the inlet (Smith, 2002). South Port, a small bay branching off the Eastern Passage of Chalky Inlet, contains caves at the northern end that were excavated by Coutts in 1970 (Coutts, 1972). Coutts found lower layers with only Maori artefacts as well as upper layers containing European artefacts, including bone buttons, within the archaeo logical material of the caves which indicates that these South Port sites was occupied from the early period through to the historic period (Coutts, 1972; Smith, 2002). Archaeological material used for this study came from middens in these caves. Maori occupation of Chalky Inlet overlapped with European explorers and sealing gangs arriving in Fiordland in the early 1800s.

c. European occupation

Chalky Inlet was first sighted by Europeans in 1803 when the sealing ship Endeavour was making its pioneering journey around New Zealand. It is likely that Chalky Inlet was visited again the following year by the sealing ship Contest (Begg and Begg, 1973).
Between 1821 and 1824 three shore-based sealing gangs were stationed at Chalky Inlet, though ship-based sealing also occurred in the area (Smith, 2002). In the early 1820’s, Captain Edwardson explored Chalky Inlet in search of flax to sell at the markets in Sydney. While in Fiordland, Edwardson introduced wild pigs to the area (Hall-Jones, 1968). A sealing gang from the General Gates was dropped off at South Port in Chalky Inlet in August 1821; the gang built huts at the head South Port and lived there for 17 months before being picked up by Edwardson (Begg and Begg, 1973). The site where the huts were located became, in 1903, the site of McCallum’s sawmill in South Port (Begg and Begg, 1973; Hall-Jones, 1968).

Figure 2.17 Catchment of South Port of Chalky Inlet. A inferred vegetation cover prior to human arrival in the area and B current vegetation cover in the area (adapted from Landcare Research, 2016).
**d. Current setting**

The Fiordland region is in the latitudes of the prevailing westerly, meaning the main rain-bearing weather systems come from the west. Most of Chalky Inlet receives an average of 2,000-4,000 mm of rain annually. However, parts of the upper catchment receive as much as 6,000 mm of rain in one year (Macara, 2014). Rainfall tends to be consistent throughout the year, occurring approximately 230 days per year (Macara, 2014). Chalky Inlet is located in a temperate region with a mean summer (December to February) temperature of 14 °C and a mean winter (June to August) temperature of 5 °C (Macara, 2014). Sea surface temperature off the coast of Fiordland varies between an average minimum of 11 °C in August and an average maximum of 15 °C in February (Macara, 2014).

The landscape surrounding Chalky Inlet comprises eroded ridges of Ordovician (490-443 Ma) and Carboniferous (360-286 Ma) intrusive igneous rocks with doleritic dikes and sills (Benson & Keeble1935; Turnbull et al., 2010). These are overlain by Cretaceous (144-65.5 Ma) sandstones which are then overlain by a partial cover of Neogene-age (23-2.5 Ma) glacial debris (Turnbull et al., 2010). The beaches on the eastern side of South Port and Lee Bay at the head of South Port are composed of Holocene-age (126,000-<10,000 years before present) alluvial and estuarine sands and gravels (Turnbull et al., 2010). Observed erosion severity in the area is slight (0.5-2% by area) (Landcare Research, 2016).

The natural environment surrounding Chalky Inlet is largely unchanged since early Maori and Europeans visited the area; it forms part of the Fiordland National Park, established in 1952. The inlet is surrounded by dense tracts of podocarp-beech forest with alpine grass and herbfield above the treeline (Figure 2.17B; Landcare Research, 2016). Johnson, however, surveyed the vegetation of Chalky and Preservation Inlets in 1977 and found introduced plant species at locations associated with historic settlements (Johnson, 1977). Introduced deer also have a detrimental effect on the undergrowth of forests and would have been modifying the vegetation of the area.
(Wardle et al., 1973). The south west of New Zealand, an area called Te Wāhipounamu (the place of greenstone), which includes Fiordland, Westland and Aoraki Mt Cook was recognised as a UNESCO world heritage area in December 1990. The area was recognised for its diversity of natural landscapes, the largely unmodified nature of the area and for the relatively intact ecosystems with flora and fauna of Gondwanan origin (World Heritage Convention, 2017).

Many areas of Fiordland, including Chalky Inlet, are accessible only by air or boat, although a backcountry tramping track connects it to Tuatapere via Preservation Inlet. Currently, Chalky Inlet has no permanent residents but is frequently visited by fishermen, hunters and tourists.

For this study, the site in Chalky Inlet provides a temperate location with very little modification to the catchment area and a site far from the impacts of urban areas.

\textit{e. Cockle collection sites}

In October 2016, a sample of 60 cockles were collected from Anchorage Cove in South Port, Chalky Inlet by the crew of the Department of Conservation vessel, \textit{Southern Winds}. 20 live cockles were collected from each of three sites in Anchorage Cove. Sites were chosen based on distance from the entrance to South Port and were chosen to reflect differing growing conditions for the cockles.
f. Archaeological material

Archaeological material for this site was provided by the Southland Museum. The archaeological material from South Port (B45/11) was excavated from a cave located in Anchorage Cove. The site was excavated by Coutts in 1970 (Coutts, 1972). Samples used in this study were taken from Trench B layer 1, spit 3 and from Layer 2, spit 1. Samples are from late prehistoric (ca. 1700’s) to early contact (ca. 1800’s), and layer 2 is older than layer 1 so layer two corresponds to the Historic period and layer 2 corresponds to late in the Late time period (Dudfield, pers. comm., February 2016).

2.4 Summary

All together, the six estuarine locations provide a spectrum of climate, impact, and time (Table 2.1).
Table 2.1 Summary of characteristics of each site used for this study

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Climate</th>
<th>Impacts</th>
<th>Time period (from which shells collected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opoutere</td>
<td>-37.109°, 175.879°</td>
<td>Warm temperate, moderate rainfall</td>
<td>Moderate/High: clearing, burning, agriculture</td>
<td>Modern, Early-Middle, Middle</td>
</tr>
<tr>
<td>Shag River Mouth</td>
<td>-45.474°, 170.811°</td>
<td>Cool temperate, moderate rainfall</td>
<td>Moderate/High: clearing, extensive agriculture</td>
<td>Modern, Early</td>
</tr>
<tr>
<td>Warrington</td>
<td>-45.714°, 170.589°</td>
<td>Cool temperate, moderate rainfall</td>
<td>Moderate: clearing, agriculture, commercial harvesting of cockles</td>
<td>Modern, Early, Mid, Late</td>
</tr>
<tr>
<td>Purakaunui</td>
<td>-45.753°, 170.626°</td>
<td>Cool temperate, moderate rainfall</td>
<td>Moderate: clearing, agriculture</td>
<td>Modern, Early-Middle</td>
</tr>
<tr>
<td>Tiwai Point</td>
<td>-46.582°, 168.409°</td>
<td>Temperate, high rainfall</td>
<td>Moderate: Wetland drainage, aluminium smelter</td>
<td>Modern, Early</td>
</tr>
<tr>
<td>Chalky Inlet</td>
<td>-46.039°, 166.599°</td>
<td>Temperate, high rainfall</td>
<td>Minimal</td>
<td>Modern, Late, Historic</td>
</tr>
</tbody>
</table>
Chapter 3 Methods

3.1 Material

In 2016 a total of 360 cockles (*A. stutchburyi*) were collected from six sites around New Zealand; 60 shells from each site (Table 3.1). The sites, outlined in the previous chapter, were: Opoutere (Coromandel Peninsula), Shag River Mouth (Otago), Warrington (Blueskin Bay, Otago), Purakaunui (Otago), Tiwai Point (Southland) and Chalky Inlet (Fiordland). Archaeological specimens from each site were analysed for comparison with modern specimens. A total of 240 archaeological cockle shells were used (20 shells for each time period for each site).

3.2 Archaeological shell preparation

The archaeological shells provided for this study tended to have the valves separated. In order to make sure that all valves measured were from different shells, each shell valve was compared to all others to identify matched pairs. Where matched pairs of valves were found, the valve in the best condition was used for the study. Archaeological material was also selected based on how intact the shell was. In some cases, the excavated material had an abundance of shells in good condition, in which case the shells in the best condition were chosen. For some sites, however, the archaeological material was in poor condition and excavated material was limited so some broken shells had to be used. In these cases, only shells that were intact from the umbo to the ventral edge along the line of longest growth (Figure 3.1), with no obvious fractures along this line were selected. Archaeological material was often covered in ash and dirt, so shells were cleaned by soaking in warm water and dish soap. They were then gently scrubbed until all dirt had been removed before drying in a drying oven at 35°C. Each shell was then labelled with an identification code, using permanent marker.
Table 3.1 Summary of shell specimen used for this study

<table>
<thead>
<tr>
<th>Site</th>
<th>Modern Shells</th>
<th>Archaeological Shells</th>
<th>Total Number of Shells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Collection</td>
<td>Number of Shells</td>
<td>Time Period</td>
</tr>
<tr>
<td></td>
<td>Site</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opoutere</td>
<td>Inner</td>
<td>20</td>
<td>Early/Mid L1</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>20</td>
<td>Early/Mid L2</td>
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<tr>
<td></td>
<td>Outer</td>
<td>20</td>
<td>Early/Mid L2</td>
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<td></td>
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<tr>
<td>Shag River Mouth</td>
<td>Inner</td>
<td>20</td>
<td>Early L1</td>
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<td></td>
<td>Middle</td>
<td>20</td>
<td>Early L2</td>
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<tr>
<td></td>
<td>Outer</td>
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<td></td>
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<tr>
<td>Warrington</td>
<td>Inner</td>
<td>20</td>
<td>Early</td>
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<td>Middle</td>
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<td>Mid</td>
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<td></td>
<td>Outer</td>
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<td>Late</td>
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<tr>
<td>Purakaunui Inlet</td>
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<td>Early/Mid</td>
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<td>Middle</td>
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<td></td>
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<tr>
<td></td>
<td>Outer</td>
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<tr>
<td>Tiwai Point</td>
<td>Inner</td>
<td>20</td>
<td>Early</td>
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<td>Middle</td>
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<td></td>
<td>Outer</td>
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<tr>
<td>Chalky Inlet</td>
<td>Inner</td>
<td>20</td>
<td>Late</td>
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<td></td>
<td>Middle</td>
<td>20</td>
<td>Historic</td>
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3.3 Modern shell collection and preparation

Three collection locations were chosen at each of the six sites. Cockle growth rate is highly variable throughout an estuary with two major trends: growth rate is lower further from the high tide line and also decreases as the distance to the mouth of the estuary increases (Irwin, 2004; Larcombe, 1971). Collection locations for modern
specimens were chosen at three places on each estuary in order to capture the most variation in growth rates by sampling along a gradient from nearest to the mouth of the estuary to further into the estuary. As it is not known where in each estuary the archaeological shells were collected from, modern shells were collected from three sites throughout the estuary that would likely give the greatest variation in growth rates, in order to capture the most variation in growth rates across the estuary and to minimise any effect of site selective harvesting. Cockle growth rates are highly variable throughout an estuary (Dobbinson et al., 1989; Irwin, 2004; Larcombe, 1971), showing growth gradients based on distance from the mouth of the estuary and distance from the high tide line (Dobbinson et al., 1989; Irwin, 2004; Larcombe, 1971). In this study the distance from the mouth of the estuary was used as a gradient from which modern shells were collected. In order to capture the most variation in growth rates across each estuary, live cockles were collected from cockle beds at three locations ranging in distance from the mouth of the inlet. At each site, living cockles were randomly sampled from an area of no greater than 2m².

At each of the sample sites, 20 living cockles larger than 25mm in length were collected at random. Cockles larger than 25mm in length were selected to target individuals that were older than 10 years old and therefore had reached a period of relatively constant annual growth rates (Irwin, 2004; McKinnon, 1996). Where possible, cockles were killed within 24 hours of collecting by immersing them in hot freshwater (no hotter than 60°C; McKinnon, pers. comm., 2015). Where it was not possible to prepare shells within 24 hours, the live cockles were placed in a refrigerator for no more than three days. It was not practical to freeze shells to process at a later date as freezing can cause the shells to become brittle (McKinnon, pers. comm., 2015). When immersed in hot water the two valves of the cockle shell opened and the tissue was removed. The shells were then washed with warm water and dish soap and placed in a low-temperature drying oven at 35°C for at least 24 hours.

Modern specimens were assigned an identifying number and code relating to the site they were from which was written on both the left and right valve of the shell. Only
one valve of each shell was used in this study but the other was kept in case of damage while sectioning the chosen valve. For each shell, the valve that was in the best condition was used. The two valves of *A. stutchburyi* are symmetrical, so this was not a potential source of error. While the shells were intact, their length from the umbo to the ventral edge at the longest point (Figure 3.1) was measured using digital callipers to the nearest 0.01mm.

![Figure 3.1 Ventral view of *A. stutchburyi* shell. The black line indicates the line of maximum growth along the shell](image)

3.4 Embedding specimens in resin

Fragile shells can be damaged easily in the process of sectioning (Mckinnon, 1996). Initially three thick layers of Selleys Allfix multipurpose glue was spread onto shells but this was too flexible to prevent the shells from breaking during the sectioning process so a harder resin was used instead. Shells were embedded in either Nuplex® K36 epoxy resin or Kleer Kast diamond clear liquid embedding resin, made up according to the manufacturer’s instructions. Both resins were equally suitable for this job. Silicone muffin trays (either 60mm or 45mm diameter) were used as moulds. A thin layer of resin (1-2mm thick) was poured into each mould and left to dry overnight. This layer ensured that all edges of the shell would be completely surrounded by a
layer of resin, so the shell would not sink to the bottom of the mould while the resin was setting. A shell was then placed in each mould and completely covered with resin, (Figure 3.2). Care was taken to avoid air bubbles and the resin was left to harden for at least 24 hours before being removed from the moulds.

![Figure 3.2](image-url) Cockle shell labelled with an identifying number and embedded in resin. View of the top and underside of the shell.

### 3.5 Thin sectioning technique

Thin-sectioning is a simple, inexpensive method that clearly shows the growth structures of *A. stutchburyi* (McKinnon, 1996). Sections can be easily stored and sufficient detail can be achieved by viewing under a standard light microscope (McKinnon, 1996). The thin sectioning method is especially useful for shells with eroded outer layers as the technique looks at the internal structure of the shell. Each resin-coated shell was cut along the line of longest growth using an Isomet© Low Speed Saw with a 0.012mm diamond edged blade. A section of 2-3mm thickness was cut from each shell at a low speed to ensure accuracy of the cut and to avoid breaking the shell. The archaeological shells were, in general, more fragile so a thicker section of 3.5-4mm was cut. The shell section was then wiped clean with a wet cloth, dried and glued onto a glass microscope slide using Crystalbond 509 Mounting Adhesive. The
glued sections were left to cure for at least four hours at room temperature to ensure sufficient adhesion. The section was then reduced in thickness to close to 0.1m, by grinding it down using 120 grit silicon carbide paper. A progression of finer grit papers (800 to 1200 grit) were then used to reduce the section to a final thickness of 0.1mm - 0.2mm or until growth lines were clearly visible when the slide was viewed under a dissecting microscope (Figure 3.3). Sanding was done in a circular motion to minimise deep scratches forming and the section was examined under a dissecting microscope before changing to a finer grit, to make sure that scratches from the previous grit paper had been removed. Once the desired thickness and clarity of bands was achieved, the shell section was polished using 0.5µm alumina polishing paste and the section was viewed again under a dissecting microscope to ensure that all scratches were removed and that the growth bands were clearly visible.
Figure 3.3 Transverse section of an *A. stutchburyi* valve through the longest point of the shell photographed under a light microscope at 2x magnification. \textbf{w} indicates winter growth bands, \textbf{n} and arrows show position of notches associated with winter growth bands, \textbf{s} indicates summer growth bands and \textbf{a} indicates an annual growth band.

3.6 Analysis of shell sections

Slides were viewed under a Vanox photographic microscope at either 2x or 4x magnification and digital images were made of each shell section. The images of the sections were used to identify annual growth bands in each shell. To assess the accuracy of growth band identification, the number of annual growth bands per shell was counted independently by two different readers, for ten percent of the shells. The two readings were used to calculate the coefficient of variance, CV (Campana, 2001) for the two counts. The CV was calculated using the following equation:
\[ CV_j = 100 \times \sqrt{\frac{\sum_{i=1}^{R} (X_{ij} - X_j)^2}{R - 1}}X_j \]

Where: \( CV_j \) is the age precision estimate for the \( j \)th shell

\( X_{ij} \) is the \( i \)th age determination of the \( j \)th shell

\( X_j \) is the mean age estimation of the \( j \)th shell

\( R \) is the number of times each shell is aged

The average CV was calculated to be 6%. A CV of close to 5% is generally deemed to be highly precise (Campana, 2001).

From the photographs, the width of the annual, summer and winter growth bands were measured using the software ImageJ (version 1.4.3.67, 2006). Growth was measured between years 5 and 12, as this range is where previous studies found that the cockles have the most constant growth rate (Irwin, 2004; Kainamu, 2010; McKinnon, 1996). To assess the accuracy of the band width measurements, multiple repeated measurements were taken independently for ten percent of the shells. From these, the measurement error was calculated using the following formula (Bailey & Byrnes, 1990):

\[ \% ME = \frac{s^2\text{within}}{s^2\text{among} + s^2\text{within}} \]

Where: \( s^2\text{within} \) is the within shell component of variance

and \( s^2\text{among} \) is the among shells components of variance

The percentage error in measuring the width of growth bands was calculated as 9.9%. This measurement error is considered acceptable (Lougheed, et al., 1991).
3.7 Statistical analyses

One-way ANOVAs were undertaken on data from each site using JMP (version 11.0.0, SAS Institute Inc., 2103) to assess the significance of the effect of time period on the growth rate of cockles. The model, Growth rate = Collection + Shell ID(Collection), was used, where “collection” refers to the time period that shells were collected from and their position on the shore (modern shells), i.e. Early, Mid and Late Maori periods and Inner, Middle and Outer Modern shells. The nesting of the term Shell ID within Collection in this model accounts for multiple measurements being taken from the same shell. Tukey’s Honest Significant Difference post hoc-tests were carried out to determine groupings when ANOVA results were significant.

Growth rates of shells from all six sites were plotted in time to assess any general trends in growth rate across all regions. In order to account for possible differences in growth rate due to natural environmental differences at each site, growth rate was plotted as a proportion of the maximum growth rate when comparing between sites. For each site, the average growth rate was calculated for every collection. The proportion change in growth rate was then calculated using the following equation:

$$\Delta \text{Growth rate} = \frac{GR}{Max \ GR}$$

Where:

GR is the average growth rate of a collection

and Max GR is the maximum average growth rate found in any collection at a specific site

These proportions were calculated for every collection and were then plotted against the archaeological age of the collections to show how growth rate changed over time. Archaeological collections that were only assigned to a time period and did not have a precise date associated with them, were plotted in the middle of the time period they were from. Where multiple undated layers from one site were from the same time
period they were placed in order from oldest to youngest within the date range defined by the time period.
Chapter 4 Results

A total of 600 shells were analysed; 360 modern and 240 archaeological. From each shell, measurements of the width of summer, winter and annual growth rates were taken for up to seven years of growth, resulting in a total of approximately 10,000 measurements.

4.1 Opoutere

4.1.1 Summer growth rate
At Opoutere, modern summer growth rate was highest at the outer site (Figure 4.1a). Shells at the Modern Outer site grew at a rate that was indistinguishable from those found in the Early/Mid L1 and Early/Mid L2 (ca. 1400-1500AD) layers of the midden. Summer growth rate was greatest in the earliest time period (Early, ca. 1300AD) and least in the later time periods (Early/Mid L1 and Early/Mid L2) (F_{58,771}=5.28; p<0.0001; Tukey’s Honest Significant Difference (hereafter HSD) pairwise tests: Early: A; Early/Mid L1: B; Modern Outer: BC; Early/Mid L2: CD; Modern Inner and Modern Middle: D).

4.1.2 Winter growth rate
Winter growth rates of modern shells were highest at the inner site. Shells from the modern middle site and the Early/Mid L2 archaeological layer were indistinguishable and had the lowest growth rates (Figure 4.1b). Winter growth rate was greatest in the earliest layer of the Early time period (F_{58,771}=7.27; p<0.0001; Tukey HSD pairwise tests: Early: A; Modern Inner: B; Early/Mid L1: BC; Modern Outer: C; Early/Mid L2 and Modern Middle: D).

4.1.3 Annual growth rate
Of the three modern sites, the lowest annual growth rate was seen in shells from the Modern Middle site, while the growth rates of shells from the Modern Inner and Modern Outer sites were indistinguishable from each other (Figure 4.1c). Annual growth rates were highest in the Early time period. A measurable decrease in growth rate occurred between the Early time period and the Early/Mid time period, a further
decrease in growth rate occurred between the two layers of the Early/Mid time period (Early/Mid L1 and Early/Mid L2). Modern growth rates were indistinguishable from the growth rates of shells from the two later midden layers (F_{58,771} = 5.69; p<0.0001; Tukey HSD pairwise tests: Early: A; Early/Mid L1: B; Modern Outer: BC; Modern Inner: CD; Early/Mid L2 and Modern Middle: D).

These patterns suggest that there has been an overall decrease in growth rate of cockles by 1.1±0.3 mm/year from early Maori occupation (Early time period, ca. 1300AD) to modern times (calculated by: average Early growth rate - average overall modern growth rate). This change occurred between the Early time period and the Early/Mid time period.
Figure 4.1 Opoutere: Average summer (a), winter (b) and annual (c) growth rates of *A. stutchburyi* from modern (black bars) and archaeological (grey bars) shell collections. Collection refers to the time period the archaeological shells were collected and the location of the modern sampling sites within the Wharekawa Harbour, in relation to the distance from the estuary entrance. Time period classifications (Early, Early/Mid L1 and Early/Mid L2) follow the dates set out in Smith (2010). Bars that do not share the same letter are significantly different (Tukey’s honest significant difference pairwise test). Error bars are ± standard error of the mean.
4.2 Shag River Mouth

4.2.1 Summer growth rate
Summer growth rates from the three modern sites were highest at the outer site (Figure 4.2a). The summer growth rate of shells from the three modern sites were all lower than the growth rates of the two archaeological layers (Early L1, ca. 1370AD; Early L2, ca. 1385AD). There was no difference in summer growth rates of shells from the two layers of the midden (Early L1 and Early L2) ($F_{54,247}= 4.98; p<0.0001$; Tukey’s HSD pairwise tests: Early L1 and Early L2: A; Modern Outer: B; Modern Inner: BC; Modern Middle: C).

4.2.2 Winter growth rate
Winter growth rate did not differ between shells from each of the three modern sites (Modern Inner, Modern Middle and Modern Outer; Figure 4.2b). Winter growth rate was highest in shells from the earliest midden layer (Early L1, ca. 1370AD). The growth rates of shells from the later midden layer (Early L2, ca. 1385AD) were indistinguishable from the earlier layer and also from the Modern Middle and Modern Outer sites ($F_{54,247}= 2.58; p<0.0001$; Tukey’s HSD pairwise tests: Early L1: A; Early L2: AB; Modern Middle and Modern Outer: BC; Modern Inner: C).

4.2.3 Annual growth rate
Annual growth rate did not differ significantly between shells from each of the three modern sites (Modern Inner, Modern Middle and Modern Outer) (Figure 4.32). Shells from the Modern Outer site grew slightly faster annually than the other modern sites (Modern Inner and Modern Middle) (Figure 4.3 C). The annual growth rates of archaeological shells (Early L1, ca. 1370AD and Early L2, ca. 1385AD) were higher than the growth rates of shells from all three modern sampling sites on the estuary ($F_{54,247}= 4.8; p<0.0001$; Tukey’s HSD pairwise tests: Early L1 and Early L2: A; Modern Outer: B; Modern Inner and Modern Middle: BC). These patterns suggest an overall decrease in growth rate of cockles by 1.6±0.2 mm/year between early Maori occupation (Early L1 and Early L2) and current times.
Figure 4.2 Shag River Mouth: Average summer (a), winter (b) and annual (c) growth rates of *A. stutchburyi* from modern (black bars) and archaeological (grey bars) shell collections. Collection refers to the time period the archaeological shells were collected and the location of the modern sampling sites within the Shag River Mouth estuary, in relation the distance from the estuary mouth. Time period classifications (Early L1 and Early L2) follow the dates set out in Smith (2010). Bars that do not share the same letter are significantly different (Tukey’s honest significant difference pairwise test). Error bars are ± standard error of the mean.
4.3 Warrington

4.3.1 Summer growth rate
At Warrington, the greatest summer growth rate of modern shells was found at the outer estuary site (Figure 4.3a). This growth rate was indistinguishable from the growth rate of shells from the Early (1330AD) and Mid (1415AD) time periods. A decline in growth rate occurred between the Mid (1415AD) and Late (1745AD) time periods ($F_{101,681} = 2.81; p<0.0001$; Tukey’s HSD pairwise tests: Early, Mid and Modern Outer: A; Late: B; Modern Middle: BC; Modern Inner: C).

4.3.2 Winter growth rate
Winter growth rates of shells from the three modern sites (Modern Inner, Modern Middle and Modern Outer) were indistinguishable from each other. These growth rates were also indistinguishable from the growth rate of shells from the Late (1745AD) time period (Figure 4.3b). Winter growth rates of shells from the Early (1330AD) and Mid (1415AD) time periods were indistinguishable from each other and were greater than the winter growth rates of modern shells (2016AD) and of those from the Late time period (1745AD) ($F_{101,681} = 2.69; p<0.0001$; Tukey’s HSD pairwise tests: Early and Mid: A; Late, Modern Inner, Modern Middle and Modern Outer: B).

4.3.3 Annual growth rate
Annual growth rate of shells from the Modern Outer site were higher than any of the other modern sites (Figure 4.3c). Annual growth rates of shells from the Modern Outer site were indistinguishable from the growth rate of shells from the Early (1330AD) time period. Annual growth rates of shells from the Early (1330AD) and Mid (1415AD) time periods were greater than the Late (1754AD) time period and the Modern Inner and Modern Middle sites ($F_{101,681} = 3.03; p<0.0001$; Tukey’s HSD pairwise tests: Early, Mid and Modern Outer: A; Late: B; Modern Middle: BC; Modern Inner: C).

On average, growth rates of archaeological shells from the Early and Mid time periods (1330 AD and 1415 AD) were $0.5 \pm 0.1$ mm/year greater than the current average growth rate across the whole estuary. Because we cannot be sure where the archaeological material was collected from and because the Modern Outer site growth rates are not
significantly different from the Early and Mid time period archaeological shells, we cannot conclusively say that the growth rate has decreased by this much.

**Figure 4.3** Warrington: Average summer (a), winter (b) and annual (c) growth rates of *A. stutchburyi* from modern (black bars) and archaeological (grey bars) shell collections. Collection refers to the time period the archaeological shells were collected and the location of the modern sampling sites within Blueskin Bay, in relation the distance from the estuary mouth. Time period classifications (Early, Mid and Late) follow the dates set out in Smith (2010). Bars that do not share the same letter are significantly different (Tukey’s honest significant difference pairwise test). Error bars are ± standard error of the mean.
4.4 Purakaunui Inlet

4.4.1 Summer growth rate

At Purakaunui Inlet, summer growth rate from modern shells was greatest in shells from the outer site and lowest in shells from the Modern Middle site (Figure 4.4a). The summer growth rates of shells from the midden (Mid, 1416AD) were indistinguishable from the Modern Inner and Modern Outer sites (F_{69,447}=6.06; p<0.0001; Tukey’s HSD pairwise tests: Modern Outer: A; Modern Inner: B; Mid: AB; Modern Middle: C).

4.4.2 Winter growth rate

Winter growth rate was highest in shells from the Modern Outer site and from the Mid (1416AD) time period (Figure 4.4b). Winter growth rate was lowest in shells from the Modern Inner and Modern Middle sites (F_{69,447}=3.14; p<0.0001; Tukey’s HSD pairwise tests: Mid and Modern Outer: A; Modern Inner and Modern Middle: B).

4.4.3 Annual growth rate

The highest growth rate was seen in shells from the Mid (1416AD) time period and from the Modern Outer site on the estuary (Figure 4.4c). Shells from the Modern Middle site had the lowest growth rate (F_{69,447}=6.60; p<0.0001; Tukey’s HSD pairwise tests: Mid and Modern Outer: A; Modern Inner: B; Modern Middle: C). We were unable to detect a change in growth rate through time at Purakaunui Inlet.
Figure 4.4 Purakaunui Inlet: Average summer (a), winter (b) and annual (c) growth rates of *A. stutchburyi* from modern (black bars) and archaeological (grey bar) shell collections. Collection refers to the time period the archaeological shells were collected and the location of the modern sampling sites within the Purakaunui Inlet, in relation the distance from the estuary mouth. Time period classifications (Mid) follows the dates set out in Smith (2010). Bars that do not share the same letter are significantly different (Tukey’s honest significant difference pairwise test). Error bars are ± standard error of the mean.
4.5 Tiwai Point

4.5.1 Summer growth rate
At Tiwai Point, modern shells grew most in summer at the outer site and least at the inner site (Figure 4.5a). Summer growth rate was greater in shells from the Early time period (1344AD), than shells from the three modern sites (Modern Inner, Modern Middle and Modern Outer) ($F_{50,359} = 4.11; p<0.0001$; Tukey’s HSD pairwise tests: Early: A; Modern Outer: B; Modern Middle: BC; Modern Inner: C).

4.5.2 Winter growth rate
Winter growth rate was lowest at the Modern Inner site, all other collections were indistinguishable (Figure 4.5b) ($F_{50,359} = 3.07; p<0.0001$; Tukey’s HSD pairwise tests: Early, Modern Middle and Modern Outer: A; Modern Inner: B)

4.5.3 Annual growth rate
Modern shells grew fastest annually at the outer site and had the slowest growth at the inner site (Figure 4.5c). Annual growth rates were higher in shells from the Early (1344AD) time period compared to all modern collections ($F_{50,359} = 4.10; p<0.0001$; Tukey’s HSD pairwise tests: Early: A; Modern Outer: B; Modern Middle: BC; Modern Inner: C).

These patterns suggest an overall decrease in growth rate of cockles by 0.7±0.8 mm/year between the Early time period and now.
Figure 4.5 Tiwai Point: Average summer (a), winter (b) and annual (c) growth rates of *A. stutchburyi* from modern (black bars) and archaeological (grey bars) shell collections. Collection refers to the time period the archaeological shells were collected and the location of the modern sampling sites within Awarua Bay, in relation the distance from the estuary mouth. Time period classification (Early) follows the dates set out in Smith (2010). Bars that do not share the same letter are significantly different (Tukey’s honest significant difference pairwise test). Error bars are ± standard error of the mean.
4.6 Chalky Inlet

4.6.1 Summer growth rate
At Chalky Inlet, shells from the Modern Inner site had the lowest summer growth rate (Figure 4.6a). Shells from the Late (ca. 1700’s AD) time period had the highest summer growth rates but these were not statistically different from shells from the Historic (ca. 1800’s AD), Modern Mid and Modern Outer collections ($F_{61,323}=3.97; p<0.0001$; Tukey’s HSD pairwise tests: Late: A; Historic, Modern Middle and Modern Outer: AB; Modern Inner: B).

4.6.2 Winter growth rate
Shells from the Modern Inner site had the lowest winter growth rate (Figure 4.6b). The winter growth rates of shells from all other collections were indistinguishable ($F_{61,323}=2.45; p<0.0001$; Tukey’s HSD pairwise tests: Late, Historic and Modern Middle: A; Modern Outer: AB; Modern Inner: B).

4.6.3 Annual growth rate
Shells from the Modern Inner site had the lowest annual growth rate (Figure 4.6c). There was no statistically significant difference between the growth rates of the archaeological shells (Late, ca. 1700’s AD and Historic, ca. 1800’s AD) and the growth rates of shells from the Modern Middle and Modern Outer sites ($F_{61,323}=4.067; p<0.0001$; Tukey’s HSD pairwise tests: Late: A; Historic, Modern Middle and Modern Outer: AB; Modern Inner: B).
Figure 4.6 Chalky Inlet: Average summer (a), winter (b) and annual (c) growth rates of *A. stutchburyi* from modern (black bars) and archaeological (grey bars) shell collections. Collection refers to the time period the archaeological shells were collected and the location of the modern sampling sites within Chalky Inlet, in relation the distance from the estuary mouth. Time period classifications (Late and Historic) follow the dates set out in Smith (2010). Bars that do not share the same letter are significantly different (Tukey’s honest significant difference pairwise test). Error bars are ± standard error of the mean.
4.7 General trends in growth rate

Overall there is a trend in declining growth rate over time for all sites (Figure 4.7). The smallest proportional decrease in growth rate is seen in shells from Chalky Inlet. The summer, winter and annual growth rates of shells from Chalky Inlet show the least change over time. Shells from Shag River Mouth show the biggest change in summer and annual growth rates (Figure 4.7a and b) and shells from Opoutere show the biggest proportional decline in winter growth rate (Figure 4.7b).

At all sites the average modern growth rates of shells were lower than the growth rate of archaeological shells. Declines in growth rate were seen in both summer and winter growth rates and thus annual growth rates. Opoutere, Shag River Mouth and Tiwai Point showed the greatest decreases which is consistent with significant changes detected in the previous analysis.
Figure 4.7 Summer (a), winter (b) and annual (c) growth rates over time plotted as a proportion of the maximum growth rate for each site. Error bars signify the error related to dating of the site.
Chapter 5 Discussion

This study is the first in New Zealand, to our knowledge, that uses archaeological cockle specimens to study changes in estuarine health dating as far back as the initial arrival of Maori in areas of the country. This study looks at the long-term impacts that humans have had on the health of the marine environment and attempts to define a baseline of environmental conditions prior to the majority of human impacts. The purpose of this study was to determine whether there has been a change in the rate of growth of *A. stutchburyi* shells from the time of early Maori settlement in New Zealand to the present day. This study used modern and archaeological shells to compare the growth rates of cockles through the studied time period. A range of sites throughout New Zealand were studied, with varying amounts of anthropogenic impact on the site and the surrounding catchment area. This approach allowed us to determine whether there is any relationship between the change in growth rate and the extent of anthropogenic impacts. We found that the growth rates of cockles have declined over time at sites that have highly modified catchments and have declined less in areas that are less modified.

5.1 Growth rate

The growth of cockles can be split into two time periods: summer growth and winter growth. The reduction of growth seen in many species of bivalves over changing seasons has been attributed to a decrease in sea surface temperature and changes in photoperiod (McKinnon, 1996; Quitmyer, 1992; Quitmyer et al., 1997). Quitmyer (1992) found that sea temperature had the greatest influence on which type of growth band was deposited. By carrying out mark-recapture experiments, McKinnon (1996) found that *A. stutchburyi* in New Zealand lay down opaque bands during spring and summer and their slowest growth (seen as narrow translucent bands) occurred between April and August each year, corresponding to autumn and winter in the Southern hemisphere.
Overall, the present study found that there has been a decline in the growth rate of cockles through time at most of the sites studied. The extent of the decline seems to be correlated to the extent of the human impact to the surrounding area and to the catchment area. For most of the sites, the biggest change in growth rates were seen between the earliest layers studied. The biggest differences in growth rates were seen in the summer growth bands and the annual growth bands. Winter growth rates are much lower than summer growth rates and did not tend to show as much of a change in growth rate through time. This is because low temperature is a limiting factor in the winter (McKinnon, 1996) and has been fairly consistent across time. Low temperature limits the growth rate of phytoplankton (Robarts & Zohary, 1987), thus constraining the food availability for filter-feeders such as cockles. Winter growth bands only made up a small proportion of the overall annual growth, therefore, the trend seen with annual growth bands was driven by the summer growth bands.

The site at Shag River Mouth was the one of the most heavily impacted sites in this study, with Opoutere being the only other site to show similar levels of anthropogenic impact to the estuary and surrounding catchment areas. As described in detail in chapter two, the catchment of the Shag River Mouth estuary has almost entirely been converted from a prehistoric state characterized by dense tracts of forest to an area of intense agricultural use in addition to a gold mining operation in the upper reaches of the catchment.

The shells from Shag River Mouth showed the biggest change in growth rate through time, with a decrease of more than 50% of their prehistoric growth rate, equivalent to approximately 1.5mm/year. The decline in growth rate of shells from Shag River Mouth occurred between Maori occupation of the area during the Early time period (ca. 1389 AD) and the present day. It is not possible in this study to define more precisely when the major change occurred at this site, however the Maori settlement of the area lasted approximately 50-100 years in the Early time period and the site was not resettled by Maori after this. There was no discernible change in growth rates of shells from the two layers of archaeological material, indicating that the major change
did not occur, to a detectable level, immediately following settlement of the area. European settlement in the area was minimal in terms of the number of people settling in the area, but there was extensive land clearance with the arrival of both the Maori and European settlers.

Opoutere also has a long history of anthropogenic modifications to the catchment of the estuary, dating back to the earliest settlement of people in the area. The catchment of the Wharekawa Harbour has been subjected to intensive burning and clearing of the previously dense Kauri forests, as well as mining in the upper catchment (King, & Morrison, 1993). The archaeological material from Opoutere paint a detailed picture of human impact in the area. Archaeological shells from the three midden layers from Opoutere belong to the period between 1250AD (at the earliest) and 1500AD, corresponding to the Early and Early/Mid time periods. Analysis of growth rates of cockle shells from these layers revealed a decline in growth rates of around 30% between the earliest and middle layer, equating to a reduction of approximately 0.8mm/year. A further decline in growth rates occurred in shells between the middle layer and the latest layer studied at this site. In this case, the growth rate declined by a further 0.7mm/year to a rate just above 50% of the initial growth rate. No further changes in growth rate were detected between the latest archaeological layer (ca. 1450AD) and present-day rates, indicating that the biggest change in growth rates of cockles occurred between 1250AD and 1450AD during Maori occupation of the area. Growth rate analysis of cockle shells from Opoutere has provided evidence of a rapid decline in environmental conditions, as indicated by cockle growth rate, in the approximately 250-year period following initial settlement of the area, before European settlement.

The study locations of Warrington, Purakaunui Inlet and Tiwai Point all have moderately impacted catchment areas. Warrington and Purakaunui are located adjacent to each other and have both been subjected to similar anthropogenic pressures including clearing and converting tracts of dense forest for the purpose of agriculture. Patches of intact native forest remain in the catchments of each estuary.
Tiwai Point has a history of wetland drainage and development of industrial areas adjacent to the Awarua Estuary. There was a significant decline in growth rates of shells from the archaeological layer, from the Early time period, and modern shells. The growth rate of cockles from Tiwai Point decreased by approximately 30%, which is equivalent to a loss of 0.75mm/year.

Warrington has a long history of Maori settlement in the area spanning from the Early time period (1300’s AD) to the Late time period (1700’s AD) and shells from each of these time periods were used for analysing growth rates. We found that there was a decline in growth rates of shells between the Mid (ca. 1415AD) and the Late (ca. 1745AD) layers. The growth rate of the Late time period shells had decreased by approximately 25% (a decrease of 0.7mm/year) from the initial growth rates. It is possible that there was a further decline in growth between shells from the Late time period and modern shells, but the results are inconclusive due to spatial variation in growth rate throughout the estuary and the possibility of selective harvesting from sites with the largest cockles. All locations used for collecting modern cockles were within easy walking distance from the midden site. The change in growth rates seen at Warrington were much less than what was seen for the more highly modified sites at Shag River Mouth and Opoutere. Purakaunui Inlet has a smaller catchment area than Warrington and was occupied later and for a shorter period of time. The shells from Purakaunui Inlet did not show any significant differences in growth rates between the archaeological (from ca. 1414 AD) and modern specimen.

Lastly, Chalky Inlet is a minimally impacted site that has seen few changes to the environmental conditions over time. The environment at Chalky Inlet is close to pristine. The growth rate of cockles from Chalky Inlet have not shown any change over time, between the 1700’s and present day. This provides evidence that the extent of impact to the surrounding catchment plays a major role in determining the change in growth rates of cockles over time.
### Table 5.1 Summary of site characteristics and mean growth rates for each time period

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude, longitude</th>
<th>Climate</th>
<th>Impacts</th>
<th>Time period (from which shells collected)</th>
<th>Mean growth rate (mm/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opoutere</td>
<td>-37.109°, 175.879°</td>
<td>Warm temperate, moderate rainfall</td>
<td>Moderate/High: clearing, burning, agriculture</td>
<td>Early</td>
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<td></td>
<td></td>
<td></td>
<td>Modern</td>
<td>1.3</td>
</tr>
<tr>
<td>Shag River Mouth</td>
<td>-45.474°, 170.811°</td>
<td>Cool temperate, moderate rainfall</td>
<td>Moderate/High: clearing, extensive agriculture</td>
<td>Early L1</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Early L2</td>
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<td></td>
<td></td>
<td></td>
<td>Modern</td>
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</tr>
<tr>
<td>Warrington</td>
<td>-45.714°, 170.589°</td>
<td>Cool temperate, moderate rainfall</td>
<td>Moderate: clearing, agriculture, commercial harvesting of cockles</td>
<td>Early</td>
<td>1.9</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Mid</td>
<td>2.0</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Late</td>
<td>1.6</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Modern</td>
<td>1.6</td>
</tr>
<tr>
<td>Purakaunui</td>
<td>-45.753°, 170.626°</td>
<td>Cool temperate, moderate rainfall</td>
<td>Moderate/Low: clearing, agriculture</td>
<td>Early-Mid</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Modern</td>
<td>1.7</td>
</tr>
<tr>
<td>Tiwai Point</td>
<td>-46.582°, 168.409°</td>
<td>Temperate, high rainfall</td>
<td>Moderate: Wetland drainage, aluminium smelter</td>
<td>Early</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Modern</td>
<td>1.6</td>
</tr>
<tr>
<td>Chalky Inlet</td>
<td>-46.039°, 166.599°</td>
<td>Temperate, high rainfall</td>
<td>Minimal</td>
<td>Late</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Historic</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Modern</td>
<td>1.5</td>
</tr>
</tbody>
</table>
5.2 Caveats

A major caveat to this study is that it is not possible to know where the shells from the archaeological deposits were collected from. We only know where they were processed and where they ended up as refuse. We can surmise that if there were large cockles close to the settlement site then those were likely collected due to convenience. However, there is no way of telling if the early food gatherers went further afield (within the estuary) to seek out the biggest and best cockles to eat. In order to account for this potential source of error in this study, cockles were collected from three sites on each estuary to ascertain variation in growth rates, and the growth rates of each of the three modern sites were compared to the archaeological shells. For some sites, one of the modern collection locations had significantly higher growth rates than the other two and in the case of the summer and annual growth rates of shells at Warrington, the shells from the modern outer site had growth rates that were indistinguishable from the Early and Mid archaeological shells sampled there. In cases like this we cannot be sure that the growth rate has declined over time, as perhaps Maori were collecting cockles from this area of the estuary only. Alternatively, the best location in the estuary for cockles to grow now may have growth rates that are indicative of the average conditions of the entire estuary in historic times. Additionally, if early Maori selected the largest cockles for harvesting and left behind smaller ones, this could lead to a size bias when comparing archaeological samples to modern samples collected without size selection. Measuring growth rates between a set number of years attempted to minimise this potential bias.

Secondly, it is possible that, for the sites that did not show a significant difference in growth rates, the archaeological material used was not from the earliest occupation of those areas. The sites at Warrington, Opoutere and Purakaunui have multiple archaeological sites in the area, not all of which have been studied (I. W. G. Smith, pers. comm., 2017). It is possible that the archaeological material used was not from the earliest occupation of those areas, so that any early anthropogenic changes could not be detected. For Shag River Mouth and Tiwai Point, the sites have been well studied
and thorough excavations have been carried out, so we can be confident that the material used in this study from these sites do correspond to the earliest human settlement in the area (I. W. G. Smith, pers. comm., 2017).

5.3 Potential factors influencing growth rate

5.3.1 Eutrophication

The current study was similar to that carried out by Kirby and Miller (2002), who looked at the growth of the eastern oyster (*Crassostrea virginica*) in Chesapeake Bay, USA. They compared the growth rates of shells from archaeological material from as early as 1500AD to modern shells, to determine the effect that anthropogenic eutrophication has had on estuarine environments (Kirby & Miller, 2005). Chesapeake Bay is a large estuary located in the mid-Atlantic coastal region of the USA. European settlements began in the area approximately 400 years ago and since then the bays catchment area has undergone extensive changes, including converting land for agriculture and rapid population growth and urbanization (Curtin et al., 2001). Kirby and Miller (2002) measured the shell height, shell thickness and the surface area of the adductor-muscle scar. They found that there was an initial increase in size both of the shell and of the soft tissue of the oyster (as inferred by change in the size of the adductor muscle) during the early stages of eutrophication in the bay, between 1760AD and 1860AD (Kirby and Miller, 2002). Anthropogenic eutrophication of the bay increased phytoplankton concentrations which resulted in an increase in the growth rate of the suspension-feeding oyster. A further increase in abundance of phytoplankton can lead to a major shift in the trophic structure of the food web of the ecosystem. A shift occurs from a metazoan-based food web where suspension-feeders consume the majority of the primary production to one that is dominated by microbes (Jackson et al., 2001; Jonas, 1997). Growth rate of oysters then declined after 1860AD. Kirby and Miller (2002) hypothesised that this decline was likely due to environmental deterioration from hypoxia, toxic algal blooms, and/or fishing disturbance.
The results of the current study found an overall decline of growth rates of the cockle, *A. stutchburyi* over time since human settlement in New Zealand. In this study, we did not see any evidence for an increase in growth rates coinciding with initial anthropogenic impacts to the study areas indicating that the changes in growth rate seen were likely not related to eutrophication. Furthermore, the sites used in this study currently do not show any major symptoms of eutrophication. Awarua Bay (Tiwai Point), for example, has patches of seagrass throughout it (Morrison et al., 2014). Seagrass is sensitive to anthropogenic impacts and would likely not be present if eutrophication processes were occurring (Morrison et al., 2014).

Alternatively, it is possible that nutrient inputs into the estuaries in this study were higher prior to human settlement and have declined over time, thus causing a decrease in productivity and subsequently a decline in cockle growth rate. Prior to human settlement, New Zealand supported higher densities of seabirds and marine mammals (Holdaway, 1999; Holdaway et al., 2001) which would have introduced high levels of marine-derived nutrients into the estuarine ecosystems (Harding et al., 2004). Additionally, early Maori settlements may have increased nutrient inputs into waterways due to a lack of sewage treatment. With the introduction of mammalian predators such as rats and increased hunting pressure from early settlers the densities of marine birds and marine mammals declined (Holdaway et al., 2001), thus decreasing the nutrient inputs (Harding et al., 2004) and possibly leading to a decline in cockle growth rates.

### 5.3.2 Sedimentation

One possible driver of the change in growth rate seen in this study is increased sediment loads entering the estuaries. There is evidence that even the earliest forest clearance carried out by Maori had ecological consequences on the nearby marine environments. A study carried out in the Whangamata Harbour, approximately 7km from the study site at Opoutere, by Sheffield et al. (1995) looked at sediment cores
taken from the harbour to determine sedimentation rates. The Whangamata Harbour has a steep sided catchment, not dissimilar to the catchment of the Wharekawa River. The climate and geology is also similar to Opoutere. Furthermore, the history of environmental impacts to the catchment area are similar to the Wharekawa catchment, with Maori settling and burning tracts of forest and later European settlers arriving and felling the Kauri forests for timber and gum. A tributary of the Wentworth River, a river that flows into the Whangamata Harbour, also had a gold mine operating in the upper reaches, like Wharekawa. Due to the similarities in geological and climatic conditions and environmental histories, it is safe to assume that the relative changes in sedimentation rates seen in Whangamata Harbour are likely to show a very similar trend to what was going on in the Wharekawa Harbour.

Sheffield et al. (1995) found that the sedimentation rate in the Whangamata Harbour prior to human arrival in New Zealand (but after the ocean level had settled at the current level) was 0.06mm per year on the sandflats of the harbour. The sedimentation rate then increased more than four-fold to 0.28mm per year during the period of Maori occupation in the area and the introduction of anthropogenic forest clearing. Fire was the primary means of clearing tracts of forest at the time and a byproduct of using fires to modify the landscape is increased erosion of the land (McGlone & Wilmshurst, 1999). It is likely that similar processes were occurring in the Wharekawa Harbour at the same time. In general, early European occupation was a period of intense land use change as much of the remaining forest was cleared, steep relief and high annual rainfall in the area caused severe soil erosion problems (Sale, 1978). By the 1940’s, during European occupation of the area and after the majority of the Kauri forests in the area had been cleared, farming was occurring in lowland areas and the sedimentation rate had increased again to 11mm per year, more than 100 times the prehistoric rate (Sheffield et al., 1995).

The results from the current study point to the effect that early Maori were likely having on their environment, and how these effects most probably continued with the arrival of Europeans. The growth rate of cockles at Opoutere changed the most
concurrently with the first increase in sediment load going into the estuary. The initial degradation of the previously pristine environment coincides with a pronounced decrease in the growth rate of cockles from that area. It is possible that similar trends would have been occurring throughout the rest of the country, coinciding with the arrival of the first people in the area. In general, the current study suggests that initial impacts have caused the greatest changes in the growth rates.

Another study by Schallenberg et al. (2012) looked at sediment cores taken from Lake Waihola, a coastal lake in southern New Zealand and compared sediment accumulation rates from prior to human arrival and after European settlement of the area. A similar trend of increasing sedimentation rates over time was found. Prior to human arrival in the area, the sedimentation rates were approximately 0.18mm/year and after the start of major European settlement in the area (from 1860AD onwards), the sedimentation rates increased by a factor of 30 (Schallenberg et al., 2012). This study did not look at the sedimentation rates during the time of Maori occupation of the area, so we cannot tell how much of an increase in sedimentation rates there was over that time period. The timing of the conversion of land in the catchment area is correlated with the increase in sedimentation rates. Other studies from throughout New Zealand have looked at sedimentation rates over time and similar trends of increasing sedimentation rates after European arrival in the study area were found (Sheffield et al., 1995; Harper et al., 1994; Nichol et al., 2000).

Sediment cores have also been taken in Fiordland showing contrasting results (Pickrill, 1993). One such core was taken in Preservation Inlet immediately south of Chalky Inlet. The cores were radiocarbon dated and were found to span the time period from 7430±140 yBP to 1950±70 yBP. Analysis of the sediment core revealed that the sedimentation rate was 0.88mm/year 7430BP and was 0.54mm/year 1950BP. The study used catchment conditions and sediment yields to derive the current sedimentation rates and estimated that the rate was 0.90mm/year in Preservation Inlet in 1993. This shows that the environmental conditions in Preservation Inlet are close to their pre-human pristine conditions and a similar history suggests that conditions in Chalky
Inlet are probably alike. In addition, sedimentation rate in these relatively pristine sites are much lower than the 11mm/year observed in the Whangamata Harbour.

After clearing of forest, an initial pulse of increased sediments enters surrounding waterways, and this is followed by a continued increase in sediment load due to increased runoff and erosion of the cleared land (Schallenberg et al., 2012). A study carried out by Norkko et al. (2006) looked at the effect that high sediment levels have on the growth of two types of suspension feeding bivalves, *A. stutchburyi* and *Paphies australis*. The study tested the effect of short-term increases in sediment as well as increased sediment over a prolonged time period. They found that elevated suspended sediment concentrations altered feeding behaviour in the bivalves, but a temporary increase in suspended sediment concentrations did not have any significant effect on either of the bivalve species. In contrast continued high levels of suspended sediment had a significant negative impact on bivalve growth and shell condition (Norkko et al., 2006). Other species such as *Atrina zealandica* and *Mercenaria mercenaria* have shown the same trend of decreased growth rate with increased sedimentation (Bricelj & Malouf, 1989; Ellis et al., 2002; Ellis et al., 2000). Increased suspended sediment concentrations can decrease the growth rate of filter feeders because the sediment can clog or cause damage to the gills of the bivalve (Jones, 2011). It is possible that increased sediment influx into the estuaries is a contributing factor for the decline in growth rates seen in this study. Shells from sites that had the most modification to their catchment areas (for example Shag River Mouth and Opoutere) showed the greatest change in growth rates.

**5.3.3 Harvesting**

Another possible factor affecting the growth rate of cockles is harvesting pressure. Harvesting of a previously virgin population has an effect on the functioning of the dynamics of that population (Fenberg & Roy, 2008), because harvesting changes the population density of the cockle beds. In highly dense beds, the growth rates of cockles can be constrained by density, lack of space to grow into, and food.
availability (Irwin, 2004). Competition is lowered when the density of cockles decreases (Irwin, 2004). Studies conducted on populations of commercially harvested cockles from Otago found that when some of the cockles in an area are harvested, the remaining cockles can show an increase in growth rate (Cryer, 1997; Holdsworth and Cryer, 1991; Irwin, 2004), as removing cockles from the population allows more space for the remaining ones to grow. Prehistorically, artisanal harvesting pressure on cockles may have been significantly greater than it is today. It is possible that early harvesting pressure of previously virgin populations caused growth rate of cockles to increase immediately following the initial settlement of an area. However, if this was a main factor driving the change in growth rates, we would expect to see a continued increase in growth rate through time as human pressure on cockle populations increased. The early Māori population is estimated to have grown by at least 2-3% per annum (Anderson et al, 2014), and the cockle harvest in the Greater Hauraki area on the northeast coast of the North Island is estimated to have reached more than 1 million tonnes per annum by the mid 1500s (Smith 2011). Currently, commercial harvesting of NZ cockles is carried out in the southern South Island by Southland Clams Ltd; they harvest a total of 800 tonnes of shellfish annually from Blueskin Bay and the Otago Harbour (O’Connell-Milne, 2015). A recreational fishing survey carried out over a year from Karitane, Otago, found that cockles were the most popular shellfish to collect and over the period of observation a total of over 22,000 cockles were harvested and the average harvest was approximately 80 cockles per person (McCarthy et al., 2013), showing that harvesting may still be having an effect on cockle growth rates. It is thus unlikely that the declines in growth rate seen in this study are due to harvesting but are instead due to other changes in environmental factors.
5.3.4 Climate change

A further environmental change that may be causing changes in growth rates of cockles is global warming. Over the last 250 years, atmospheric carbon dioxide (CO₂) levels have been rapidly increasing. Current CO₂ levels are 40% higher than they were prior to the industrial revolution around the beginning of the 1800s (Doney et al., 2009). Uptake of CO₂ by the ocean is causing the pH of the ocean to become more acidic and is lowering the CaCO₃ saturation levels in the surface water (Doney et al., 2009). Since preindustrial times the average pH of the ocean has decreased from approximately 8.21 to 8.1 and as the atmospheric CO₂ levels continue to rise, the pH of the ocean is predicted to decrease further. Organisms that use CaCO₂ to construct hard parts such as shells are at risk with decreasing ocean pH levels (Gazeau et al., 2007). Gazeau et al. (2007) conducted an experiment to determine how the calcification rates of *Mytilus edulis* and *Crassostrea gigas* were affected when grown in water with acidity levels predicted to occur by the end of this century. They found that the calcification rates decreased by 25% for *Mytilus edulis* and 10% for *Crassostrea gigas*. Decreased calcification rates are seen as a decline in the growth rates of these shellfish or as thinning or deformation of the shell (Talmage & Goble, 2010).

It is likely that the change in pH that has been seen in the ocean today has already had an effect on the growth rates of calciferous organisms, but the extent of this effect is poorly understood (Talmage & Goble, 2010). If climate change has been having a significant effect on the growth rate of cockles it would be seen as a decrease in growth rates corresponding with the timing of the industrial revolution. In this study, the most significant changes in growth rates occurred after initial Maori settlement of areas, well before anthropogenic climate change began. In addition, a study carried out by Shears and Bowen (2017) found that ocean warming is not occurring evenly throughout New Zealand. Long-term sea surface temperature records showed that over the past 50 years the largest changes in temperature have occurred in southern New Zealand and there have been negligible changes in sea surface temperature in north-eastern New Zealand over that time period (Shears &
Bowen, 2017). If changing ocean temperatures and increased acidification were driving changes in growth rates cockles throughout New Zealand, it would be expected that the greatest declines in growth rate would be occurring in estuaries in southern New Zealand and that there would be little to no change in growth rate of shells from estuaries in northern New Zealand. The results of this study did not show this trend, but rather showed a decline in growth rate of shells from the northernmost site and no change in growth rate in shells from one of the southern sites. It is thus unlikely that the changes in growth rate seen in the current study can be explained by climate change.

However, it is likely that increasing CO₂ in the atmosphere and the associated acidification of the ocean in the future will have significant effects on the growth rates of organisms with CaCO₃ hard parts, including cockles.

5.3.5 Multiple stressors

It is possible that no single one of these potential factors is causing change in the growth rate of cockles but that the changes are by the interaction of multiple stressors acting on the estuarine environment at the same time. When multiple factors are influencing the health of an environment it is possible for the stressors to act in several ways: the stressors have an additive effect, a synergistic effect, or an antagonistic effect. Crain et al. (2008) analysed previous literature that had measured two or more stressors marine and coastal ecosystems to determine the types of interactions that were occurring between multiple stressors. They found that synergistic interaction effects were most common in marine systems although the overall effects depended on the specific scenarios being studied (Crain et al., 2008). Crain et al. (2008) also suggested that the order in which organisms faced environmental stressors could affect their response to further stressors. For example, a negative effect of the first stressor may pre-condition the species or population to be more or less sensitive to further stressors (Crain et al., 2008). Examples of stressors acting in the estuarine...
setting that influence the effect of other stressors include changes in salinity, sedimentation, nutrient levels, toxins, temperature and CO₂ (Crain et al., 2008).

5.4 Implications of reduced cockle growth rate

This study suggests that anthropogenic effects on the land surrounding estuaries and in turn the estuaries themselves are having detrimental effects on the growth rate of cockles. Continued reduction of the growth rate of cockles is possible if modification of the environment continues. Continued reductions in the growth rate of cockles can have flow-on effects for the rest of the estuarine ecosystem.

In soft shore, sandy environments where cockles are found there is a lack of hard substrate to provide habitat for other organisms. The hard shell of the cockle modifies the soft shore environment by providing a hard substrate on which other organisms can attach and live. In many areas, this is the only hard substrate available for organisms to adhere to (Thomas et al., 1998). For this reason, cockles are known as ecosystem engineers. Ecosystem engineers have the ability to create, modify and/or maintain the surrounding habitat (Gutierrez et al., 2003). Two invertebrate species that are commonly found living on the shells of live and dead cockles are the anemone *Anthopleura aureoradiata* and the limpet *Notoacmea helmsi*. Larger cockle shells can support more individuals of a certain species living on it, they can also support a greater diversity of species than smaller shells (Hayward et al., 1999; Gutierrez et al., 2003). Decreasing cockle size over time due to reduced growth rate may have altered the abundance and diversity of invertebrate communities using the shells of cockles as a habitat.

Benthic infaunal organisms can alter the physical and chemical processes occurring within sediments, through activities such as burrowing, irrigation and bioturbation (Yingst & Rhoads, 1980; Kristensen, 1984; Kristensen & Blackburn, 1987; Rysgaard et al., 1995). Bioturbation is the process of animals or plants reworking and irrigating the sediment and the biodeposition of faeces and pseudofaeces (Kristensen et al., 2012). In this case, reworking refers to the movement of sediment particles and irrigation refers
to the movement of water (Kristensen et al., 2012). In marine ecosystems, the process of bioturbation leads to an increased sediment-water interface, which increases particle exchange between the sediment and the water column (Norkko et al., 2012). These exchanges have a role in regulating the fluxes of organic matter, nutrients and contaminants in the ecosystem (Mermillod-Blondin, 2011). In soft-sediment marine habitats, large suspension feeding organisms or organisms that bioturbated, such as *A. stutchburyi*, can have important effects on the nutrient cycling and productivity of the area (Norkko et al., 2012). Studies on the bioturbation potential of *A. stutchburyi* showed that they have the ability to enhance primary productivity and sediment denitrification potential in a sandy shore environment (Jones et al., 2011). It was also suggested in the study by Jones et al. (2011) that the size of the individual cockle may influence the effectiveness of bioturbation. In dense beds of *A. stutchburyi*, individuals move horizontally by only a minimal amount, the main effect is from vertical movements. Cockles make small vertical movements in the sediment with the tidal cycle. When exposed at low tide the cockles bury themselves 2-3cm under the surface and as the tide comes back in they move to the sediment-water interface to feed. The amount of vertical movement occurring may be dependent on the size of the individual cockle, with larger cockles burying themselves slightly deeper in the sediment (Jones et al., 2011). Larger cockles are therefore likely to have reworked the sediment more than smaller cockles (Jones et al., 2011). A trend of declining growth rate of cockles through time may be having a negative effect on the ability of *A. stutchburyi* to enhance the productivity and denitrification potential in estuarine ecosystems.

In *A. stutchburyi*, the time at which an individual reaches maturity is determined by the size of the individual rather than the age (Larcombe, 1971). Maturity tends to be reached when the individual is between 18-20mm in length. Reductions in the growth rate of *A. stutchburyi* will mean that individuals reach sexual maturity later. It is likely that this would have a negative impact on the structuring of the population and the overall size of the population (Norkko et al., 2006). Increasing the age at first spawning
is likely to decrease the number of times an individual will spawn in a lifetime (assuming that an individual’s maximum age does not change). Therefore, in a population where growth rate is declining, it is likely that recruitment into the population may decline over time.

Bivalves incorporate into their shells a record of past environmental conditions. If the health of the environment they grew in was poor then their growth rate will be less. The decrease in growth rates seen in this study are indicative of declining health of estuaries.

5.5 Future research

This study gives an overview of the changes that have occurred to the growth rates of cockles since early human arrival in New Zealand. The results of this study provide a baseline for growth rates of cockles from a time where the land had been subjected to minimal anthropogenic impacts. These baseline growth rates can be used to inform management of *A. stutchburyi* and of estuarine areas in general. The current study indicates that in order to gain a baseline measurement for an area or population it is necessary to study specimens (where available) from as far back as the first arrival of people in that area. The results from this study indicate that it is not enough to look back to the state of the environment during the time of European arrival in New Zealand, as many ecosystems were already being subjected to anthropogenic inputs centuries before this. Further studies are required to build up a more detailed record of anthropogenic impacts over time. In order to generalise this study to the whole of New Zealand, it would be necessary to include more locations from throughout New Zealand and the surrounding offshore islands. If possible, use of archaeological material from sites that have many layers (spanning a period of centuries) would help to understand the changes on a finer scale and to determine more precisely when the greatest changes occurred.

Further studies using trace element analysis of these cockle shells could provide a more definitive idea of the factors influencing the decline in growth rate. Pollutants in
seawater become incorporated into the shell over the lifetime of the cockle and analysis of natural trace elements in the shell can provide information about the environmental conditions during that cockle’s life (Raith et al., 1996). Thus, trace element analysis can be used both to further investigate how anthropogenic changes to the surrounding environment affect the health of shellfish and to measure where and when such impacts have occurred.

5.6 Conclusions

In conclusion, this study suggests that anthropogenic effects on the land surrounding estuaries and in turn the estuaries themselves have had detrimental effects on the growth rate of cockles throughout human occupation of New Zealand, indicating a detrimental effect on the overall health of the estuaries.

Studying the long-term impacts that humans are having on the environment is critical for understanding the drivers of environmental change and for predicting future changes to ecosystem health. In New Zealand, we are placed in an ideal position to study the impact that human settlement has had on a previously pristine environment as, compared to other countries, New Zealand has a relatively short history of anthropogenic environmental modification. Archaeological material provides an opportunity to infer past environmental conditions that would otherwise be difficult to recreate and can be used to determine baseline conditions of ecosystems prior to extensive modification. The natural baselines determined in this study can be used to inform future management plans for cockles and estuarine environments and can provide a target for habitat restoration.
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