Management of Sand Beaches for the Protection of Shellfish Resources

By

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Frontispiece

Sand balls made by shellfish disturbed by vehicle driving.

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Abstract

Exposed sand beaches are increasingly under pressure from human population growth and recreation. Activities, such as vehicle driving and horse riding, can pose a significant threat to specialist fauna living in the sediment. Few studies have evaluated how vehicles affect sand beach fauna and none have examined the impacts of horse users on burrowing bivalves.

The research questions addressed were: do vehicles and/or horses on sand beaches impact on intertidal shellfish populations? Following on from this, can management policies mitigate any negative impacts from such activities on sand beaches? This research required an interdisciplinary approach utilising methodologies from coastal geomorphology, biological science and management. The intertidal distribution of the New Zealand surfclam *Paphies donacina* (southern tuatua) determined seasonally on six exposed surf beaches along Pegasus Bay. The impacts of vehicle and horse users on shellfish survival were experimentally investigated, and novel *in situ* methods were developed to examine the effects of horses on bivalve survival.

Intertidal tuatua were small (< 30 mm) and shallowly buried. Found approximately 30 m below the last high tide line, they may be exposed to vehicle and horse users. There was a positive linear relationship between the number of vehicle passes and tuatua mortality (% tuatua mortality = 4.8 + 0.23 x number of vehicle passes). On average, horse riding resulted in 36.9% tuatua mortality within a single hoof print, but walking resulted in lower mortality than trotting or galloping. Extrapolative modelling predicted that the long-term presence of these users would be highly detrimental to shellfish. Reducing the temporal frequency and spatial extent of vehicle and horse users on sand beaches could decrease shellfish mortality. The thesis results were used to evaluate current management techniques and provide management options to minimise the potential impacts of beach users on shellfish resources.

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List of Terms and Abbreviations

In alphabetical order:

Environment Canterbury: the Canterbury Regional Council

Foreshore: the seabed between MHWS and MLWS (i.e. the intertidal bed)

Horse user: any person driving a horse on the beach regardless of riding style

Intertidal zone: the area between the MHWS and MLWS

Juvenile tuatua (this thesis): individuals less than 30 mm shell length

MHWS: Mean High Water Spring

MLWS: Mean Low Water Spring

New Zealand’s seasons
- Autumn: March to May
- Winter: June to August
- Spring: September to November
- Summer: December to February

Northern Pegasus Bay Bylaw 2010: refers to the Waimakariri, and Hurunui, Northern Pegasus Bay Bylaw 2010

NZCPS 2010: New Zealand Coastal Policy Statement 2010, the mandatory national policy statement for the coastal environment

Off Road Vehicle (ORV): A vehicle suitable for off-road-purposes (e.g. Toyota Hilux, Mitsubushi Pajero)

RMA 1991: the Resource Management Act 1991, New Zealand’s main piece of environmental legislation

Tuatua: *Paphies donacina* (unless otherwise stated)

Vehicle user: a person who is driving motorised vehicle on the beach

Whitebaiter: A person who is catching whitebait (juvenile galaxiid spp.) from a river

Chapter 1 Introduction to sand beaches: fauna, dynamics, human use, and management

1.1 Thesis statement

Sand beaches play host to a wide range of human recreational activities which include fishing, swimming and walking as well as vehicle driving and horse training. With the rise in human populations living close to the coast and the frequency of these recreational activities increasing, sound beach management strategies become crucial to maintaining the many resources of coastal environments. Often public safety and geomorphologic issues take precedence in management policies for beaches. Diverse biota are present on sand beaches, often where recreational activities occur, making beach management an important tool for the prevention of ecological damage. In order for management to succeed, scientific information is needed that quantifies the damage inflicted to the biota and habitats of sand beaches as a result of human activities.

The present research concerns vehicle and horse use on sand beaches; activities that may have high impacts on intertidal shellfish populations which inhabit sand beaches. In particular, it examines relationships between shellfish distribution and abundance with physical environmental factors, and the impacts of human activities on intertidal shellfish within Pegasus Bay, Canterbury, New Zealand (43°21'38.38"S 172°42'9.95"E). The damage resulting from the different types of activities are compared experimentally and extrapolated to make predictions of their long-term effects. Current sand beach management strategies are evaluated and recommendations are made for the protection of shellfish resources.

Two key questions the present research seeks to answer are: do vehicles and/or horses on sand beaches impact on intertidal shellfish populations? Following on from this, can management policies mitigate any negative impacts from such activities on sand beaches?

To answer these questions, three key objectives were devised:

1. To examine the relationship between physical habitat properties and intertidal shellfish distribution and abundance;
2. To experimentally evaluate the effects on shellfish survival of human use of vehicles and horses on sand beaches;

3. To review and evaluate sand beach management policies to minimise potential effects of vehicle and horse users.

1.2 Introduction to sand beaches

Sand beaches are the most widely spread intertidal habitat worldwide (Dexter, 1992). Such beaches are physically dynamic environments and can be defined by three interacting physical variables; wave energy, tidal range, and sand particle size (Pethick, 1984; McLachlan, 1996; McLachlan & Dorvlo, 2005). These three variables, as well as latitude, influence the species richness and community structure present on a sand beach (Dexter, 1992; Dolbeth *et al.*, 2007).

Approximately 60% of the world's population are forecasted to live within coastal floodplains by 2100 (Nicholls & Mimura, 1998), and because the size of the population is increasing (Hammond, 1992) there is increased development that alters the dynamics of sand beaches (Schlacher *et al.*, 2007). While some developments, such as marinas and protection structures, are viewed as necessary to provide access to coastal resources and mitigate hazards, others are desired to support coastal economies. One of these is eco-tourism, which aims to have low environmental impact but often requires the use of Off-Road-Vehicles (ORVs) to gain access to areas. These vehicles cause coastal erosion as well as having immediate adverse effects on the benthos that are driven over (Wolcott & Wolcott, 1984; Schlacher *et al.*, 2008a; Schlacher *et al.*, 2008b; Thompson & Schlacher, 2008; Sheppard *et al.*, 2009; Walker & Schlacher 2011).

Throughout the world, sand beaches are spread across a wide range of tidal scales and wave exposures. In New Zealand, most sand beaches occur on meso-tidal coasts exposed to swell wave environments. Stating specific seasonal trends in erosion and accretion of sand beaches as well as the overall distribution of the beaches in New Zealand is difficult. This is because no organisation has been designated with the collection of ongoing data of this type. This type of data would be useful for referring back to, like that of hydrological data that regional councils are required to gather (Hesp *et al.*, 1999).

The National Institute of Water and Atmosphere (NIWA) Coastal Explorer is a database that currently summarises the available beach profile information, but it is still patchy along certain areas of the coast (NIWA, 2011b). Beach profile data gathering currently does not take place in a consistent manner across all regions of New Zealand. However, effects-based decision making, an outcome of the Resource Management Act, 1991, has resulted in increased amounts of science being carried out which examine the physical processes and ecosystems of New Zealand's sand beaches.

1.3 Sand beach fauna

Compared to rocky ecosystems, sand beaches are less diverse and have lower amounts of primary production (Knox, 2001). An overarching reason for lower diversity is that sand beaches lack habitat heterogeneity; a characteristic that facilitates species diversity by creating microclimates (Le Hir & Hily, 2005). On most sand beaches there are a wide range of biota, including crustaceans, amphipods, isopods, bivalves, and polychaete worms to name a few. Most functional feeding groups inhabit this area except grazers, which are usually absent due to no algal species being present (Knox, 2001). Sand beaches are frequently utilised by shorebirds, such as dotterels, which nest on, within or below sand dunes (Lord *et al.*, 2001).

As mentioned, sand beaches are physically dynamic environments with varying amounts of disturbance. To maintain populations in a habitat with such dynamics requires a wide range of adaptations for the biota present on these beaches. Wave action is the most dominant environmental factor on sand beaches, to which organisms must adapt (Nybakken & Bertness, 2005). A common adaptation to resist wave action is for organisms to burrow into the sediment (Dugan *et al.*, 2000; Seike, 2008). Mobile organisms, such as crustaceans (crabs), often leave burrows to feed and mate. This is usually at night to avoid bird and fish predation (Williams, 1969). In contrast, more sedentary organisms, such as polychaete worms and bivalves, remain within the sediment and rarely become exposed to above ground conditions.

Sand beach communities are important to neighbouring ecosystems because they provide a unique set of ecosystem services including filtration of large volumes of water and recycling of nutrients (Waldbusser *et al.*, 2004). Unlike rocky shores, where primary production is carried out by algal species in the ecosystem, sand beaches receive nutrient inputs from phytoplankton in the water column and terrestrially derived organic inputs (Mclachlan & Erasmus, 1983). These nutrients are then consumed by zooplankton and bivalve filter-feeders and passed through the food web. These processes facilitate the high productivity of nearshore fisheries around sand beaches (Mclachlan *et al.*, 1996). Facilitation of fisheries makes sand beaches a valuable economic resource worldwide. Sand beaches also contribute economically through recreational uses, though these can be at odds with the beach's ecological resources.

1.3.1 Shellfish

Shellfish belong to the phylum Mollusca, which includes over 50,000 described species and contains the class Bivalvia. This class includes animals enclosed in two shell valves (Gosling, 2003) of which there are approximately 7500 species. Bivalves are responsible for high rates of filtration in the ecosystem (Dame, 1993; Marsden, 1999b; Gosling, 2003), making such species useful as indicators of environmental contamination by heavy metals (Boening, 1999). In addition, shellfish are a significant food source for many predatory organisms in the ecosystem (Williams, 1969), as well as for humans.

There are economic benefits in protecting sustainable shellfish populations. For example, in 2007 bivalve fisheries generated US $13.6 billion of revenue worldwide (FAO, 2007). Traditional users, such as the iwi of New Zealand, also view shellfish as a valuable food resource. Accordingly, the sustainability of this valuable resource rests with a range of stakeholders. These groups include those directly focused on shellfish resources, such as fishermen, conservationists and territorial authorities, and those indirectly impacting populations, such as vehicle and horse users. The latter user groups may influence the outcomes of shellfish populations through the associated ecological impacts of their activity.

Bivalve populations are highly abundant on sand beaches. Animals inhabit the surf zone as adults as well as juvenile stages in some species (Cranfield *et al.*, 2002). Shellfish found in the surf zone are known as surfclams. These individuals have specific adaptations that allow inhabiting of this zone. The main adaptation is burrowing into the sediment using a muscular foot by carrying out a series of probing-anchoring sequences to pull the individual until it is buried (Dame, 1993; Hull *et al.*, 1998; Gosling, 2003). Shellfish populations migrate within the beach; this can be on daily, seasonal, annual, and intertidal cycles (Marsden, 2002). In addition to these patterns of migration some species, such as *Paphies donacina* (tuatua), move seawards as they get older (Cranfield *et al.*, 2002). There are several advantages of tidal migration; it allows bivalves to avoid desiccation by staying in a tidal zone where the moisture level is right; it keeps them too shallow for fish predators but safe from bird predators; and it also allows them to stay in a suitable zone for feeding (McLachlan & Erasmus, 1983).

New Zealand's geographical isolation has led to a high level of endemism. There are two species of tuatua are present in New Zealand; *Paphies donacina*, found on the South Island and southern shores of the North Island, and *P. subtriangulata*, found mainly in the North Island (Richardson *et al.*, 1982; Marsden, 1999a). Tuatua populations inhabit the intertidal zone of sand beaches as juveniles and move to the surf zone as adults. Tuatua (*P. donacina*) is the dominant species of shellfish on the beaches of Pegasus Bay (Marsden, 2010). Toheroa (*P.ventricosa*), another important species of surfclam, has recently had its fishery closed due to a large decline in its population (Ministry of Fisheries, 2012). These species are present intertidally, both as juveniles and adults (Cranfield *et al.*, 2002; Marsden, 2002; Kingett Mitchell Ltd., 2003). Other species of surfclams inhabiting New Zealand's sand beaches include *Spisula aequilatera*, *Mactra murchisoni*, *M. discors*, *Dosinia anus*, *D. subrosea* and *Bassina yatei* (Cranfield *et al.*, 1996); however, many of these remain subtidal throughout their lifespan. Reproduction of surfclams is through broadcast spawning (Dawson, 1954; Cranfield *et al.*, 2002). This process is largely seasonal in the South Island, with high production of gametes occurring in the warmer, summer months (Marsden, 2002).

Historically the two species of tuatua and toheroa have been important to Māori who have gathered them as a customary food source, or *mahinga kai* (Moller *et al.*, 2009). In some parts of New Zealand customary gathering has reduced. For example, it has been reported that local iwi no longer collect tuatua (*P.donacina*) from certain areas of Pegasus Bay, Canterbury, due cultural sensitivity to sewage outfalls in the area (Cranfield *et al.*, 2002).

1.4 Human use of sand beaches

In many parts of the world, the most utilised sand beaches are usually dissipative allowing space for a wide range of on-beach activities. These activities include general recreation, such as walking, running and swimming. Activities also exist that have potential to be environmentally damaging if they were to continue uncontrolled such as vehicle driving, horse riding (including professional training), fishing, and shellfish gathering. The occurrence of these activities can vary temporally or spatially due to peoples' perceptions. For example, shellfish collection often occurs away from the estuaries and sewage outfalls due to health concerns over potential contaminants.

This thesis is focused on the effects of vehicles and horses on these ecosystems and hence these will be discussed in more depth than other activities. Off-road-vehicles (ORVs) are commonly used on sand beaches throughout the world for activities such as access to fishing spots, launching of boats, four-wheel-drive recreation and eco-tourism. Most ORV traffic is concentrated in the intertidal zone where the sand is compact and easiest to drive on. The use of ORVs on sand beaches is of growing concern to conservationists and beach managers due to recent literature indicating a negative effect from vehicle traffic when driven over sand dunes and through the intertidal zone of sand beaches (Moss & McPhee, 2006; Schlacher & Thompson, 2007; Schlacher *et al.*, 2008a; Sheppard *et al.*, 2009). Vehicle speed is also a growing concern in relation to public safety.

Previously, literature has focused on the effects of vehicles driven over sand dunes and the associated biota (Luckenbach & Bury, 1983; Anders & Leatherman, 1987; Priskin, 2003; Thompson & Schlacher, 2008). Emerging research evaluating the effects of vehicles on infaunal benthos in the intertidal zone of sand beaches has raised new issues for conservation and management. A majority of these studies show that with increasing vehicle traffic there is a higher mortality rate of the beach biota.

Schlacher and Thompson (2007) conducted a study at several beaches in Queensland, Australia, and found beach traffic reached up to 500 vehicles per day for a particular area during a low tide period. That study also examined species distributions, including crustaceans, bivalves and polychaetes, on the beach and identified that as high as 65% of the total beach fauna was present in the area where vehicles had driven over. In light of such evidence, understanding the possible effects of these activities becomes essential. New Zealand beaches are unlikely to have sustained traffic volumes of this number; however, vehicle traffic is still likely to impact populations of infaunal organisms that are distributed in the intertidal zone. During some time periods, there may be unusually high impacts from vehicles as a result of special events that require beach driving for logistical purposes (e.g. the Northland marathon on 90 Mile Beach).

In addition to vehicle use, horses are also commonly exercised on beaches throughout the world and in areas of New Zealand where equine sports are popular. From personal observations, horse use predominantly occurs in the intertidal zone of beaches where the sand is flattened; however, some beach users will swim their horse in the shallow swash zone area.

Figure 1.1: Horses being ridden on the intertidal zone of Sumner Beach, Canterbury.

Perceptions of the ecological effects of vehicle and horse users differ. van Polanten Petel & Bunce (2012) conducted a survey of beach users and found that 77% of users rated vehicle use as highly disturbing to shore birds. However, the same participants were mixed in regards to perceptions of horse disturbance. These mixed perceptions may have driven the focus of earlier research which has focused largely on the ecological effects of vehicles and not of horses.

There is no previous literature on the effects of horse riding on coastal ecosystems. Pikering *et al.* (2010) conducted a terrestrial study which identified the main effects of horse riding to be invasive species vectoring and addition of nutrients to the ecosystem via defecation. The introduction of invasive terrestrial plant species is less important in intertidal ecosystems due to high salinity levels on sand beaches, lower organic content, larger substrate, and frequent disturbance events; factors which make it difficult for terrestrial organisms to survive. Nutrient addition from horse droppings may have some highly localised short-term effects, but is likely to be minimised due to tidal cycles washing away the low volumes of deposits made. The physical effects of horse hooves crushing infaunal species are likely to be the most important effects in a sand beach ecosystem. No studies have recorded the frequency of horse traffic on sand beaches in Pegasus Bay, but it is likely that high use areas are used by over 25 horses per tidal cycle (Author observations).

A study by Moffett *et al.* (1998) investigated the effects of human trampling during a series of volleyball games in East Cape, South Africa, and found that higher trampling intensities resulted in increased mortalities of the bivalve *Donax serra* and *D.sordidus*. Both of these species have similar shell morphology to *P. donacina*. These results indicate increased human trampling has adverse effects on organisms and this is likely to be a comparable trend for horses due to the similar nature of sediment disturbance (i.e. penetrating the sediment matrix).

1.5 Management on sand beaches

Current management of sand beaches employs policies and strategies which aim to mitigate the impact of activities on these beaches. There is no cosmopolitan law or standards for sand beach management, so it is up to a particular country to decide how to mitigate the negative impacts of beach activities on its coastal environment. This is often done by balancing many different values, including socio-economic, cultural and ecological. Traditionally, management approaches have been guided using singular scientific disciplines which can result in the coast becoming altered away from its natural state (Tintoré *et al.*, 2009). Given that sand beaches are physically dynamic environments, utilisation of a single discipline may result in one issue being addressed while another is ignored or adversely affected. This makes use of a multidisciplinary approach increasingly important when considering implementation of bylaws that change the way the beach face is used.

Coastal management strategies have traditionally focused on recreational and geomorphic issues and less on environmental issues (James, 2000). This is often due to a lack of suitable scientific information which can lead to difficulties in implementing successful management strategies. Stakeholder interests are another factor affecting management techniques, for example, democratic governments need to implement policies without being voted out for doing so. For environmental issues to be addressed in management strategies, scientific information must act as a voice in this debate.

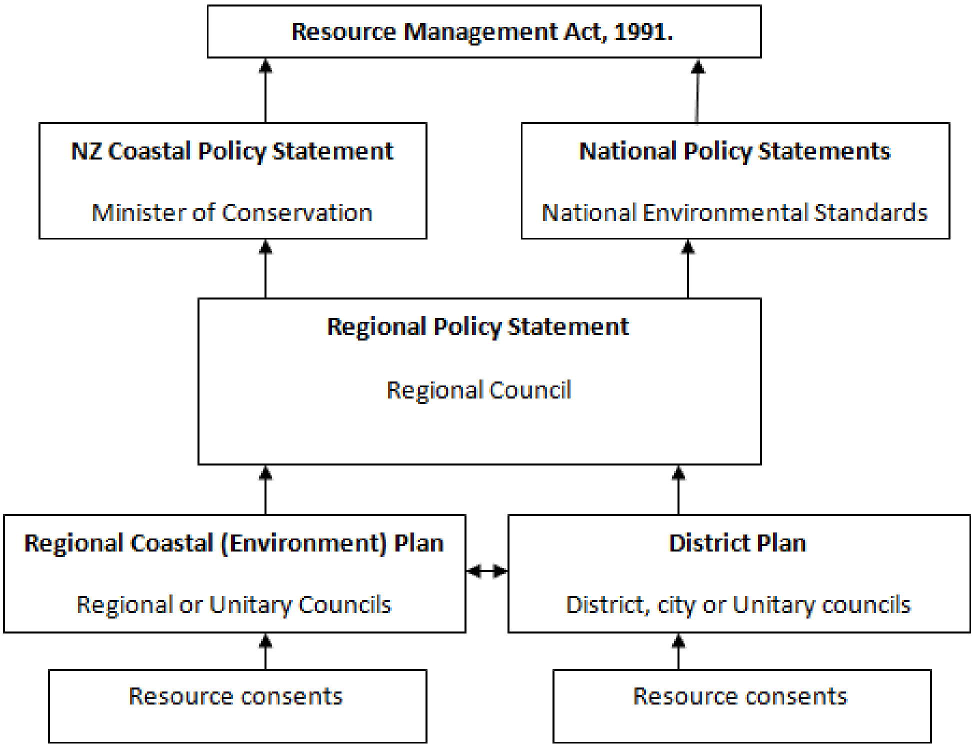


Figure 1.2: The policy framework of New Zealand under the Resource Management Act, 1991. Arrows indicate to which policy another must be aligned

In countries, such as New Zealand, there is often a set framework for development of management strategies (Figure 1.2). These can be imposed at a national, state/regional or a local level. In New Zealand, environmental and resource management policies are created within a framework stipulated by the Resource Management Act (RMA) 1991. This framework is designed to achieve a national consistency for identifying and resolving environmental issues. The RMA (1991) and the New Zealand Coastal Policy Statement are the two key pieces of legislation which guide councils in relation to coastal management. The Resource Management Act (1991) gives power to regional, district and unitary councils to decide which activities the general public can and can’t undertake. Activities which do not meet these standards require resource consent. Local bylaws can also be implemented to ban or put limits on the activity being carried out in its entirety.

The territorial authorities in Pegasus Bay include the Christchurch City Council, Waimakariri District Council and Hurunui District Council. Environment Canterbury, the regional authority, oversees management of the air, land and water resources for the Canterbury region, including its coastal area. Environment Canterbury is responsible for producing a

Coastal Environment Plan and also makes suggestions to steering committees about possible changes to bylaws. This took place in 2009 when Environment Canterbury issued a non-compulsory bylaw to the Waimakariri District Council and Hurunui District Council to change vehicle use on beaches in Pegasus Bay, Canterbury.

One suggested recommendation aimed to prevent damage to the surrounding ecosystem including bird nests and sand dunes- “Vehicles may only travel along the beach below the last high tide mark”. To increase user safety, vehicles must not exceed 30 kmh^{-1}, or 10 kmh^{-1} within 50 m of people (The Northern Pegasus Bay Coastal Management Plan Steering Committee, 2008). This bylaw was adopted by the Hurunui and Waimakariri District Councils in 2010. It is not known if and how this management strategy has affected shellfish populations by changing the way in which vehicles and horses are used within the bay.

1.6 Thesis Aims and Objectives

Until recently, use of beaches in much of New Zealand, including Pegasus Bay, has been a free-for-all with little management being put in place in relation to vehicle driving and horse riding. The implementation of the New Zealand Coastal Policy Statement 2010 which specifically addresses the need to control vehicles on beaches in coastal management plans (e.g. the Northern Pegasus Bay Bylaw 2010). This has often resulted in activities being confined to the intertidal zone where infaunal biota, such as tuatua (*P. donacina*), are vulnerable. The initial question that this thesis sets out to answer was: do vehicles and/or horses on sand beaches impact on intertidal shellfish populations? Following on from this, can management policies mitigate any negative impacts from such activities on sand beaches?

To answer these questions, three objectives have been devised:

1. To examine the relationship between physical habitat properties and intertidal shellfish distribution and abundance;
2. To experimentally evaluate the effects on shellfish survival of human use of vehicles and horses on sand beaches;
3. To review and evaluate sand beach management policies to minimise potential effects of vehicle and horse users.

1.7 Study System: Pegasus Bay, Canterbury, New Zealand.

Formation of Pegasus Bay

Pegasus Bay is a large (55 km wide) eastern facing bay situated in the province of Canterbury in the South Island of New Zealand (Figure 1.3). The coastline is progradational. Underneath the surface of the coast, the plains are composed of Pleistocene fluvio-glacial outwash deposits, whereas the upper surface progradational plain is comprised of continental shelf and river deposits (Brown *et al.,* 1988). The progradational shelf is 1 km wide in the north and 6 km wide in the south (Shulmeister & Kirk, 1997). This progradation is said to have ceased in the north but continuing in the south at a rate of a few millimetres per year (Gabites, 2006). Overall, the Bay is said to be relatively stable and has changed little since 4000 years B.P. (Before Present) (Allan *et al.,* 1999).

The adjacent land mass that makes up the Canterbury Plains is predominantly made up of Quaternary sediments. The quaternary period extends from 2 million years ago until present day, and includes the earlier Pleistocene era (2 million years to approximately 11,500 years BP) (Bradshaw & Soons, 2008). The Quaternary may be divided up into 9 different stages using Marine Oxygen Isotope Stage to classify the bay's sediments (Forsyth *et al.,* 2008), with Q1 being the oldest and Q9 the most recent. These have been used to establish the movement of the shoreline around the Christchurch area (Forsyth *et al.,* 2008). Using these classifications, the Pegasus Bay coastline was found to have migrated seawards between Q1 and Q5, and Q5 and Q7. However, between Q7 and Q9 the coastline did not prograde over its entire length, but rather realigned its curvature to form a relatively stable platform shape under the prevailing current systems (Figure 1.4). In the present Holocene (beginning 11,500 years ago) this coastline stabilised. As sea level dropped, coastal transgression halted and the beaches prograded further seaward, stabilising around 4,500 years BP in its present orientation and location.

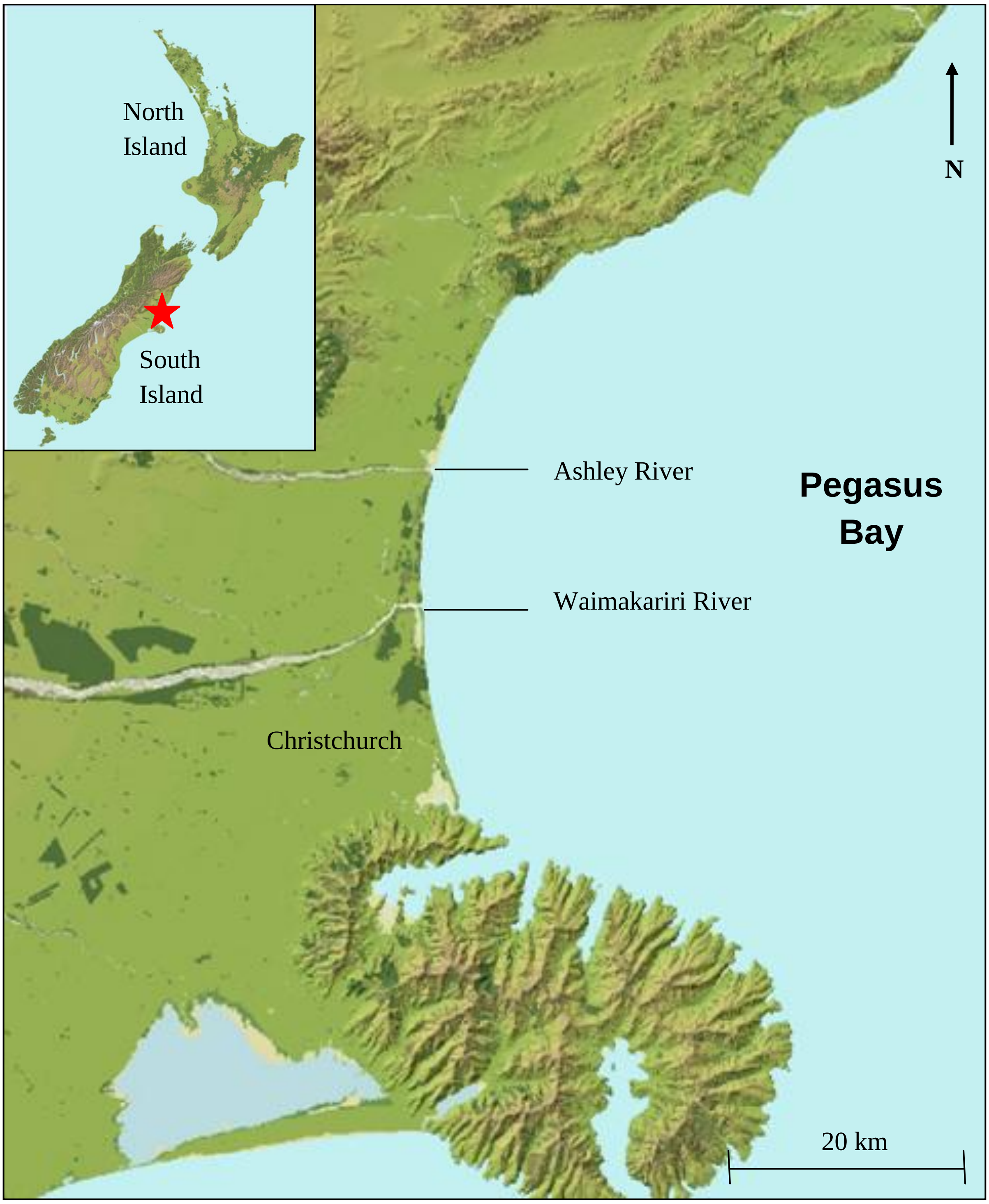


Figure 1.3: Map of Pegasus Bay, Canterbury. Inset showing New Zealand (Red Star = position of Pegasus Bay).

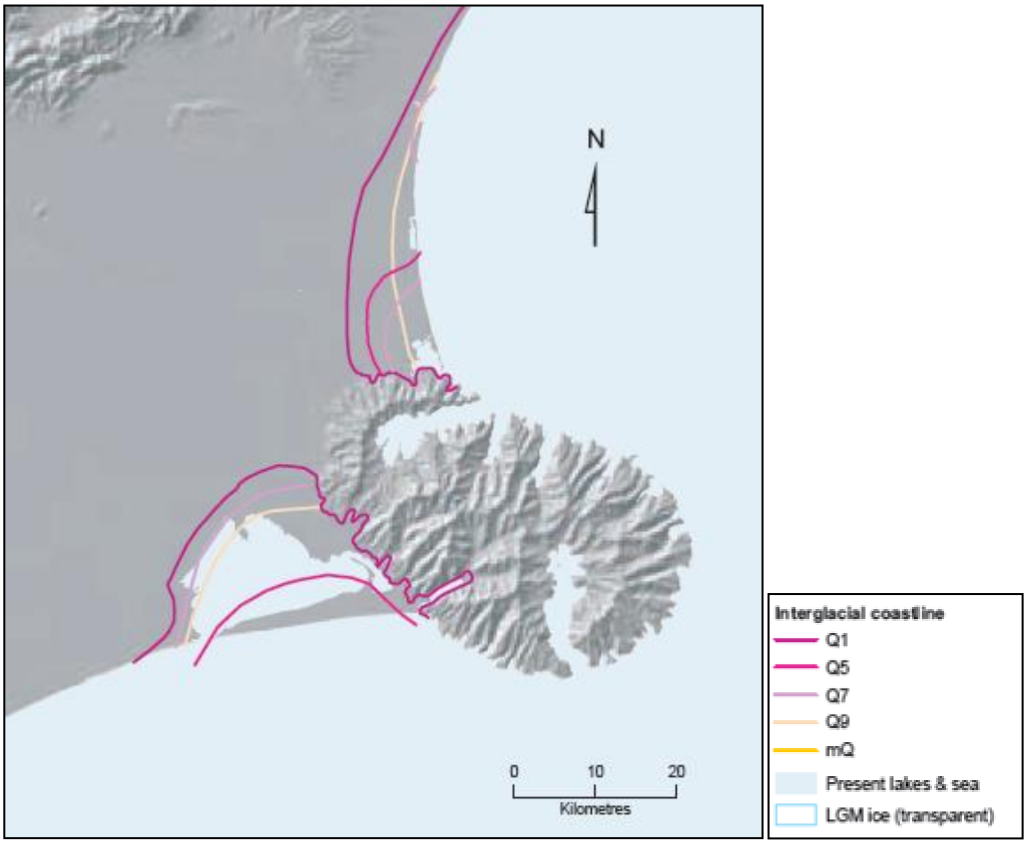


Figure 1.4: Approximate limits of interglacial coastline in Christchurch area.
Q= quaternary. mQ= mid quaternary (Adapted from Forsyth *et al.*, 2008; 39).

Today, a large amount of wave action influences the beaches of Pegasus Bay making this environment a physically dynamic area. In the past, wave action was responsible for the formation of beach deposit barriers between the alluvial fans of Canterbury and the sea (Soons, 1994). Continued presence of wave action is important as it acts to nourish the shore. This prevents erosion through losses of terrestrial derived sediment particularly that delivered to the coast by the Waimakariri River.

Present state

In its present state, Pegasus Bay extends approximately 55 km in length; from Banks Peninsula in the south, to the Waipara River in the north. The beaches within this bay include gravel, composite and sand types (Kingett Mitchell Ltd., 2003; Hart *et al.*, 2008). Sand beaches start at the southern end of Pegasus Bay beside Banks Peninsula and extend northwards for approximately 40 km. Tuatua are abundant along most of this area, except adjacent to the mouth of the Waimakariri and Ashley Rivers (Marsden, 2010).

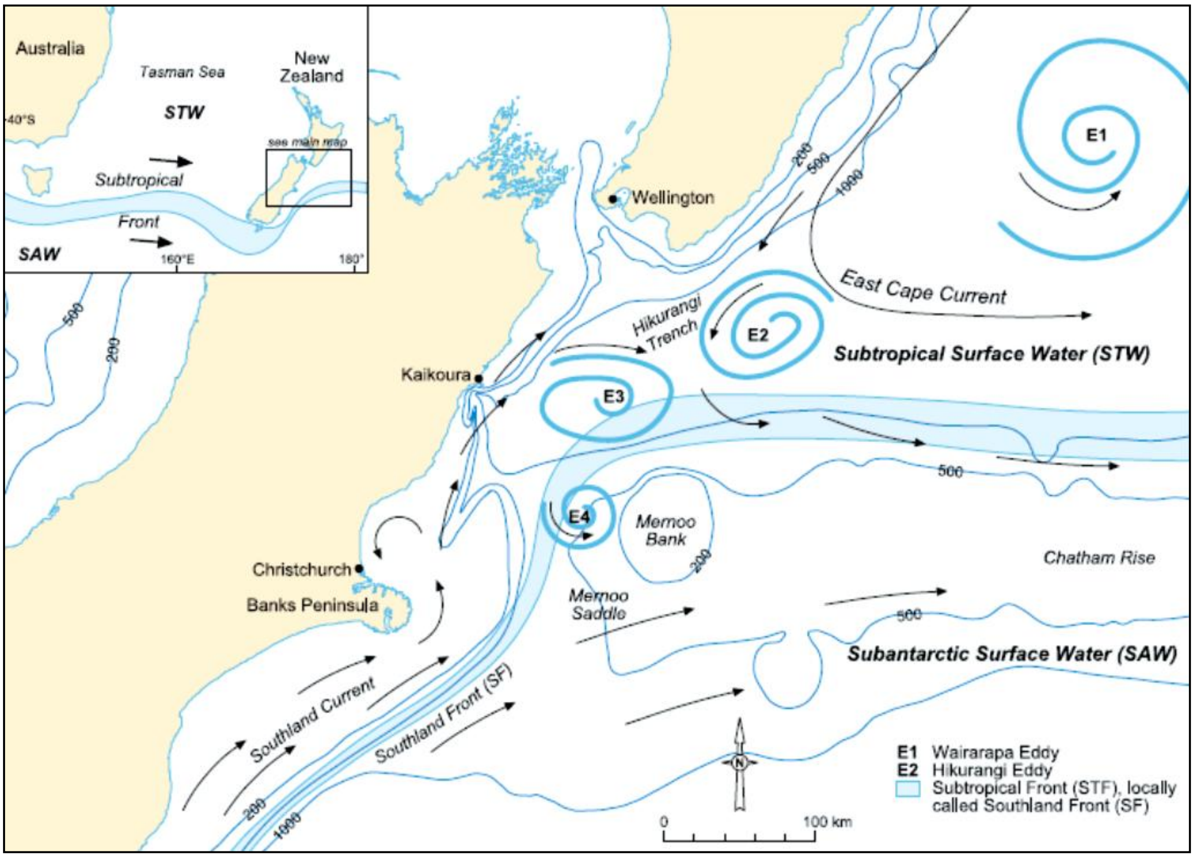


Figure 1.5: Image showing the Southland Current (SC) moving up the east coast of the South Island, New Zealand. The eddy caused by the interference of this current causes sand to be swept south along the shore and deposited on at the southern end of Pegasus Bay (Hart *et al.*, 2008; 657).

The presence of sand beaches at the southern end of Pegasus Bay is due to sheltering by Banks Peninsula creating a lower energy wave climate (Goff *et al.*, 2003; Reynolds-Fleming & Fleming, 2005). This results in disruption of the Southland Current that moves northwards on the east coast of the South Island (Figure 1.5) forming an eddy that transports sediment north to south from the river mouths. The profiles of these beaches lack significant seasonal variability but can change from year to year depending on the processes that have occurred in that year (Allan *et al.*, 1999). Cusps are common on many of the beaches within the bay (Nolan *et al.*, 1999), and storms frequently produce scarp formation (author observations) (Figure 1.6).

Figure 1.6: A scarp formed shortly after a storm event on South Waimakariri Beach (photo taken May 2010).

The beaches in Pegasus Bay are semi-meso tidal on diurnal cycles (Goff *et al.*, 2003). The intertidal zone of these beaches ranges in width from 30 m up to 160 m. Most beaches within Pegasus Bay are intermediate longshore bar-trough as determined using the morphodynamic beach model, as shown in

Figure 1.7 (Wright & Short, 1984; Short, 1999; NIWA, 2011b), but become more reflective as you travel north. Characteristics of Pegasus Bay beaches which place them in the intermediate category include: between one and three lines of breaking waves in the surf zone, cellular currents, profiles with cusps, and fine to medium sediment with a high shoreline mobility.

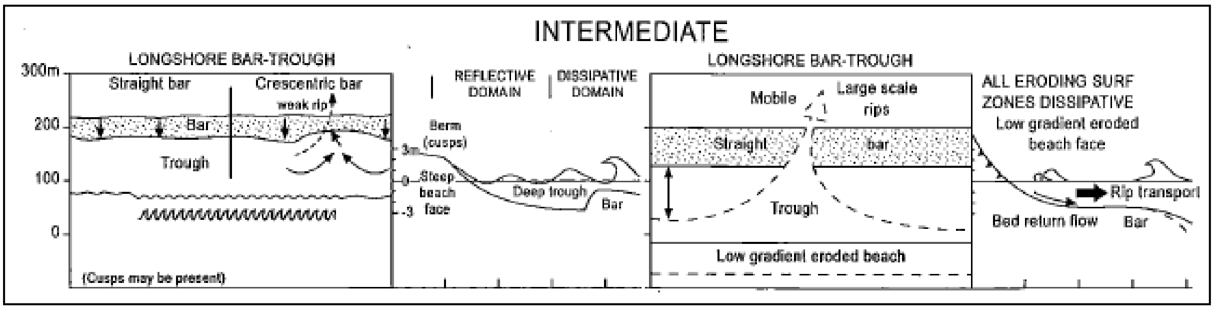


Figure 1.7: Diagram of a typical intermediate longshore bar-trough beach which represents that found in Pegasus Bay (Short, 1999; Pg. 179).

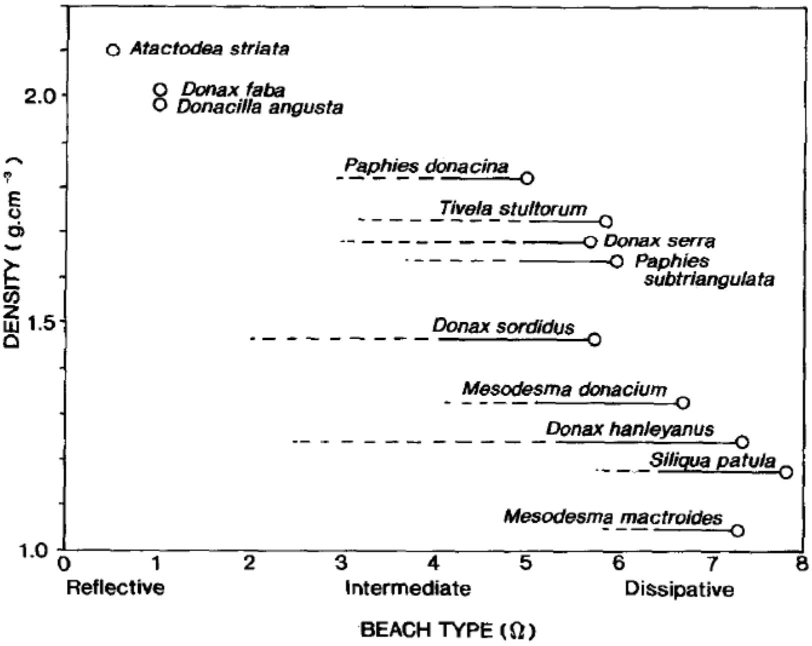


Figure 1.8: Density of 12 bivalve species in relation to beach type. O is the beach type where individual was collected and horizontal line shows other types of beaches where adult populations exist. (McLachlan *et al.*, 1995).

In addition, evidence presented by McLachlan *et al.* (1995) shows tuatua (*P. donacina*), one of the predominant species of shellfish in Pegasus Bay, to inhabit intermediate beach types. However, Figure 1.8 shows that *P. donacina* is found in a range of beach classes within the intermediate range unlike that of *Donax faba,* which is found exclusively in reflective beaches. This suggests that a range of adaptations are required and the adaptations of *P. donacina* are such that it can inhabit a wide variety of habitats.

Freshwater inputs

Pegasus Bay receives freshwater inputs from several natural and artificial sources. The two largest sources of freshwater input are from the Avon and Heathcote Rivers via the estuary and the Waimakariri River. Other rivers include the Ashley, Kowai, and the Waipara. Environment Canterbury river flow data has shown that the Waimakariri River can carry a large amount of suspended solids at times of high flows, which then get deposited in Pegasus Bay. The input of suspended sediment affects water clarity as the offshore water has lower turbidity than the river waters (Kingett Mitchell Ltd., 2003). The river mouths can be changeable especially after storm events. Non-natural inputs in the form of effluent outfalls are also present. These are the Christchurch City ocean outfall, which discharges 3 km offshore of New Brighton Beach, and the Kaiapoi-Rangiora outfall which discharges 1.5 km offshore of Woodend Beach. These outfalls release treated wastewater on a daily basis (Christchurch City Council, 2010).

Sediment sources

Adjacent to Pegasus Bay are the Canterbury Plains, which are a broad plains made up of Tertiary and Quaternary sediments. These are believed to be up to 600 m thick (Wilson, 1985) and are a result of alluvial fans from the Southern Alps (Shulmeister & Kirk, 1993). Three major rivers currently flow out into Pegasus Bay: the Waimakariri, Ashley and Hurunui Rivers. Each of these acts as a vector, transporting sediment from the Southern Alps to the open coast.

Sediment from the continental shelf supplies 5% of the sediment in Pegasus Bay. The other 95% is from the river systems, of that the Waimakariri River making up 77% of the total river input (Griffiths & Glasby, 1985). Overall, fine sand (2.5 to 3.5 phi) makes up a majority of the sediment that remains on the foreshore (Gabites, 2006). Blake (1967) previously determined the Waimakariri River was the source of most of the sediment that comprises the foreshore. The sediments from the Waimakariri River catchment are predominantly siltstone and sandstone (greywacke); while those from the Ashley River catchment are mostly greywacke, but also comprise some tertiary sediment. Historically, sediment supply was from offshore sources but presently it is largely made up of sediments supplied by the rivers in the bay.

In addition to river inputs, some sediment is supplied from Banks Peninsula, in the southern end of Pegasus Bay. This sediment is transported north and deposited within the eddy created from disruption of the Southland current (Figure 1.5). Banks Peninsula is an extant volcanic land mass approximately 1170 km² in area. Therefore, the sediment supplied from this end of Pegasus Bay is of Tertiary and Pleistocene volcanic origin (Blake, 1967).

1.7.1 Human use and management of beaches in Pegasus Bay

The wide, low sloping sand beaches of Pegasus Bay make this a very useable environment for a wide range of beach activities. These activities include swimming, running, walking, fishing, horse riding, motorbike riding and vehicle driving. Some of these activities are correlated with others. For example, vehicle driving is often by fishermen wanting to access the river mouths. This is likely to occur more frequently during the whitebaiting season (August to November) and during times of salmon runs (October to April). Several management authorities oversee the activities that take place on the beach in Pegasus Bay including regional and district councils, fisheries officers, and park rangers. This research is focused on activities that take place on the foreshore, so only those relevant authorities will be discussed in detail.

Each local authority has their own area of coast which they are required to manage. These authorities are the Christchurch City Council which manages beaches to the south of the Waimakariri River mouth, the Waimakariri District Council which manages the beaches from the north bank of the Waimakariri River to the south bank of the Ashley River mouth, and the Hurunui District Council which manages the area extending north of the Ashley River mouth (Figure 1.9). Each Council must prepare a District Plan which must give effect to the objectives and policies of the New Zealand Coastal Policy Statement and the Canterbury Regional Policy Statement and must not be inconsistent with any objective, policy, rules or other methods in a regional plan (i.e. the Regional Coastal Environmental Plan).

The District Councils are responsible for managing land use activities occurring landward of the Mean High Water Spring (MWHS) level. The Regional Council is instead responsible for managing activities occurring seaward of the MHWS to 12 nautical miles offshore (Gregory, 2008). Of the recreational activities which take place on the foreshore of beaches in Pegasus Bay, horse riding and vehicle driving are the two most restricted by the Waimakariri Northern Pegasus Bay Bylaw 2010 and Hurunui Northern Pegasus Bay Bylaw 2010 (referred to as the Northern Pegasus Bay Bylaw 2010 from here on).

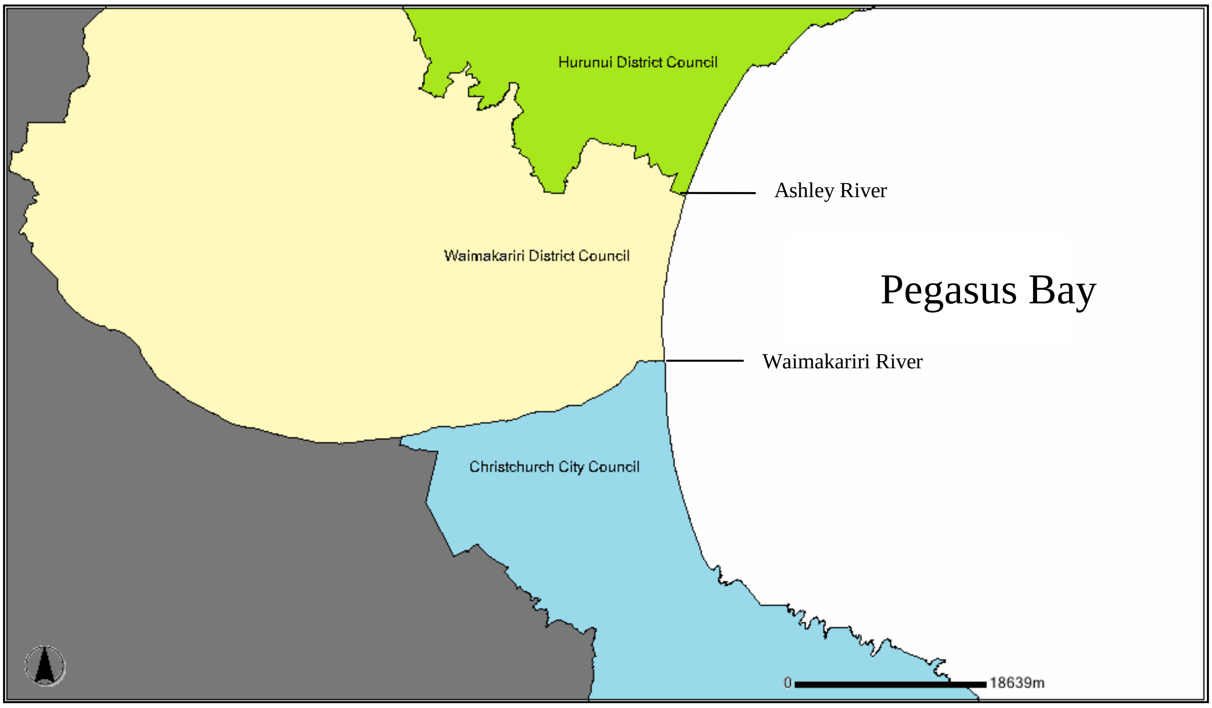


Figure 1.9: GIS map of the area that the Christchurch City Council, Waimakariri District Council, and Hurunui District Council manage within Pegasus Bay, Canterbury. The mouths of the Waimakariri and Ashley Rivers are also indicated.

Vehicle use in Pegasus Bay

Vehicles are commonly driven on the sand beaches of Pegasus Bay to carry fishing and whitebaiting gear and to access fishing spots and other off-road coastal areas. Vehicle driving is permitted; north of the Heyders Road entrance but south of the Waimakariri River mouth, Kairaki, south side of the Ashley River mouth and Ashworths Beach. The current bylaws in Pegasus Bay stipulate that vehicles should enter and drive directly to the intertidal zone and must not exceed a speed of 30 kmh^{-1} or 10 kmh^{-1} when within 50 m of people. Others areas of beach do get driven on but this is only done by park rangers, fishing officers or emergency services.

This bylaw results in traffic being concentrated in the intertidal zone where shellfish and other intertidal organisms are vulnerable to being run over. No restrictions exist for the number, type or weight of vehicles that can be used; however, 4-wheel-drive Suburban Utility Vehicles (SUVs) are the most common, as seen in Figure 1.10.

Figure 1.10: Four-wheel-drive vehicles used by whitebaiters parked on the intertidal zone at the Waimakariri River Mouth, Pegasus Bay, Canterbury.

Horse use in Pegasus Bay

Along with vehicle driving, horse riding is also common on beaches within Pegasus Bay. The most frequent horse users on the beach are professional trainers which ride their trotters (horse with a sulkie) on the intertidal zone. This is more frequent when the track at the stud is too wet to be used. The recent bylaw adopted by the Waimakariri and Hurunui District Councils permits horses to be ridden across the whole beach but like vehicles, they must go directly to the intertidal zone upon entering. No speed limit is set for horse users. The implementation of this bylaw has acted to concentrate traffic towards the intertidal zone of Pegasus Bay. While this prevents erosion and damage to bird nests above the high tide line, little is known about the effects on animals in the intertidal zone.

1.8 Study species: southern tuatua (*Paphies donacina)*.

This thesis is focused on the southern tuatua (*Paphies donacina*); the most abundant surfclam on beaches within Pegasus Bay (Marsden, 2010). Tuatua populations inhabit sand beaches and are dispersed intertidally and subtidally (Cranfield *et al.*, 2002). This species has relatively high ecological significance for these beaches. Tuatua are an important prey species for many individuals in the ecosystem, being commonly preyed on by fish, birds and crustaceans (Knox, 2001). They also filter large quantities of water which lowers turbidity, making the water more aesthetically pleasing to humans. This filtration also facilitates other benthic macrofaunal species (Gosling, 2003; Norkko *et al*., 2006). Filtration also allows humans to use shellfish populations as indicators of contamination by heavy metals which accumulate in the tissues of the animal (Boening, 1997).

Morphology

Like other bivalves, tuatua are completely enclosed by a hard shell which is predominantly made up of calcium carbonate (Gosling, 2003). The shell is symmetrical and flattened at the posterior end (Figure 1.11). The thickness of the shell strongly correlates with the length of the shell (Cranfield, 1996). Hydroids are commonly found attached to the shell of adults. These hydroids are often visible from above the sediment and aid seabirds in identifying shellfish. The shell has clearly visible concentric growth rings (Figure 1.11). A hinge ligament is present on its dorsal side and the shell is pulled closed using anterior and posterior adductor muscles (Figure 1.12).

Like other surfclams, the foot of tuatua is far larger in size than in other hard shore bivalve species (Gosling, 2003). The foot is in the centre of the soft tissue and protrudes out from the gills (Figure 1.12). *P. donacina* breathe through four gills: these are separated by the foot, with two gills on either side of the animal. Feeding is done by taking water into the mantle through the inhalant siphon and directed to the stomach by the labial palps. The water is filtered and then released by the exhalant siphon (Figure 1.12).

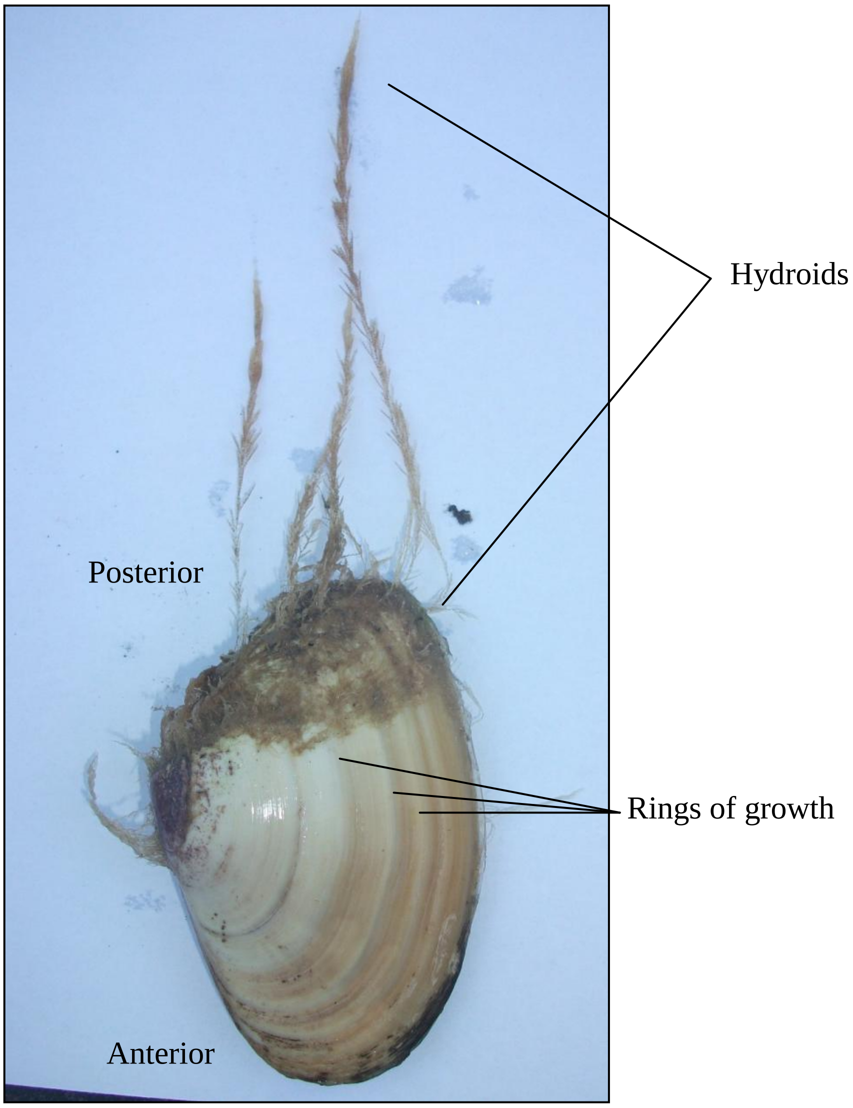


Figure 1.11: The external features of an adult tuatua, *Paphies donacina*.

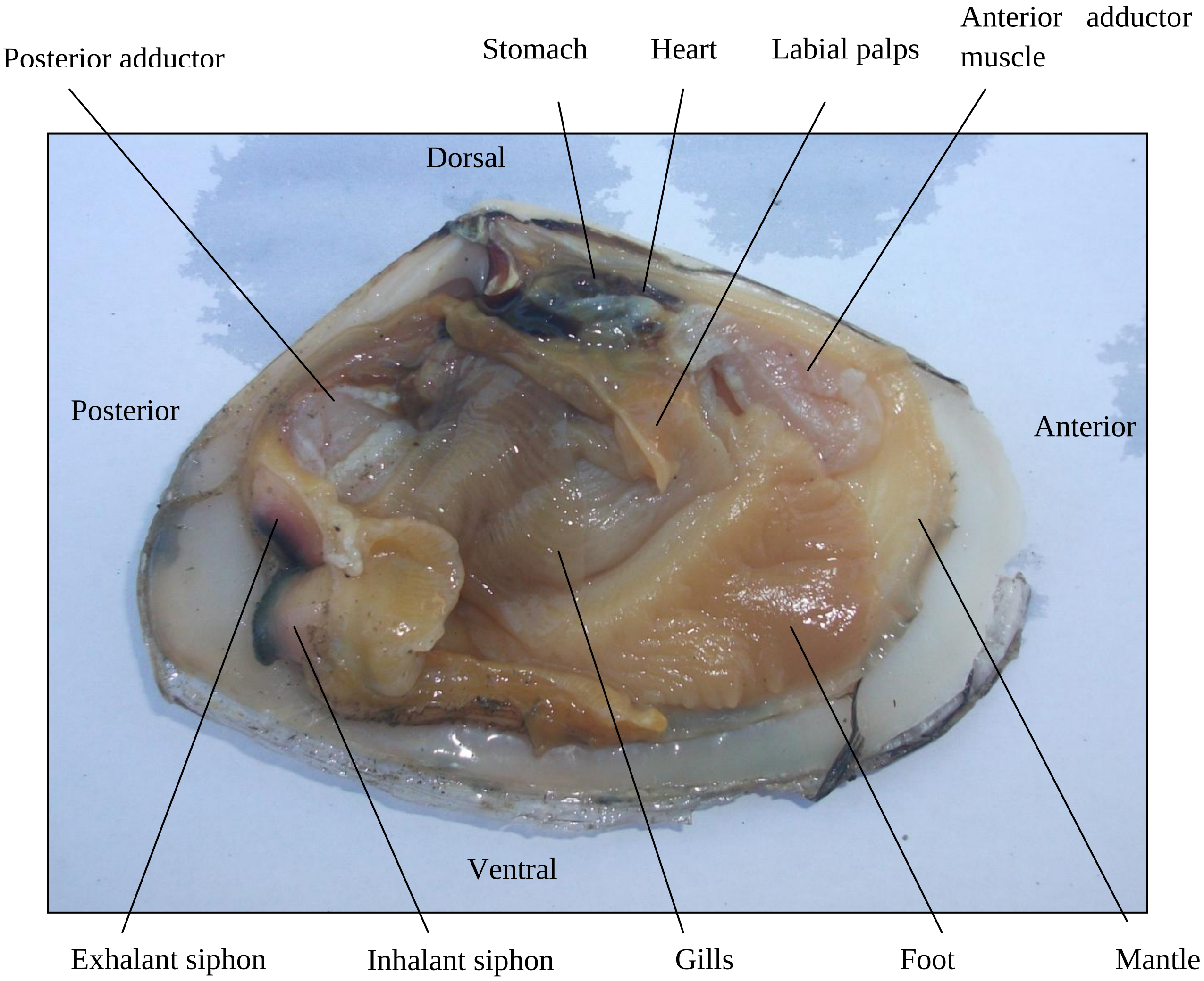


Figure 1.12: The internal features of tuatua, *Paphies donacina*, viewed with one half of the mantle removed.

Growth and reproduction

Shell growth in bivalve species is through the addition of material to the edge of the mantle. The calcium needed for this growth is obtained from the diet or from seawater (Gosling, 2003). A study by Cranfield *et al.*, (1996) compared the growth of *P. donacina* with other surfclams in Cloudy Bay, Marlborough, and found that growth rates are variable among shellfish. This study showed that growth rates were higher in smaller animals and slowed as individuals got larger. Growth rates were as high as 10.8 mmy^{-1} for *P. donacina* (Cranfield *et al.*, 1996).

Marsden, (1999), has showed that growth could vary depending on environmental conditions, as could reproduction. *P. donacina* have separate sexes that use broadcast spawning for reproduction. Broadcast spawning occurs in the warmer summer months at the southern end of its geographical range, but can be continuous in warmer northern waters (Marsden, 1999a). Once successful reproduction has occurred, the larvae of *P. donacina* are planktonic for 18-21 days (Cranfield *et al.*, 1993) and are dispersed using passive mechanisms of transport (Marsden, 2002). There is a two month lag between the maturation of females and the settlement of recruits (Marsden, 2002). In this time the spat are planktonic. When this stage is completed, recruitment takes place in the intertidal zone; a process which is suggested to be greatest nearer to the high tide mark (Cranfield *et al.*, 1996).

Tuatua dispersal

The dispersal of *P. donacina* populations in Pegasus Bay, Canterbury has been described in a few studies (Dawson, 1954; Cranfield *et al.*, 2002; Kingett Mitchell Ltd., 2003; Marsden, 2010). Most of these papers noted *P. donacina* was distributed in both the subtidal and intertidal zone of beaches in Pegasus Bay. Surveys by Kingett Mitchell Ltd. (2003), and Marsden (2010) found that there was a distinct band of individuals approximately 20-30 m below the high tide line. Tuatua present in this zone were generally juveniles of less than 30 mm in length and buried at a depth up to 10 cm in the sediment (Marsden, 2010). However, adult individuals were distributed subtidally at depths of 2-3 m underwater (Cranfield *et al.*, 2002). Adults can also be present in the intertidal zone where they are often easily identified by the hydroids that attach to the posterior end of their shell (Marsden, 1999a). Gosselin and Qian, (1997) stated that bivalve species are subject to two major selection pressures; desiccation and predation. Desiccation is prevented by being burrowed in the sediment and closing the shell to retain moisture. Predation on juvenile tuatua is reduced by distributing higher on the shore, at levels where crab predators are unable to survive desiccation (Knox, 2001). As tuatua grow, they exceed the critical size for predation by crabs but birds become a larger threat (Boulding, 1984). It is therefore expected that larger individuals distribute subtidally in order to escape bird predators.

1.9 Conclusion

Sand beaches play a host to a wide range of human activities. The increasing prevalence of these activities and the effects on the surrounding ecosystems requires management to prevent further damage. These beaches are physically dynamic environments containing species with specific adaptations to withstand such conditions. These ecosystems are often ignored in management decisions.

Tuatua have distinct morphological adaptations that allow it to inhabit both the subtidal and intertidal zones of sand beaches. The formation of a strong foot means that tuatua can burrow into the sediment, reducing the effects of desiccation and keeping the individual sheltered from strong wave forces. A strong calcareous shell also helps tuatua to withstand predation pressures. Some animals are still able to overcome this defence, making tuatua and important food source for many organisms in sand beach ecosystems. The filtration services that tuatua provide make it an important species for the ecosystem through reducing turbidity and facilitation of other species in the benthos.

Many sand beaches worldwide are focal points for high frequencies of vehicle and horse users. Pegasus Bay is also utilised by such users. Some user groups may have minimal impacts on the surrounding ecosystem, whilst others may cause significant levels of damage. The impacts of vehicles have been studied by multiple authors internationally; however, horses have not. Vehicle studies have taken place in New Zealand on Toheroa beds, but not tuatua (*P. donacina*) and information is needed which quantifies such impacts. Horses are also likely to impact tuatua, and terrestrial studies indicate impacts could be relatively high.

A key focus of sand beach management is safety and geomorphologic factors, and very little emphasis is placed on protecting the entire ecosystem. Through the provision of scientific information quantifying ecological impacts of current users of the coastal zone, managers can then be informed of the ramifications of their decisions. Essentially, this type of information will give a voice to the stakeholders without a voice; sand beach biota. Ultimately it is hoped that multidisciplinary information can be utilised to guide practitioners to develop robust management strategies and thereby sustain these valuable resources for future generations. This aspiration is a key purpose of the Resource Management Act, 1991.

1.10 Thesis outline

This thesis aims to improve the management of recreational users in order to prevent ecological damage to intertidal shellfish. To successfully evaluate the impacts of beach users, the study species and ecosystem must be understood. Therefore chapters not only evaluate the impacts of users, but also understand the sand beaches of Pegasus Bay and tuatua populations within them. The final chapter provides management recommendations using all information presented in prior chapters. This is to provide a more robust management model compared to that produced using single-sources of information (Nicholson *et al.*, 2009).

An outline is shown in Figure 1.13 which shows how chapters are linked.

Chapter 2: *Management of vehicle and horse users on sand beaches.*

Chapter 2 reviews sand beach management of vehicle and horse users both locally and internationally. Literature is used to identify the effects of the identified management options on shellfish beds in the intertidal zone.

Chapter 3: *Habitat and tuatua distribution.*

Chapter 3 examines the relationship between physical beach dynamics and tuatua distribution. This comprised of a two year study of six beaches in Pegasus Bay measuring cross-sectional beach profiles, sedimentary analysis and tuatua distribution.

Chapter 4: *The potential vulnerability of tuatua in Pegasus Bay*: *size as an indicator of physical impacts*

Chapter 4 describes the size structure of tuatua populations in Pegasus Bay over the same two year period as in Chapter 3. Two experiments also evaluate size-burial depth relationships and test compression strength of the tuatua shell. The findings are discussed in relation to vulnerability of intertidal tuatua to heavy beach users.

Chapter 5: *The effects of vehicles on tuatua in Pegasus Bay.*

Chapter 5 presents an experimental *in situ* study of the impacts of vehicle passes on shellfish mortality and reburial success. The results are discussed and recommendations to mitigate such impacts are made.

Chapter 6: The effects of horses on tuatua in Pegasus Bay.

Chapter 6 presents findings from observational and experimental *in situ* studies to evaluate the impact of horse users on tuatua. The results are used to determine possible implications of frequent horse use and mitigation measures are discussed.

Chapter 7: Synthesis of chapter findings

Each chapter prior to Chapter 7 has made management recommendations are made using a single source of information; however, this chapter utilises all information presented in this thesis to make robust recommendations. These recommendations are evaluated with extrapolative modelling to predict the outcomes for intertidal shellfish.

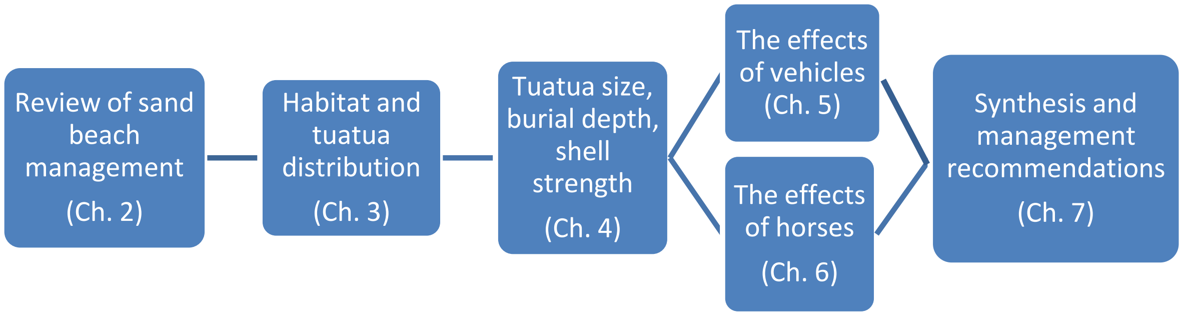


Figure 1.13: Thesis structure and links between chapters.

Chapter 2 Management of vehicle and horse users on sand beaches: a review

2.1 Introduction

Management of sand beaches in regard to human activities does not usually have a high level of consideration for ecological implications. If ecology is considered, only easily visible species are protected, and ‘hidden’ infaunal intertidal biota is ignored. This often results in coastal assemblages being altered from their natural state. Designation of the intertidal zone for recreational activities, such as vehicle driving and horse riding, is a good example of how this could occur. Such designation protects bird nests, but the effects that this may have on intertidal biota is not considered. If this disregard for intertidal biota continues, the effects are likely to be felt by future generations.

The aim of this chapter is to review and identify key drivers of management of vehicle and horse users which affect intertidal shellfish. This chapter discusses why ecological considerations are important (Section 0), reviews current management that exists for vehicle and horse users internationally (Section 2.4 and 2.5), and in New Zealand (Section 2.7). It then examines how intertidal shellfish may be affected by these methods (Section 2.6). The successfulness of New Zealand’s management system is evaluated in relation to shellfish (Section 2.8) and Pegasus Bay as a case study with implications for intertidal shellfish discussed (Section 2.9).

2.2 Ecological impacts of beach management

Sand beach management has a significant focus on physical, or geomorphic, hazard reduction and recreational safety; however, ecological protection is largely overlooked. This is perhaps most evident with physical hazard management which is used to both protect and enable human development. For example, seawalls and breakwaters, commonly built to enable shipping and reduce beach erosion, can drastically alter species assemblages. Beach nourishment, another method to combat erosion, can instead smother infaunal species. It is therefore important that management practitioners understand the impacts of the methods they choose to employ (Connell, 2001).

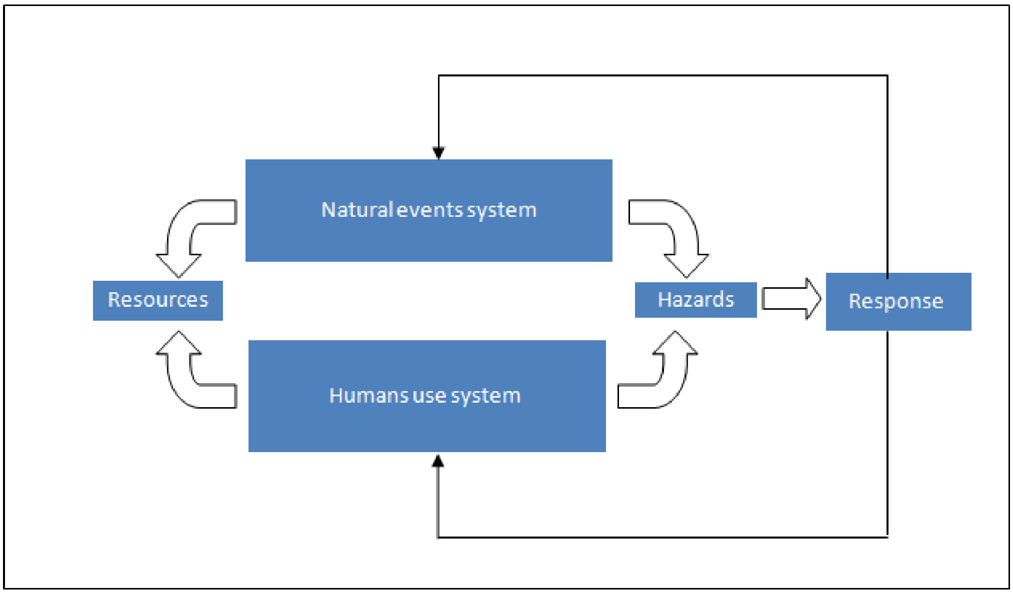


Figure 2.1: Flow diagram of the interaction between nature and humans that create resources and hazards which initiate response from management authorities (Adapted from Burton *et al.*, 1978).

A hazard cannot be easily defined; its definition depends on how humans are using environmental resources (Burton *et al.*, 1978). Therefore, a hazard depends on the interaction between humans and the environment (Figure 2.1). Management involves identifying and mitigating these hazards.

Methods used in hazard management can have detrimental effects on ecosystems such as smothering infaunal species, changing and disturbing substrate (Thrush *et* al., 2004; Bulleri, 2005). Understanding of the effects of hazard reduction methods is important if ecosystems are to benefit. For example, Komar (1997) has classified management options for a receding coast into four categories:

1) No action – the coast is allowed to encroach into development.
2) Retreat and relocation – the human population and sometimes buildings are moved away from the coast.
3) Beach nourishment – considered a ‘soft’ engineering option and involves depositing sand on the beach and allowing wave action to build the beach
4) Stabilisation – a ‘hard’ engineering solution: solid structures are made that aim to take or dissipate wave energy and reduce erosion.

‘No action’ and ‘retreat and relocate’ responses to coastal erosion may be considered to be the best responses where ecosystems are concerned. This is because it allows for the ecosystem to be left as natural as possible and so it can continue to adapt to natural disturbances. However, this option is unpopular due to human developments being valuable and perceived as worthy of protection.

Beach nourishment is another option considered to be successful in preventing coastal erosion in certain situations (Komar, 1997) and is deemed to be an aesthetically and ecologically favoured option over ‘hard’ solutions. Such methods include using similar sediment to the natural shore and dumping small amounts over time, or placing material on the backshore (Spreybroeck *et al*., 2006). However, literature shows that large deposits of sediment can have negative effects on intertidal ecosystems through smothering (Thrush *et al.*, 2004). The quantity of the deposit also influences the rate of recovery (Zajac & Whitlach, 2003). Beaches that contain shellfish populations are more likely to experience adverse effects from this sediment deposition.

Predators, such as birds, are also affected by nourishment methods. A study found that beach use by shore birds was reduced by 70-90% on nourished beaches as a result of the reduction of prey species and habitat area (Peterson *et al.*, 2006). Although this study found that the time taken for the bird population to recover may be as little as one season, this is still an unnecessary pressure. In New Zealand, beach nourishment occurs but is not a highly popular option due to high initial and ongoing maintenance costs. Beach nourishment has also been used to create recreational beaches as seen in Oriental Bay, Wellington. Often these nourishment projects are amenity driven, such that the methods used to construct these aesthetically pleasing beaches could result in detrimental effects the naturally occurring infaunal biota.

One of New Zealand’s main ‘soft’ engineering methods of coastal protection is dune enhancement, primarily using planting programmes that trap sediment landward of the Mean High Water Springs (MHWS) line. This method attempts to mimic natural processes to create dunes; however, it can take a long time to build a dune that will provide sufficient protection from the coast. The plant species introduced in this process can also displace indigenous ecosystems and lead to dramatically different types of dune systems.

‘Hard’ engineering solutions to coastal erosion are another popular option due to the perceived permanence and reliability of such structures. The two main types of ‘hard’ defences are shore-paralleled seawalls and revetments, and shore-normal groynes and breakwaters (Komar, 1997). Seawalls are the most common method employed and are designed to take the full force of coastal waves. Groynes and breakwaters are used to create buffer zones by trapping sediment and dissipating coastal forces (Komar, 1997). These structures can have a range of adverse effects on coastal ecosystems and ecological implications associated with the nature of the structure.

Breakwaters are situated in the subtidal zone and can alter species assemblages by increasing the heterogeneity of the environment through the addition of a new substrate. A breakwater designed to incorporate long-shore processes can be more beneficial than other hard solutions because sand builds up over time. This process allows shellfish to maintain a stable population, adapting to slow changes over time.

Increased habitat heterogeneity created by breakwaters allows new organisms to enter an area that otherwise would not (Bulleri, 2005). Invasive species are known to use artificial structures, such as breakwaters, as vectors for transport (Floerl *et al.*, 2009) and breakwater used in harbours facilitate invasive species dispersal via ship ballast discharges and other fouling organisms on the hull. Species assemblages may be altered and community success reduced.

Breakwaters and groynes also have indirect effects on shellfish by facilitating other species. For example, artificial structures attract fish, increasing the presence of predator species (Clynick, 2008). Wave climates are also reduced, creating less turbidity and better vision for fish predators making the protruding siphons of shellfish in the sand more visible.

The loss of suitable habitat is a large problem that exists when artificial structures are placed in coastal areas. This is caused by sea level rise induced by climate change. In New Zealand, seawalls are used to protect coastal infrastructure and as sea levels rise; these hardened backshores prevent intertidal and saltmarsh ecosystems from retreating via the process of succession. This process has been termed ‘Coastal Squeeze’; when sea level rise causes horizontal shrinkage and coastal retreat and erosion is stopped by hard defence structures resulting in a loss of habitat. A good example of this occurring is a boulder wall constructed at Scarborough Beach, Canterbury. Although this wall protects the Sumner Township, there is no beach face landward of the Mean High Water Spring (MHWS) because the wall is now positioned on the foreshore. The reduced habitat space prevents some species from being able to inhabit the area.

Future hazard management practices require both sub-aerial and intertidal/submarine ecological impacts to be considered. Failure to do so may result in direct impacts on populations from smothering in 'soft' solutions or replacement of habitat in 'hard' solutions. The facilitation of predators and invasive species can also have adverse effects on the shellfish population.

Why beach management should consider intertidal shellfish

Sand beach management must not only consider visible species, such as birds, but also infaunal biota because all components of an ecosystem are necessary for functioning. Bivalves are a major infaunal component of sand beach ecosystems and exert control of ecosystem function and structure (Vaughn & Hakenkamp, 2001). Intertidal biota, such as tuatua (*Paphies donacina*), carry out a range of ecosystem services and failure to recognise their importance can have flow-on effects for a coastal ecosystem. Such services include facilitation of other species, filter feeding and being an important food source. Facilitation is a key attribute of bivalves in an ecosystem. Bivalves burrow into the sediment of sand beaches (Hull *et al*., 1998) and facilitate microbial activity by increasing the oxygen levels of the sediment with bioturbation (Vaughn & Hakenkamp, 2001). Filter feeding by bivalves also recycles nutrients into the ecosystem by increasing nitrogen in the water column (Pfister, 2007).

The value of bivalves to humans is under appreciated; if their filtering of the water is disrupted this could result in more turbid water, which can be less appealing for human beach users (Vaughn & Hakenkamp, 2001). Water turbidity can influence tourism and coastal economies that are driven by beach visitors.

The ecological importance of bivalves is also high. These animals occupy a low trophic level in the ecosystem, providing food for fish, crustaceans, and birds (Knox, 2001). Due to their importance in sand beach ecosystems bivalve changes have both bottom-up and top-down trophic effects when abundances are altered. A loss of a single species of bivalve can trigger trophic cascades which can have large impacts on ecosystem functioning. If bivalve abundance reduces then it would be expected that its predators of a higher in trophic status will also be reduced due to lack of food (Bhattacharya & Sarkar, 2003). Species that were previously facilitated by bivalves, such as polychaete worms, would be expected to be less abundant.

Management of shellfish is largely focused on two aspects; contamination and sustainable fisheries. However, while emphasis is placed on maintaining a healthy adult population of shellfish, no consideration is given to the juvenile stages (World Health Organization, 2010). Many species of bivalves are restricted to the subtidal zones of beaches, but some species utilise the intertidal zone at certain stages of their life cycle, usually at juvenile stages. As mentioned in Chapter 1, tuatua (*P. donacina*) are one example of these bivalves in New Zealand. Other species include *Donax deltoides* in Australia (Schlacher & Thompson, 2007), and *Donax variabilis* in North America (Ellers, 1995). Management practices need to consider juvenile intertidal shellfish because failure to do so would adversely affect the population if recruitment is reduced.

2.3 Potential effects of vehicle and horse use on biota

Recreational use of sand beaches often entails the use of vehicles and horses: each of which has the potential to detrimentally impact this delicate ecosystem. Amenity users and tourists use vehicles to access fishing spots or hard-to-reach areas. In Australia, tourist vehicles can reach traffic volumes of up to 500 per day and can affect up to 65% of species present on sand beaches (Schlacher & Thompson, 2007). Horses are used by tourists and locals who enjoy riding in the coastal environment. Commercial trainers also use beaches to train gallop and harness racers. A majority of vehicle and horse traffic occurs within the intertidal zone where the sand is more compact, making driving and horse riding easier. Management strategies that control vehicles and horses often focus on safety of other users and protection of shore bird species, such as the fairy tern (*Sterna nereis davisae*) (Department of Conservation, 2011). As shore birds nest above the high tide line, this results in vehicles and horses being restricted to the intertidal zone.

The impact of vehicle users on shellfish populations has previously been underestimated (Wolcott and Wolcott, 1984); recent literature has quantified these relationships (Schlacher *et al.,* 2008a; Schlacher *et al.,* 2008b). Despite research on the distribution of bivalve species in the intertidal zone, shellfish are largely overlooked in management policies (Table 2.1). This could be due to perceptions of the shell providing sufficient protection to the individual from disturbance (Wolcott & Wolcott, 1984).

Table 2.1: Table showing the focus of international literature sourced that examines the effects of recreational activities in coastal environments

Impact type	**User Type**	**No. of papers**	**Crustaceans**	**Bird**	**Plant**	**Shellfish**	**Other**
Mortalities	Vehicle	11	2	4	5	2	2
	Horse	0	0	0	0	0	0
	Both	0	0	0	0	0	0
	Other	2	0	1	1	0	0
Sub-lethal	Vehicle	12	8	0	3	3	3
	Horse	0	0	0	0	0	0
	Both	0	0	0	0	0	0
	Other	3	0	0	1	0	1

Vehicles affect intertidal infaunal organisms, with higher traffic causing increased mortality (Foster-Smith *et al.*, 2007; Schlacher *et al.*, 2007; Schlacher *et al.*, 2008a; Schlacher *et al.*, 2008b; Moller *et al.*, 2009; Marsden & Taylor, 2010). There are sub-lethal effects on organisms such as changes in behaviour (Schlacher & Lucrezi, 2010) and the morphology of individuals (Lucrezi & Schlacher, 2010). Little is known of the effects of horse traffic in the intertidal zone. Previous studies in terrestrial environments have shown that trampling by horses has had significant effects on diversity and biomass of vegetation (Whinam & Comfort, 1996; Whinam & Chilcott, 1999; Torn *et al.*, 2009). Quantifying the effects of vehicle and horse users on shellfish is vital for management plans to protect intertidal biota.

2.4 Vehicle management issues and practices

A study by Priskin (2003) found that tourists perceive vehicle driving on sand beaches as harmful for multiple reasons, but not due to crushing of biota in the intertidal zone. A lack of knowledge of biota on sand beaches is likely that this reason was not mentioned. Vehicle management on sand beaches is focused on three main issues including safety of beach users, erosion, and wildlife conservation, and employs a variety of options including permits, area and zone based designation, seasonal closures and complete bans. In most cases these methods are not used with the intent to benefit shellfish. Often perceptions of sand beaches are that of a 'dead' zone with very few living organisms. This may also be the view of management practitioners because in many places around the world vehicles are allowed on beaches with very little or no control.

Vehicle management for safety

The safety of both vehicle and other types of beach users is a key concern in sand beach management. In New Zealand, bylaws are put in place to control vehicle users on beaches, but every country has their own legislative systems for managing activities. The two main options used worldwide to ensure user safety are permit systems and the designation of areas. Designating areas for certain activities allows a specific use to occur without compromising safety of other users. Area-based designation is good for addressing safety because some activities are not compatible in the presence of others, especially if they require similar environmental characteristics (Phillips & House, 2009). For example, the use of vehicles and horse riding requires low profile beaches with compact sand, so both activities usually occur in the intertidal zone. Safety can be compromised when both users are present so other methods of management may be needed to address this. Permit systems are another method that can be used to address safety of user groups. This allows management authorities to control traffic volumes on the beach and gives them the opportunity to inform users of the risks before they use the beach.

Vehicle management for erosion prevention

Erosion is a key concern with vehicle use on sand beaches and, if such effects are unmanaged, this could significantly impact on coastal settlements. This is because some coastal settlements may rely on sand dunes for protection. Previous studies on dune ecosystems have found the use of vehicles in sand dunes to be hugely detrimental. Vehicles reduce vegetation (Brodhead & Godfrey, 1977; Anders & Leatherman, 1987), result in high mortalities of dune biota (Luckenbach & Bury, 1983), decrease species richness (Hosier & Eaton, 1980), and accelerate shoreline erosion through vegetation damage and removal (Thompson & Schlacher, 2008). Importantly, if above ground vegetation is reduced then the sand trapping capacity of the dune system is decreased. Erosion effects occur indirectly from reduced dune vegetation not holding sediment together, rather than vehicles displacing sediment. Most countries recognise the effects of vehicles on dune vegetation so management policies aim to keep vehicles away from areas that are susceptible to erosion. Most policies permit traffic on the remainder of the beach which contains other vulnerable biota. This can be seen in the Waimakariri and Hurunui Northern Pegasus Bay Bylaw, 2010 which has pushed vehicles below the high tide line.

Vehicle management for ecological protection

Ecological protection is also an issue that should be considered when controlling any activity that takes place on a beach (and any other natural resource). The two main methods commonly applied for reducing wildlife loss from vehicle use on beaches are, firstly, seasonally closing the beaches and, secondly, designating areas of the coastal zone: that is, only allowing vehicles below the high tide line. If vehicle use is considered to be too detrimental, a complete ban may be enforced. South Africa has opted for a complete ban but still allows the deputy-director general to grant exceptions (Department of Environmental Affairs and Tourism, 2004). South Africa is not unique in banning vehicles on beaches. The French coastal law (La Loi Littoral, 1986) also bans these users. The main benefit of keeping vehicles away from wildlife is that floral and faunal habitation of beaches can occur without disturbance from human activities. This allows for assemblages to remain in a natural state.

2.5 Horse management issues and practices

In many countries, including New Zealand, South Africa, and Australia, sand beaches are popular areas for horse riding by tourists and amenity users, but management of these users is less common than for vehicles. Where management does occur, similar methods are used. As such, management of horse use on beaches focuses on safety for other users and erosion. If ecological considerations are made, these typically disregard intertidal biota. For example, many coastal plans push traffic into the intertidal zone to protect other species above the high tide line.

A significant problem is that many countries and relevant authorities have no management in relation to horses; these tend to be poorer countries such as Mozambique. A lack of management means that horses can be ridden at any speed, time, or location on the beach, which can result in widespread environmental damage and affect safety of other users. Literature suggests that horses are likely to cause similar damage to dunes and nesting birds as vehicles (Luckenbach & Bury, 1983). Whether the damage would be similar for shellfish is unknown and an aim of the present research is to determine this (see Chapter 6).

Figure 2.2: A trotting trainer running a horse on the Woodend Beach, Canterbury.

Horse management for safety

Safety of other users is a key concern in controlling horse riders. Permit systems are a reliable system for this and are used to control and monitor horse users. Permit systems can be informative to managers by providing knowledge as to the amount of users in a given day as well as to make users aware of regulations. This system is widely used for many beaches in the United States of America (U.S.A.) and is being developed for use in Sefton, UK (Fylde Borough Council, 2011). The permit system for Island Beach, USA, allows horse use of the beach to occur between 1st October and the 30th April (New Jersey Department of Environmental Protection, 2011). This is presumably when there are less people on the beach, making it the safest time for horse riding to take place. A permit system is also used for Crane Beach, USA, to prevent large amounts of horse users by only allowing 50 horses per day. Again, this is mostly for the safety of other users rather than ecological protection.

Horse management for erosion prevention

Horses have similar effects on dune systems as vehicles so the impacts on erosion are likely to be comparable. The effects include vegetation reduction, altered community composition (Törn *et al.*, 2009) and accelerated erosion due to the churning of tracks (Whinam &

Comfort, 1996). For this reason, the horse management strategies are the same as for vehicles with horses not being allowing on sand dunes and in other erosion prone areas.

Horse management for ecological protection

Ecological protection is important in sand beach management but deciding which species to protect over others is a contentious issue. Past decisions have resulted in more visible species being protected over others. This prioritisation can be detrimental to ecosystems by altering natural abundances of certain species. In New Zealand, horse use is generally controlled by bylaws introduced by the territorial authority responsible for that beach. Unlike vehicles, horses tend to be allowed almost everywhere on some beaches and may be allowed to be ridden above the high tide line (Tauranga City Council, 2007). It is more beneficial for shellfish if horses are above the high tide line because aquatic fauna do not inhabit the dry beach face (Davenport & Macalister, 1996). However, avoidance of nesting birds above the high tide line at times of the year may encourage horse users to concentrate lower down the beach face. Horse users can be difficult to control in large expanses of coast and additional incentives may be needed help prevent environmental degradation. Awards, such as the Green Business Award given to Tassariki Ranch, Australia, in 2007 and 2008 (Tassariki Ranch, 2011), can encourage companies to participate in more environmentally practices. This company arranged horse treks during low tide so that riding was done on the intertidal zone; this was in order to protect the nesting bird populations.

In the USA, nesting species such as hooded plovers and loggerhead turtles utilise the dry beach face and are protected by management policies that only permit horses on the intertidal zone (Cape Hatteras National Seashore Off-Road Vehicle Negotiated Rulemaking and Management Plan/EIS, 2010). Restricting horse users to the intertidal zone could be causing detrimental effects to the intertidal ecosystem. Nesting birds have also influenced the management of beaches in some areas of the USA by stipulating which seasons a beach can be ridden on. For example, at Crane Beach, Massachusetts, horses are only allowed on the beach by permit from the 1st October to the 31st of March and have to be ridden below the high tide line (Ipswich Council, 2011). Seasonally closing the beach to protect nesting species is very beneficial as it prevents destruction of nests during these times of vulnerability. These methods can achieve effective protection of native shorebirds, but protection of prey species, such as shellfish, crustaceans, and polychaetes, which inhabit the intertidal zone should also be considered and incorporated in these plans to give beneficial outcomes for the ecosystem as a whole.

2.6 How shellfish are affected by management techniques

Management to mitigate the impacts of vehicles and horses on sand beaches often utilises similar methods due to the perceived similarity of the two activities. There are five main methods which are used to control horse and vehicle movements which have the potential to impact shellfish populations. These methods are issuing permits, designating areas for use, designation of specific zones of the beach face, seasonal closures, or complete banning of the activity (Table 2.2). To successfully manage shellfish populations it is necessary to understand the benefits and disadvantages of choosing a particular system. The following sections review the ecological effects each management method and discusses how these could be applied to protect shellfish.

Table 2.2: A summary of management papers found that control vehicle and horse use on beaches with number of documents listed. The overall effects of management of shellfish is rated as beneficial (+), neutral (0) and disadvantageous (-).

			Areas benefited			Areas disadvantaged			
Activity controlled	Method of control and number of times employed		Dunes	Beach face	Intertidal zone	Dunes	Beach face	Intertidal zone	Managements effect on shellfish (+/0/-)
Vehicle only	Permit	1	✓	✓	✓				+
	Seasonal Closure								
	Area Designation	3	✓	✓	✓	✓	✓	✓	+
	Zone Designation	1			✓			✓	+
	Banning	1	✓	✓	✓				+
Horse only	Permit	1							+
	Seasonal Closure	1	✓	✓	✓				+
	Area Designation								
	Zone Designation	1	✓	✓				✓	-
	Banning								
Both Vehicles and Horses	Permit	1	✓	✓	✓				+
	Seasonal Closure	2	✓	✓	✓				+
	Area Designation	3	✓	✓	✓	✓	✓	✓	**0**
	Zone Designation	3	✓	✓				✓	-
	Banning								

Permits

Permit systems for vehicle and horse users is a method for monitoring and informing users of a particular area of coast. This system could be used to ensure safety of other users and the environment. By issuing daily permits, the management authority can easily monitor the number of vehicle and horse users on the beach for a given day. This data could then be used to identify seasonal trends in beach use.

Permit systems are most widely used in the United States of America to control vehicle and horse users, and implementation of such systems varies between management and may only be focused on a single user group. At Cannon Beach, Oregon, the application for a permit must be for a specific reason such as retrieval of gear or to access hard-to-reach areas. This requirement is beneficial to shellfish beds because it would limit the amount of beach traffic by excluding ‘joy riders’ from accessing the beach. In Donegal County, Ireland, horse users require permits to use the beach during June, July and August between 11 am and 7 pm. These times are when beaches are busiest, so management of horse use is necessary to ensure safety of other users.

Permit systems could also be utilised to allow authorities to ensure vehicles are not modified in a way that intertidal shellfish will be detrimentally affected. For example, vehicles fitted with off-road tyres dig deeper in the sediment and may cause more damage. The use of a permit system allows the authority to inform users of possible outcomes of their behaviour and how impacts can be mitigated. A permit system is beneficial for shellfish because it limits traffic and prevents unwanted behaviour, but it is often necessary to use other methods of control to ensure environmental protection.

Seasonal or temporary closures

Seasonal closures are used to ensure safety of other users or to protect wildlife at vulnerable life stages. A seasonal closure is when a particular activity is not allowed on the beach during certain months of the year. For example, when safety is the main issue, beaches are closed from vehicle and horse use during warmer months when more bathers are present. Seasonal closures for wildlife conservation largely focus on nesting species and do not include intertidal biota. In Cape Hatteras, U.S.A., vehicles are managed by a permit system which restricts use during certain months which are at times of birds and turtles nesting (Cape Hatteras National Seashore Off-Road Vehicle Negotiated Rulemaking and Management Plan/EIS, 2010). Protecting a species during this vulnerable life stage removes artificial selection pressure (e.g. vehicle driving and horse riding). A study on birds found that up to 81% of nests were run over by vehicles during the incumbent period (Buick & Paton, 1988). In addition to crushing, vehicle tracks can increase the effect of other selection pressures. For example, tyre tracks increase the time Loggerhead turtle (*Caretta caretta caretta*) hatchlings take to reach the sea, increasing the predation risk from birds (Hosier *et al*., 1981).

Seasonal closures tend to focus on species that are visible, such as birds and turtles, and species hidden from human eyes are ignored. Bivalves are one of these species because when they inhabit the intertidal zone, are small, and buried shallowly in the sediment. Incorporating these 'hidden' species into sand beach management policies relies on obtaining reliable and in-depth scientific information.

Using seasonal closures to protect shellfish during vulnerable life stages would be beneficial to the population because it would give them a chance to recruit without vehicle and horse traffic crushing individuals. The timing of seasonal closures could then align with shellfish recruitment. A key issue with this approach is that more investigation is needed to identify when recruitment takes place. Marsden (2002) suggests that recruitment of bivalves occurs during the warmer months, but often the difficulty in obtaining this can further stymie and delay efforts to understand their population and protect it.

Area-based designation

Area-based designation is a common option used by many management authorities worldwide, including those in New Zealand. The areas closed to vehicle and horse traffic tend to coincide with popular swimming areas. If areas closed for safety reasons contain shellfish populations, they are likely to benefit from this option. However, area-based control can result in traffic being condensed into smaller areas, which can bring with it additional safety issues and ecological damage for those areas. The main ecological benefit of this method is that there would be an area with no human activities, allowing the ecosystem to function naturally. Studies have shown that beaches that are open to vehicle traffic have altered and less-diverse assemblages than closed beaches. For example, ghost crabs (*Ocypode* spp.) change behaviour, compress home ranges, and even stop reproduction in areas with vehicle traffic (Steiner & Leatherman, 1981; Lucrezi & Schlacher, 2010; Schlacher & Lucrezi, 2010). A closed area would be likely to benefit all species that are protected from these users. However, if traffic is to continue at the same frequency but concentrated within a smaller area, ecological damage could be increased to a level that species abundance is reduced.

If area-based management was adapted to protect shellfish, there are a range of factors that need to be considered. It is difficult to designate specific areas for the protection of shellfish, and many other intertidal biota, because reproduction patterns can vary and are not easily detectable. The population is also hard to detect, with sampling techniques being labour intensive. When the population's distribution is found, knowing what size area to close can be very contentious. Identifying the species that management strategies are to protect is important because the individuals' mobility and dispersal range are two key factors in deciding the size of the area required (Halpern & Warner, 2003). The dispersal range of shellfish is very hard to determine because they have a planktonic life stage (Marsden, 2002) and dispersal patterns can depend on longshore processes like current speed and direction, factors which can vary day-to-day and year-to-year. If long shore processes result in juveniles being taken into neighbouring zones where high beach traffic exists, crushing may occur during this crucial time of recruitment. Restricting users to a certain zone of the beach, away from vulnerable species is another option to combat this issue.

Zone-based designation

Designating particular zones of the beach is another common method to control activities and prevent erosion and ecological damage. Under current management practices, this method has the most potential to be detrimental to intertidal biota because the majority of strategies in New Zealand and worldwide designate the intertidal zone for horse and vehicle use, usually to protect bird life (e.g. Waimakariri Northern Pegasus Bay Bylaw, 2010). Furthermore, the intertidal zone is likely to be selected because beach zones are difficult to define due to the dynamic nature of the coastal environment. The most recognisable part of beach zones is the high tide line, which can be easily identified by the visual change from dry to wet sand (Figure 2.3).

The visibility of the last high tide line may be the reason it is used in many strategies that designate zones for activities. For example, on beaches that protect nesting birds, all vehicles and horses must be used below the high tide line. Permitting traffic below the high tide line is very common and is done on most beaches with vehicle management in place (Table 2.2). One exception to this is in Cape Cod, USA, where no vehicles are permitted below the high tide line. This is because marked vehicle tracks are in place above the high tide line.

Restricting traffic to below the last high tide line has the most potential to be harmful to intertidal biota including shellfish. This is because traffic effects get condensed so there is a higher frequency of disturbance to biota.

In order to protect intertidal biota, traffic would have to be restricted to zones above the high tide line where nesting birds are present. This creates a conflict between which wildlife species are protected; a diverse intertidal population that is an important food source for many species versus a single bird species. If shellfish and birds are to be protected from vehicle and horse use, a dynamic plan catering for all would need to be created. In areas where environmental protection is a high priority, the banning of detrimental activities, such as vehicle and horse use on sand beaches, should be considered.

Figure 2.3: The last high tide line, where the dry (light) sand meets the wet (dark) sand.

Complete banning of horses and vehicles

A complete ban of activities which adversely affect sand beach ecosystems is by far the most favourable conservation outcome, especially in areas of high ecological value. This is because this method essentially removes vehicles and horses; a use which may have been acting as a selection pressure. A complete ban of vehicles would allow any organism living on a sand beach to be protected from human disturbances during all life stages. For shellfish, recruitment in the intertidal zone could take place without the risk of being crushed.

If a ban was implemented on an area that previously was affected by horse and vehicle users, expected outcomes would be an increase in species diversity and abundance, and the size of individuals. The rate of recovery may be rapid because clean sand communities, like those found in exposed sand beaches, are found to have fast recovery times (Dernie *et al*., 2003). The benefit of increasing diversity is that communities can be more resilient to other environmental changes allowing faster recovery in the future (Loreau *et al*., 2001). By banning vehicles and horses, conservation goals can be easily achieved; however, this can create opposition from stakeholders that use coastal resources. It is necessary for scientific information which evaluates the effects these users on the environment in order for ecological stakeholders to have a larger voice.

2.7 Management of Sand Beaches in New Zealand: recreational use vs. shellfish protection

Management of recreational activities on New Zealand’s sand beaches, such as vehicle and horse use, is highly important to protect the unique ecosystems that the coastline facilitates. The New Zealand coastline is arguably made up of a network of every type of beach system that exists (Hesp *et al*., 1999). Sand beaches are widely distributed along the coastline and, using Short’s (1999) international classification scheme can be classified into three different types: dissipative, intermediate and reflective. Dissipative beaches are low flat beaches and wave energy is dissipated across the surf zone, whereas reflective beaches are steep with breakers that surge up the beach and reflect energy back out to sea. Such characteristics can make certain beaches more desirable to user groups than others. For example, surfers prefer reflective beaches with high profile waves in the surf zone, whereas families prefer more dissipative beaches (Phillips & House, 2009). These types of preference can be used to classify beaches according to their recreational purpose.

In New Zealand there is limited conflict between users, due to the 11,000 km of coastline (Woodroffe, 2002), which provides sufficient space for all activities without encroaching on each other. Tensions between beach users may however become more prevalent in centralised locations. In New Zealand 96.6% of the population is within 50 km and 64.6% are within 5 km of the coastline (Statistics New Zealand, 2011). For example, during the summer months Taylors Mistake Beach, Canterbury, is a popular swimming and bathing location for Christchurch residents, but surfers also use this beach in high numbers. Safety issues can occur if swimmers are in the surf zone; therefore, some form of management control is required. In this case, surfers are not allowed inside the flags which swimmers are required to swim between.

New Zealand's coastal systems contain unique endemic biota which is due to the country's geographical isolation. The dispersal range of these species is not large enough to reach other land masses, allowing speciation to occur (Shluter, 2001). Consequently, many species have adapted independently to inhabit New Zealand's beaches. For example, on wave exposed sand beaches, tuatua species (*P. donacina* and *P. subtriangulata*) bury into the sediment to avoid wave forces, and they filter water in order to feed (Cranfield *et al*., 2002).

Unique biota inhabiting New Zealand influences the way in which some beaches are used. For example, whitebaiting is a common seasonal activity. Whitebait (*Galaxiidae* spp.) is caught using large nets and gear that are taken to the water's edge by vehicles. High abundance of whitebait in certain rivers attracts higher numbers of people and vehicles. In Canterbury, the Waimakariri River is heavily populated during whitebait season and, on average, 50 vehicles are daily parked at the river's mouth (personal observations). River mouths are important nesting areas for endangered seabirds, such as the Fairy Tern (*Sterna nereis davisae*), which nest on the ground camouflaged amongst shells (Department of Conservation, 2011). Protecting and preserving such species in their surrounding ecosystems makes sand beach management important to ensure environmental damage does not occur.

Figure 2.4: Whitebaiters and vehicles parked on the beach at the Waimakariri River mouth, Pegasus Bay.

New Zealand's coastal management system

New Zealand uses a top-down system of coastal management; with statutory framework guided by the Resource Management Act (RMA) 1991. The purpose of the RMA 1991 is 'to promote the sustainable management of natural and physical resources'. Sustainable management is further defined as 'managing the use, development, and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their social, economic, and cultural wellbeing and for their health and safety while- (a) sustaining the potential of natural and physical resources (excluding minerals) to meet the reasonably foreseeable needs of future generations; and (b) safeguarding the life-supporting capacity of air, water, soil, and ecosystems; and (c) avoiding, remedying, or mitigating any adverse effects of activities on the environment.

Coastal policies focus on particular areas of the coast and are prepared and administered by the relevant local and central government authorities (Figure 2.5). The functions, powers and duties of these authorities are defined in Part 4 of the RMA 1991 and the Local Government Act 2002. This guiding piece of legislation has the key goal of using integrated effects-based decision making to achieve positive environmental outcomes for future generations. It seeks to avoid, remedy or mitigate adverse effects of activities on the natural environment (e.g. sand beaches) and ensure that these resources are managed in a responsible manner.

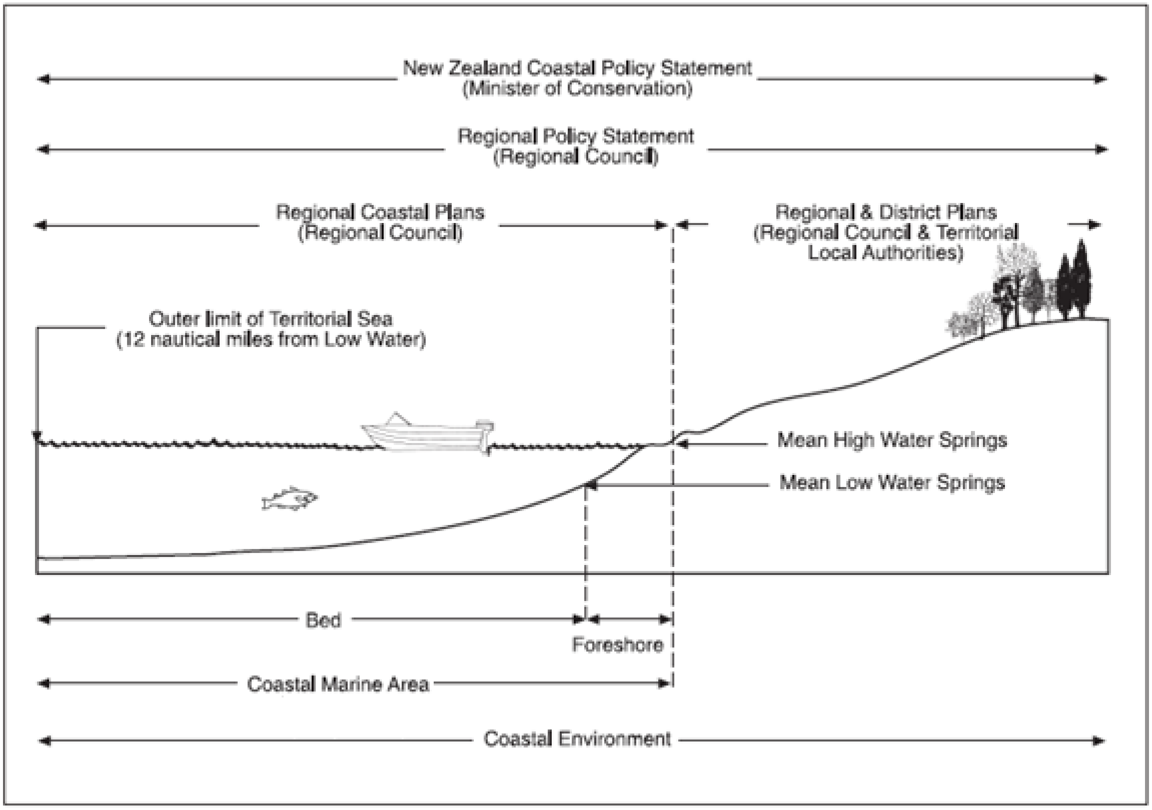


Figure 2.5: Management policies that control areas of the beach face and the relevant government agency responsible for their creation (in brackets) (figure taken from the Regional Coastal Environment Plan for Canterbury Region 2005).

The New Zealand Coastal Policy Statement (NZCPS) 2010, which sits beneath the RMA 1991, is the main environmental policy that guides local authorities during development of coastal plans. This policy is prepared by the Department of Conservation and ultimately signed off by the Minister of Conservation. Each territorial authority has the responsibility for preparing their own coastal policies and plans. The plans and policies created for the coastal zone by local authorities must not be inconsistent with the NZCPS 2010 and more significantly, the purpose of the RMA, 1991 (Figure 1.2).

In New Zealand, the responsibility for addressing regional coastal issues falls to local authorities. Each territorial authority has a set area over which they govern, the extent of these boundaries are often aligned with geographical features or around community structure.

For example, the Christchurch City Council's northern boundary is set as the southern edge of the Waimakariri River, while Environment Canterbury's boundary covers several catchments. Although different management techniques exist for managing coastal issues, many authorities enact bylaws for particular areas of beaches. Bylaws are perhaps the most commonly used tool to limit vehicle and horse use on beaches.

Local New Zealand authorities have power to make create bylaws under the Local Government Act (2002) Part 8 Subpart 1. Under Section 145, territorial authorities, such as Waimakariri District Council, are empowered to make bylaws with the purpose to (a) protect the public from nuisance, (b) protecting, promoting and maintain public health and safety, and (c) to minimise potential for offensive behaviour in public places. It is this focus that has seen a range of bylaws which pay little attention to ecological protection which is often left up to the regional authorities, such as Environment Canterbury, to develop. Under Section 149 Subsection 1, regional authorities can make bylaws for any land owned or controlled by the authority. In addition, the focus of such bylaws is not prescribed which allows ecological protecting from bylaws made by regional authorities.

Vehicle and horse use on New Zealand's sand beaches

Low sloping sand beaches are used by vehicles and horses and unless controlled, have the potential to damage these unique coastal environments. Vehicles are driven to access fishing spots, joy ride and to access events. Horses are ridden on sand beaches for general recreation by amenity users as well as by professional trainers. Studies indicate that horse training on sand is beneficial for horse strength and rehabilitation (Crevier-Denoix *et al*., 2010). Horse racing generates a similar amount of revenue to the wine and seafood industry in New Zealand. Racing earns $1,635 million annually and has 52,732 people who are employed or participate in the industry. Most training occurs in Waikato (4,400 Thoroughbred & 364 Harness horses) but Canterbury has the highest number of trainers of harness racers (2,229) and is second in thoroughbred training (1,025) (New Zealand Racing Board, 2010). The intertidal zone of the beaches is most commonly utilised by these trainers due to the compact nature of the sand.

Traffic on the intertidal zone can disturb the many species that inhabit this zone, including the native toheroa (*Paphies ventricosa*), which has suffered a significant decline in numbers over recent decades causing the fishery to be closed (Ministry of Fisheries, 2011). Events such as the 'Burt Munro Challenge' (a motorcycle race) have caused detrimental effects on Toheroa, destroying juvenile populations, and are still permitted (Moller *et al*., 2009). Other events, such as the ‘90 Mile Beach run’, a marathon event, and the ‘Snapper Classic’, a surfcasting fishing tournament, can be detrimental to beach fauna due to their associated logistics. Vehicles are driven on the beaches to access areas and carry equipment. If these activities are not controlled this has the potential for major environmental damage. Surf lifesaving national competitions also bring additional traffic to the beaches. In 2011, the Nationals were held in Mount Maunganui, Bay of Plenty. The Tauranga City Council Beaches Bylaw 2007 has a specific clause allowing vehicles to be used for such events.

Figure 2.6: Pictures of various events throughout New Zealand. Clockwise from top left; 90 Mile beach run, Karekare Beach horse races, racers in the Burt Monro Challenge and competitors of the Surf Lifesaving Nationals, 2011. (http://www.90milebeachrun.com/procedures.cfm, www.karekare.co.nz, http://www.surflifesaving.org.nz/Article.aspx?ID=12675#galleries, http://www.burtmunrochallenge.com/.

The Karekare Race Day, an annual horse racing event, could have adverse impacts on the ecosystem because it is concentrated in the intertidal zone where shellfish and polychaetes are abundant. The Onetangi Race Day on Waiheke Island, Auckland, permits horse racing, tractor racing and amphibious vehicle races. The weight and penetrability of tractors would be likely to cause large amounts of damage to the infauna. There are similar exemptions in the bylaws for Pegasus Bay, Canterbury, that allow for these events to take place. The horse associated traffic is likely to cause major disturbance to intertidal populations and could have a range of long-term effects.

2.8 Management of vehicle and horse users on New Zealand beaches

Despite the NZCPS 2010 having particular mention to the control of vehicles in the coastal zone (Policy 20), issues relating to vehicle and horse use on sand beaches have not yet been addressed by all local authorities. Management strategies employed to control vehicles and horses differ between regions and each has its pros and cons. Utilisation of information from a range of sources is a key strength of New Zealand's resource management system, but some aspects may be ignored resulting in environmental damage. Two of the most common methods used include banning vehicles on certain beaches (Tauranga City Council, 2007) or in certain areas (Whangarei District Council, 2008; Kapiti Coast District Council, 2009). Other authorities have designated certain parts of the beach face for vehicle use (e.g. the Northern Pegasus Bay Bylaw, 2010). In these situations, horse users are also confined to the intertidal zone.

Adopting the precautionary approach

Integrated management can be successful in achieving sustainable outcomes by using information from a wide range of sources. If this is done correctly an outcome will be achieved that balances stakeholder interests and achieves the purpose of the RMA 1991. Policy 3 of the New Zealand Coastal Policy Statement (NZCPS), clause 1 advocates that managers "adopt a precautionary approach towards proposed activities whose effects on the coastal environment are uncertain, unknown, or little understood, but potentially significantly adverse".

The precautionary approach has been ignored on all of New Zealand's beaches that permit heavy traffic (e.g. vehicles and horses). When such management policies are ignored the outcome could fail to achieve its goals. As mentioned in Section 2.2, there are a wide range of known effects from vehicles on flora and fauna of sand beaches. Horses are expected to have similar effects yet have very little or no control is placed on them in New Zealand. If the precautionary approach was used it would be expected that vehicles, horses and other such traffic would not be permitted on New Zealand's sand beaches.

The influence of defined management boundaries on ecological protection

In the coastal zone, many ecological processes can take place over large spatial scales and will nearly always overlap management boundaries. As such, the populations within those boundaries may be subject to differing effects from recreation. An ecoregion is the term given to boundaries that a species can inhabit. Ecoregions are often defined by geographic boundaries, not boundaries defined by people (Bailey, 2005). Long-shore processes are a key factor in determining these for the coastal environment. Ecoregions overlapping management boundaries increases the importance of integration between neighbouring authorities. A lack of integration will mean that biological communities will receive protection in one part of its ecoregion and not in another. As such population dynamics would be altered.

Policy 4 of the NZCPS 2010 aims to achieve consistency within regions by encouraging integration between management authorities. This form of management is particularly effective when authorities each have the capacity to fulfil its responsibilities (Lyver, 2005). When a neighbouring authority does not have the necessary resources, they will be unable to provide the same level of protection as their neighbour. As a result only areas of the coastal zone will be protected by those that can.

Utilisation of integrated management could be used to ensure biological communities receive equal amounts of protection throughout New Zealand. Management efforts can focus on the same goals with ecological protection and resource use being balanced equally. Management needs to remain relative to the region; the idea that one-size-fits-all is not always applicable. For example, absence of sand beaches in a particular management authority's boundary would see no need for them to be involved in development of policies of this type. Promoting integration between management authorities needs to continue for effective policy development and implementation. More importantly, these organisations, unbound of geographical boundaries, could achieve protection of ecoregions as a whole.

Consideration of intertidal biota for ecological protection

Coastal management in New Zealand has largely focused on safety, erosion and protecting bird nests, so policies that control vehicle and horse users usually confine these activities to the intertidal zone. For example, the Kapiti Coast District Council Beach Bylaw 2009 permits traffic on the foreshore of beaches, but not above the high tide mark. However, some management authorities permit vehicle and horse use to occur in all areas of the beach face (e.g. Whangarei District Council Vehicles on Beaches Bylaw, 2008). Intertidal biota, such as shellfish, will benefit because traffic is spread over the whole beach reducing the probability of high levels of disturbance. New Zealand’s beaches contain diverse native fauna which fulfil important ecosystem services. For example, tuatua are a large prey species that reduce water turbidity (Vaghn & Hakenkamp, 2001).

Increased traffic in the intertidal area may result in the functioning of sand beach organisms being reduced. This will not only affect the biological community, but also humans. For example, shellfish disturbed by vehicles may reduce the amount of filtration of water due to stress, which would result in more turbid water. This is not aesthetically appealing for humans, and could decrease phytoplankton production due to sunlight not penetrating as deep into the water column. Overall, less energy is then passed through trophic levels reducing productivity of the ecosystem.

It could be argued that the most ecologically beneficial outcome for intertidal biota would be achieved by banning vehicle and horse users. As many stakeholders are unlikely to meet this option with enthusiasm, local authorities, in permitting vehicle and horse use, must aim to reduce the frequency and impact of these disturbances. Reducing the spatial distribution and volume of traffic on the foreshore of beaches would be two suitable methods to limit impacts. Currently, no management policies in New Zealand do this; an effective permit system would need to be implemented to ensure limited numbers of users are accessing the beach by vehicle or horse.

The effects of frequent use of New Zealand’s sand beaches on intertidal fauna

Vehicle and horse users can be found on beaches all year round, subjecting fauna to daily disturbance. The intensity of this disturbance also varies temporally and is likely to be most damaging during sensitive life stages such as reproduction and recruitment. For example, activities, such as whitebait and salmon fishing, occur in the warmer months, at the same time when many sand beach species reproduce. The majority of management policies in New

Zealand allow vehicle and horse users beach access all months of the year. Kapiti Coast District Council is the only known exception to this; they do not allow horses on beaches between 11am and 5pm from 1st December to the end of daylight savings (around April).

Intertidal species could be protected during important life stages, such as during reproduction, if management policies were designed to protect intertidal shellfish populations. Juvenile populations would be able to recruit without pressure from vehicles and horses. For this management option to work effectively, scientific information on the species life cycles is needed to identify appropriate timing of closures. The following section gives a brief summary of how management bylaws are used to control vehicle and horse users in Pegasus Bay, Canterbury. The environmental outcomes of these are discussed in relation to the impacts on shellfish populations.

2.9 Case study: Management of vehicle and horse users in Pegasus Bay, Canterbury.

Variation between regions of sand beach management makes it necessary to focus on one area of coast to evaluate the effects a particular strategy may have; Pegasus Bay, Canterbury. Pegasus Bay is eastern-facing bay which hosts a wide range of activities including vehicle driving and horse riding. Management that controls these activities aims to ensure safety of users and mitigate environmental damage. Beaches in Pegasus Bay are classified as wave dominated long-shore bar trough beaches (NIWA, 2011a). Horse riding most commonly occurs on Ashworths, Woodend and Spencerpark Beaches on a daily basis. Vehicles are usually driven around the river mouths (Waimakariri and Ashley) during the whitebait and salmon seasons, but are present at lower numbers outside of these times.

2.9.1 Current management of users in Pegasus Bay

Vehicle and horse users are controlled through bylaws that are implemented by the Councils that manage the area. Details on these Councils can be found in Chapter 1, section 1.7.1. These bylaws are known as the Waimakariri District Council Northern Pegasus Bay Bylaw 2010 (Appendix 2.1) and the Hurunui District Council Northern Pegasus Bay Bylaw 2010. The Christchurch City Council does not have any bylaws directly relating to control of vehicles on its beaches; however, the Regional Coastal Environment Plan for the Canterbury Region 2005 (Policy 8.10) does cover this issue.

Horse riding is permitted along most of the beach in these bylaws, however it is not allowed near the flags at surf lifesaving clubs dotted along the coastline. Vehicle use is not as widely permitted. This is allowed north of the Heyders Road gate to the Woodend Beach access way, and on Ashworths Beach. If drivers have a permit they may drive along an access way at Waikuku Beach. Permits can also be granted for access to other areas as needed. Vehicles have speed restrictions of 30 kmh^{-1} and which is reduced to 10 kmh^{-1} when within 50 m of people. Vehicles must also give way to other users, including horse riders. Another key requirement of this plan is that all vehicles and horses must go directly to the marked track or below the last high tide line. This is mostly to protect shore birds that seasonally nest above the high tide line. This use pattern is likely to have large effects on the intertidal biota as well as those in the tracks to the intertidal zone.

2.9.2 The expected effects of the Northern Pegasus Bay Bylaw 2010 on intertidal shellfish

Like any management strategy, those for Pegasus Bay are likely to have a range of ecological effects on fauna. There are four main points of interest discussed for Pegasus Bay: the distribution of traffic on the beach face, free range of horses, high-use occurrence of traffic, and generally used definitions. The above management strategies have the potential to affect the success of shellfish populations on Pegasus Bay; the effects of these are examined below.

Distribution of traffic on the beach face

Shellfish, polychaetes and shorebirds inhabit and utilise the intertidal zone of these beaches. Frequent disturbances from vehicles and horses are perceived to have large effects on these populations but scientific research is needed to confirm this. A common species on these beaches, the South Island Pied Oystercatcher (*Haematopus finschi*) forages on polychaetes and other species in the intertidal zone. Human disturbance has been found to reduce the foraging potential of oystercatchers which could influence survival success (Stillman & Goss-Custard, 2002). Not only are visible species vulnerable, but also infaunal species, such as juvenile Tuatua (*P. donacina*), which are found in high numbers in the intertidal zone. The current management policies have condensed vehicle and horse use to a small area which will further exacerbate the effects discussed in Section 2.2. Traffic must enter and drive directly onto the intertidal zone; however, a defined path is not present which creates a fanning of vehicle tracks so that the effects of vehicles are spread over the beach face (Figure 2.8).

This will not only affect birds, which this bylaw is trying to protect, but will also results in high volumes of vehicle traffic in several areas of the beach. If a prescribed track was made this would be mitigated by reducing the spatial area of disturbance. Whilst the area that is selected for the track will likely suffer mortalities, the surrounding areas will benefit due to reduced disturbance. Mitigation of this would require for a set track to be established where low amounts of biota are present. The mobility of the river mouth, a key factor in the path's longevity, would also need to be considered in the design stages.

Figure 2.7: Satellite image showing the fanning of vehicle tracks (yellow lines) from the vehicle entrance point (red dot) at the Waimakariri River mouth, Pegasus Bay, New Zealand.

The free-range of horse users

Horses are currently used every day on the beaches of Pegasus Bay with no restrictions on the number of horses that can be brought onto the beach by an individual. For example, one person can run several horses on the beach multiple times with the potential to cause a large amount of damage to biota. It can be observed that many horse riders do not like to ride at speed over churned-up areas and will go higher or lower up the beach, depending on where existing tracks are situated, creating wider areas of disturbance (Figure 2.7). This results in disturbance to higher numbers of individuals than if the same tracks were to be used repeatedly.

Figure 2.8: Horse tracks distributed on the intertidal zone of Woodend Beach in Pegasus Bay, Canterbury.

High-use timing of vehicles

Vehicles are used in higher frequencies between the months of August and April, during the whitebait and salmon seasons which coincides with many intertidal species' vulnerable life stages. This includes recruitment and reproduction in shellfish populations (Marsden, 2002). Shellfish at recruitment stages are smaller, with weaker shells, making them more vulnerable to vehicle crushing. Recruitment takes place in the intertidal zone with individuals washing up and burying. A majority of the traffic is concentrated on the river mouths; however, the southern bank of the Waimakariri River mouth is 5 km north of the entrance, so vehicles are driven on the beach to access this area. Doing this would still allow access for whitebaiters and salmon fishermen but would reduce disturbance to the ecosystem. As a result, a small proportion of the ecosystem would be affected; however, river mouths have been shown to be areas where little recruitment takes place (Schoeman & Richardson, 2002).

Figure 2.9: Vehicles parked on Kairaki Beach by whitebaiters.

Non-specific definitions: *the potential for environmental damage*

Definitions that are used in bylaws are important. If definitions are too general, other undesired users could have free access due to the loop-hole created. This could occur in the Hurunui and Waimakariri District Councils Northern Pegasus Bay Bylaw, 2010, which uses the same definition given by the Land Transport Act 1988 for a motor vehicle. This is defined under section 2(1) of the Land Transport Act 1988 as:

(a) means a vehicle drawn or propelled by mechanical power; and
(b) includes a trailer; but
(c) does not include—

- *(i) a vehicle running on rails; or*
- *(ii) [Repealed]*
- *(iii) a trailer (other than a trailer designed solely for the carriage of goods) that is designed and used exclusively as part of the armament of the New Zealand Defence Force; or*
- *(iv) a trailer running on 1 wheel and designed exclusively as a speed measuring device or for testing the wear of vehicle tyres; or*
- *(v) a vehicle designed for amusement purposes and used exclusively within a place of recreation, amusement, or entertainment to which the public does not have access with motor vehicles; or*
- *(vi) a pedestrian-controlled machine; or*
- *(vii) a vehicle that the Agency has declared under section 168A is not a motor vehicle; or*
- *(viii) a mobility device*

This definition covers a wide range of vehicles including bulldozers and other heavy machinery. If such machinery was driven on the intertidal zone it could only take one pass to cause large amounts of damage to shellfish populations. While it is unlikely that this is common, I have observed that bulldozers and diggers being driven on the beaches of Pegasus Bay to clear access roads and lift stranded boats onto trailers. A large amount of environmental damage could occur if this was to happen frequently. It is suggested here that the definition needs to be changed to only control private vehicles, and heavy machinery is addressed separately.

2.10 Conclusion

Internationally, ecological protection is a small focus of sand beach management policies and practices and is often superseded by physical and geomorphologic hazard management focusing on erosion protection and recreational safety. Where ecological protection does occur, policies are mostly focused on nesting shorebirds and turtles that are visible and no infaunal species are protected. Horses are less controlled on sand beaches than vehicles, but both have been shown to cause a wide range of effects on sand beach biota. If management is present, focus is on user safety, preventing erosion, and protecting nesting wildlife. Five common vehicle and horse management options have emerged. These include permit systems, seasonal closures, designation of beach areas or zones, and complete bans. Each of these systems has benefits for shellfish; however, most benefits are indirectly achieved. For shellfish populations to be protected from the adverse effects of vehicles and horses on sand beaches a dynamic system using a combination of management methods should be employed.

Within New Zealand, management authorities are guided using an integrated effects-based framework set out by the Resource Management Act, 1991. As a result, some policies may be ignored amongst the plethora of information guiding management decisions. Some areas of New Zealand have developed policies that control vehicles and/or horses, but the method of control is not consistent. Variations occur in how vehicles and horses are controlled; however, a common method is to designate a zone of the beach for use; usually the intertidal zone. If vehicle and horse use is to continue on sand beaches throughout New Zealand more methods of control are needed to provide sufficient ecological protection. This may include permit systems to reduce traffic or seasonal closures at critical times of an organism's lifecycle.

On the local scale, Pegasus Bay beaches are well managed when it comes to ensuring safety of users and erosion, but protection of intertidal biota is not addressed. Vehicles and horses are often used on a daily basis, and higher numbers of vehicles are used in the months between August and April. While most of this increased traffic is focused on the river mouths due to whitebait and salmon seasons, travel to and from these areas may be done over large stretches of beach which could be causing damage to shellfish populations. Management practitioners need to mitigate the effects of users by limiting the number of horses and/or vehicles on the beaches. In addition, seasonally closing beaches may be necessary. Definitions for vehicles in these management plans are not specific to cars, so heavy machinery such as bulldozers and diggers could be used on the beach. Definitions need to be made to be specific for the bylaw.

Chapter 3 Beach characteristics and abundance of intertidal tuatua (*Paphies donacina*) in Pegasus Bay, Canterbury.

3.1 Introduction

Sand beaches are physically dynamic environments which contain a wide range of biota that are adapted to survive in this hostile environment. It is the interrelated nature of this environment and the fauna that makes understanding of abiotic and biotic processes and their relationships necessary. In a South African study by Schoeman and Richardson (2002), geographic and biotic factors were used to identify where recruitment takes place for the surf clam *Donax serra*. This study identified beach gradient to be an important factor in recruitment; however, beach gradient is highly changeable due to the dynamic nature of exposed sand beach systems (Short, 1999). The surfclam, *Paphies donacina* (tuatua) is abundant on exposed sand beaches in New Zealand, but little is known of the drivers determining the abundance and distribution of this species. To accurately assess the population of tuatua (*Paphies donacina*) in Pegasus Bay, a range of factors must be considered. These include the distribution of individuals in relation to habitat characteristics such as stability and sediment properties. Each of these factors could influence the overall success of tuatua populations. Other factors such as human impacts could also be influencing populations.

The coast of Pegasus Bay, Canterbury is made up of sand beaches in the south and composite or mixed sand and gravel beaches in the north beyond Ashworths Beach. Tuatua populations are mostly confined to open sand beaches. Tuatua (*P. donacina*) are the predominant shellfish species on the sand beaches of Pegasus Bay. Dispersal and abundance of juvenile tuatua in the intertidal zone of Pegasus Bay has been documented (Cranfield *et al.*, 2003; Kingett Mitchell, 2003; Marsden, 2010), but no studies have examined the seasonal changes in the distribution of the population. It is not uncommon for shellfish species to be found in the intertidal zone. Other examples include; *Paphies australis* (pipi) (Cole *et al.*, 2000), *P. ventricosa* (toheroa) (Akroyd *et al.*, 2002), *P. subtriangulata* (Northern tuatua in New Zealand) (Richardson *et al.*, 1982), *Donax deltoides* (pipi/goolwa cockle) in Australia (James & Fairweather, 1996), and *D. variabilis* (coquina) in North America (Wilson, 1999; Wolcott & Wolcott, 1984).

Characterisation of the beaches in Pegasus Bay in relation to factors that influence shellfish distribution is important. Tuatua are thought to be active dispersers, being able to leave the sediment to be moved by wave forces. Whilst shellfish cannot freely swim, they are able to resurface out of the sediment and ‘swash ride’ which allows individuals to move from unfavourable areas (Ellers, 1995). Such dispersal means that spatial distribution of tuatua is likely to be influenced by a range of factors, such as physical disturbance, freshwater inputs, competition and predation (Compton *et al.*, 2009). If any of these factors are detrimental to tuatua, a reduction in densities would likely result. This reduction would occur due to tuatua mortality or active dispersal away from affected areas. Identifying differences in sedimentary beach processes between locations may help to identify trends in tuatua distribution in Pegasus Bay. If there is no difference in beach dynamics between locations, other environmental factors, such as water contamination, may be having an influence on the population.

Tuatua have planktonic larval and post-settlement dispersal stages, both having importance for the subsequent adult population. Planktonic dispersal allows individuals to disperse over large distances, whereas post-settlement dispersal is more locally focused so the scale of movement is considerably smaller for shellfish. For this reason, the latter is considered to be less important (Norkko *et al.*, 2001), but this may not always be the case. For example, on beaches heavily used by vehicles and horses, post-settlement dispersal could influence the success of an individual.

Shellfish are known to be associated with particular sizes of sediment due to the physical dynamics that can be associated with sediment characteristics. For example, coarse sediment indicates high wave forces, so biota in this area must also be adapted for such forces. Sassa *et al.* (2011) found that shellfish change burrowing behaviour in relation to sediment compactness. If sediment properties change in a way that is less preferential, shellfish would be likely to move to areas where conditions are better suited. Burrowing time is also influenced by sediment size with sand sediments allowing the fastest burrowing times (Nel *et al.*, 2001). Shellfish would be expected to be found where sediment properties are such that optimal burrowing can be achieved.

A key assumption of this study is that, like sand, juvenile shellfish stocks build up in the offshore and are washed up onto the beach during accretion stages (Carter, 1995). Shellfish would remain in the intertidal zone until an erosion event occurs, then move offshore.

Identification of these events and the ability to relate them to shellfish abundance could prove an important tool in protecting these species. It would allow for a rapid assessment of shellfish populations without having to undertake the extensive labour associated with such research. This could allow management authorities to coordinate management plans according to the beach's seasonal processes to better protect intertidal species.

This study was conducted to not only evaluate the habitat of tuatua but also to describe the spatial and temporal distribution in Pegasus Bay over a two year period. Environmental variables such as sediment size are evaluated to assess its effect on shellfish distributions. Tuatua movement relies on long-shore transport, so it would be expected that densities would be influenced by environmental variables. For example, the Waimakariri River mouth would be likely to break the southward flowing current and cause high densities of tuatua to be held in the area. Other studies have found a distinct band of shellfish occurring on the shore (Cranfield *et al.,* 2003; Kingett Mitchell Ltd., 2003; Marsden, 2010), so it was expected that this would be present, although the band may move up and down the shore seasonally.

For population dynamics of tuatua to be understood, it is necessary for temporal studies to be conducted. This would identify important life stages, such as recruitment, which could allow for management to better protect the species. For example, recruitment events involve individuals washing up on the sediment surface where they are highly vulnerable to trampling from vehicle and horse users. If timing of recruitment is identified, ecological damage could be prevented by restricting potentially harmful users during these times.

3.2 Aims and Objectives

The research presented in this chapter addresses the first aim of the thesis: to provide information on the shellfish resources in Pegasus Bay and to record any observed changes in the seasonal distribution of tuatua. The two objectives designed to achieve this aim were to evaluate the habitat of tuatua and describe the spatial and temporal distribution and abundances of the bivalves. This was achieved using cross-sectional profiling and sediment cores at six selected sites in which tuatua are abundant in Pegasus Bay, Canterbury. The overall distribution of juvenile tuatua on the beach face was described to identify important dispersal patterns.

Other studies in Pegasus Bay have found juvenile tuatua to be in high densities further up the shore (Cranfield *et al.*, 2002; Kingett Mitchell Ltd., 2003; Marsden, 2010), so it was expected that this would also be found in the present study. It was also expected that there would be small seasonal changes in measured beach profiles, and that sedimentary characteristics would stay relatively stable throughout the period of the study.

3.3 Methods

The methodology used in this research utilised established geomorphological and biological techniques to quantify the physical variables and tuatua distribution to understand the relationships between them. Physical beach characteristic results were combined with biological data to test for correlations. The methods provided seasonal qualitative and quantitative data on beach processes and tuatua dispersal patterns.

In order to develop achievable and appropriate methodology, a pilot study was conducted. This had the primary aim of evaluating the required resources to complete a round of sampling at six sites in Pegasus Bay during one week of spring tides. The time period in which the beach face was exposed to complete a down-shore transect study in Pegasus Bay was found to be four to five hours. This was found to be enough time to complete and record two transects with 15 m quadrat spacing at one site with a single field person. This method would require six days to complete the sampling round, which did not leave time for environmental disruption such as storm events. Cross sectional surveying also could not be completed with one person, so methodology required two field workers for this portion of the study. The logistics of the study locations meant the second worker would remain on site, so methods were developed on the assumption that two field workers would also be transect sampling.

The pilot study found that, between two field workers, two transects with quadrats every 15 m, a single sediment sample, and a single measured beach profile line was achievable for each site in the time constraints of the spring tide period each quarter. It was found with two field workers a full sampling round could be completed over four days because the Spencer Park and South Waimakariri, and the Kairaki and Woodend sites could be completed together in one day respectively. The remaining sites, South Brighton and Waikuku, could only be sampled individually due to reduced accessibility. As this pilot was successful, the sampling methodology and sites continued unchanged for the duration of the study.

3.3.1 Study sites

Six sites were selected for the purpose of cross section profiling and seasonal population sampling to examine spatial and temporal trends in shellfish distribution (Table 3.1). These sites were also used to indicate their suitability for use in other experiments. The criteria used to select sites were that they:

1. contained a population of tuatua at the time of first sampling,
2. were stable enough to provide data for all seasons,
3. reflected a specific use for that area at the time of selection (e.g. horse, vehicle, control),
4. were accessible without a vehicle, and
5. were roughly equidistant from neighbouring sites along the coast of Southern Pegasus Bay.

All sites generally fulfilled these criteria. In relation to criterion 3, there were two sites that were selected to represent each use based on the frequency of users in that area (Table 3.1). While most of the sites were evenly spread, Kairaki and South Waimakariri were closer together. This was because the presence of the Waimakariri River mouth is likely to serve as a geographical barrier to shellfish, resulting in independent tuatua populations. All the sites selected were gently sloping sand beaches on an open coast exposed to a mixed local wind-wave and refracted-swell environment. The sediments contained were generally well sorted. Using the morphodynamic model developed by Short (1999), all of the beach sites were classed as long-shore bar trough beaches; a sub category of the intermediate sand beach class.

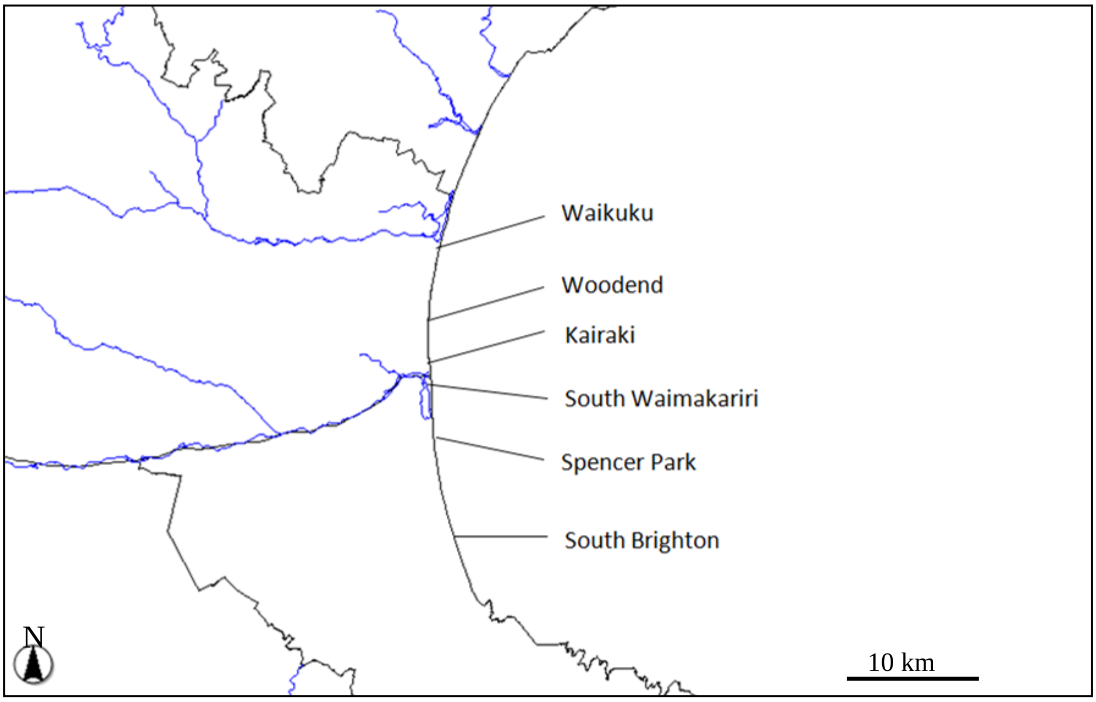


Figure 3.1: The location of the six seasonal sampling sites on Pegasus Bay, Canterbury; South Brighton, Spencer Park, South Waimakariri, Kairaki, Woodend, and Waikuku.

Table 3.1: Summary of study sites showing the relative levels of three different types of activity. Some activities take place despite bylaws prohibiting them, an X denotes where prohibited activity occurs. A sight with the absence of vehicles and horses was considered a control site.

		Activity types occurring on site		
Site name	**GPS coordinates**	**Vehicle**	**Horse**	**General recreation**
South Brighton (Control)	43°31'24.06"S 172°44'16.51"E	Low-none X	None	High
Spencer Park	43°26'7.51"S 172°42'50.00"E	Low-none X	High	Medium
South Waimakariri	43°23'41.90"S 172°42'42.57"E	High	Low-none	Medium
Kairaki	43°23'14.96"S 172°42'37.87"E	High	Low-none	Medium
Woodend	43°21'33.87"S 172°42'33.67"E	Low-none X	High	Low
Waikuku (Control)	43°17'20.13"S 172°43'16.35"E	Low-none X	Low-none	High

South Brighton

This is the most southern site of the six and situated approximately 2 km south of the New Brighton Pier. The width of the beach face (from the dune toe to low tide level) spans up to 200 m with an intertidal zone approximately 160 m wide. Currently this area is used for light recreational activities such as walking and running, with vehicle use prohibited. An exception allows emergency and council vehicles to pass through on occasion. Dune vegetation in this area consists mostly of marram grass (*Ammophila arenaria*), with patches of ice plant (*Disphyma australe*) and yellow tree lupin (*Lupinus arboreus*) throughout the profile. While some of these species have dispersed and colonized the area naturally, others are present through dune planting programmes (Christchurch City Council, 2012).

Figure 3.2: South Brighton Beach looking north.

Spencer Park

This site is situated approximately 9 km north of the South Brighton site and 500 m south of the Spencer Park Surf Lifesaving Club. This beach face spans approximately 150 m wide with an intertidal zone up to 100 m wide. The bylaws for this area currently allow horse use but prohibit vehicle use. However, council ranger vehicles are permitted to drive in this area, and do so a few times a week. Horse use in this area is light compared to other sites (e.g. Woodend). Dune vegetation for this area consists of species commonly found in Pegasus Bay (marram grass, ice plant, and yellow tree lupin), but there are some tree species that have spread from the neighbouring plantation forests. These are mostly small *Pinus radiata* seedlings.

Figure 3.3: Spencer Park Beach looking south.

South Waimakariri

This site is approximately 4.25 km north of the Spencer Park site and 500 m south of the Waimakariri River mouth. Access to this area is from a gate at the end of Heyders Road approximately 3.75 km south of the Waimakariri River mouth. This site has no above tide area due the river mouth inlet moving south and shifting the high tide line up to the toe of the sand dunes via erosion of beach width. The intertidal zone for this site is up to 75 m wide. Bylaws for this area allow for vehicles to be driven from the gate at Heyders Road north to the river mouth. The dune vegetation in this area mainly consists of marram grass and yellow tree lupin but small wilding *P. radiata* seedlings are scattered amongst the dune area.

Figure 3.4: South Waimakariri Beach looking south.

Kairaki

This site is approximately 1 km north of the South Waimakariri site and 1 km south of the Pines Beach Surf Lifesaving Club. Access to this area is via the entrance approximately 600 m west, through the Kairaki Settlement. This is the widest and flattest site, up to 350 m wide with an intertidal zone up to 165 m wide. Bylaws in this area currently allow for vehicles to be driven in the intertidal zone. Most vehicle activity takes place around the river mouth in the whitebait and salmon seasons; however the river became contaminated after the 4th September 2010 earthquake, preventing usual activities from occurring. The Waimakariri

Northern Pegasus Bay Bylaw, 2010, permits horses in this area, but this use is likely to be minimal due to vehicles being a safety concern for riders. The dunes in this area are smaller than those at other sites and also contains embryonic dune. Where dunes are present, marram grass is the main plant species present.

Figure 3.5: Kairaki Beach looking south.

Woodend

This site is approximately 3 km north of the Kairaki site and 2.5 km south of the main horse entrance way on Waikuku beach. Access to this area is via the horse trainer's entrance at the end of Ferry Road, Woodend. The beach in this area spans up to 140 m wide with a 90 m wide intertidal zone. This is the most heavily used horse riding area due to bylaws permitting such activity and local horse training facilities being situated nearby. Trotting trainers are the largest users in this area and training mostly occurs in the intertidal zone. This site features established secondary dunes as well as embryonic types. Vegetation includes marram grass and yellow tree lupin but pine forests also neighbour the beaches of this area.

Figure 3.6: Woodend Beach looking north.

Waikuku

This is the northernmost site, situated approximately 1.5 km south of the Ashley River Mouth and 7.8 km north of the Woodend site. Access to this area is via the entrance at the Waikuku Surf Lifesaving Club, 150 m north of the site. The beach for this site spans up to 120 m with a 90 m wide intertidal zone. When this site was selected the area was allowed to be used only for general recreation but the implementation of the current bylaws in July 2010, allowed for horses to be used in this area except for when the surf patrol flags are out. Surf patrolling takes place only during the summer months from December to February (Waimakariri District Council Northern Pegasus Bay Bylaw 2010). Vehicles are prohibited from this area; however, to the north vehicles a have a designated track for accessing whitebait areas at the Ashley River mouth. The dunes in this area are large and well established with marram grass, yellow tree lupin, and pine seedlings making up the vegetation at this site.

Figure 3.7: Waikuku Beach looking south.

3.3.2 Characterisation of Pegasus Bay Sand Beach tuatua habitat

Cross-sectional beach profiling

Cross-sectional beach profiling was carried out at each site on the same day as intertidal shellfish population sampling. This was done using a SOKKIA Set 10(5) Total Station. The profile line was aligned at right angles to the shore and so that was in the middle of the two population sampling transect lines, with the Total Station on top of the highest seaward dune (Figure 3.9). A second benchmark was put in front of this to set angle of the line for the profiling, and a third benchmark was put behind the Total Station benchmark. These benchmarks were maintained at each site throughout the period of this study to keep the same profile line each time population sampling was conducted. All benchmarks were established using Virtual Reference Station (VRS) ibase data from a Trimble Global Positioning System (GPS) (Figure 3.8) and are recorded in relation to the New Zealand Vertical Datum 2009 (NZVD09). Establishing benchmarks with this method has an approximate accuracy of 4 cm horizontally and 10 cm vertically. Profiling was carried out along the beach face until the water became too deep for the prism to be reliably steadied and vertically aligned. This was usually at approximately 60 cm water depth.

Figure 3.8: The Total Station (SOKKIA Set10/5) survey equipment set on top of a sand dune at South Waimakariri Beach (left) and the Trimble GPS set on an Environment Canterbury bench mark at Waikuku Surf Lifesaving Club (right).

Sediment characteristics

A 50 mm diameter corer was used to sample sediment to 50 mm depth from each profile 30 m below the last high tide line. This was approximately at the upper mid tide level. The pore water, organic content, and sediment texture were measured. This location was chosen as it represented the peak shellfish band in the intertidal zone (Marsden, 2010). Sediment was returned to the laboratory and washed in freshwater before being dried in a 60˚C oven for 3 days. The dried sediment was then put through a series of sieves from 0 to 4 phi increasing at 0.5 phi intervals. After being shaken mechanically for 10 minutes, the sediment caught in each sieve was weighed and recorded according to the standard sieving method outlined in Lewis and McConchie (1994).

3.3.3 Tuatua abundance and distribution

The distribution of the intertidal population of tuatua was sampled every three months from May 2010 to February 2012 (eight times in total). The sampling for each month was done on the spring tide to maximize sampling of the intertidal zone to lowest tidal levels. All sites were sampled over a period of four days when the low tides would be at their lowest levels for that spring tide period.

Paired transect lines with quadrat sampling was used. The two transect lines 20 m apart were established at each site and their locations were recorded using GPS (Garmin: GPSmap 60CSx). These positions were then reused at each sampling to relocate the transect lines.

A 31.7 x 31.7 cm (0.1 m²) quadrat was sampled every 15 m along the transect line. The first quadrat was taken at the last high tide mark and the final at the swash zone with two replications at each sampling point (Figure 3.9). These were laid down and the sediment was dug to approximately 15 cm depth and put through a 5 mm mesh sieve. Shellfish that were caught in the sieve were recorded for numbers and the shell length of individuals. The number of shellfish per quadrat was multiplied by ten to give the density of shellfish per m².

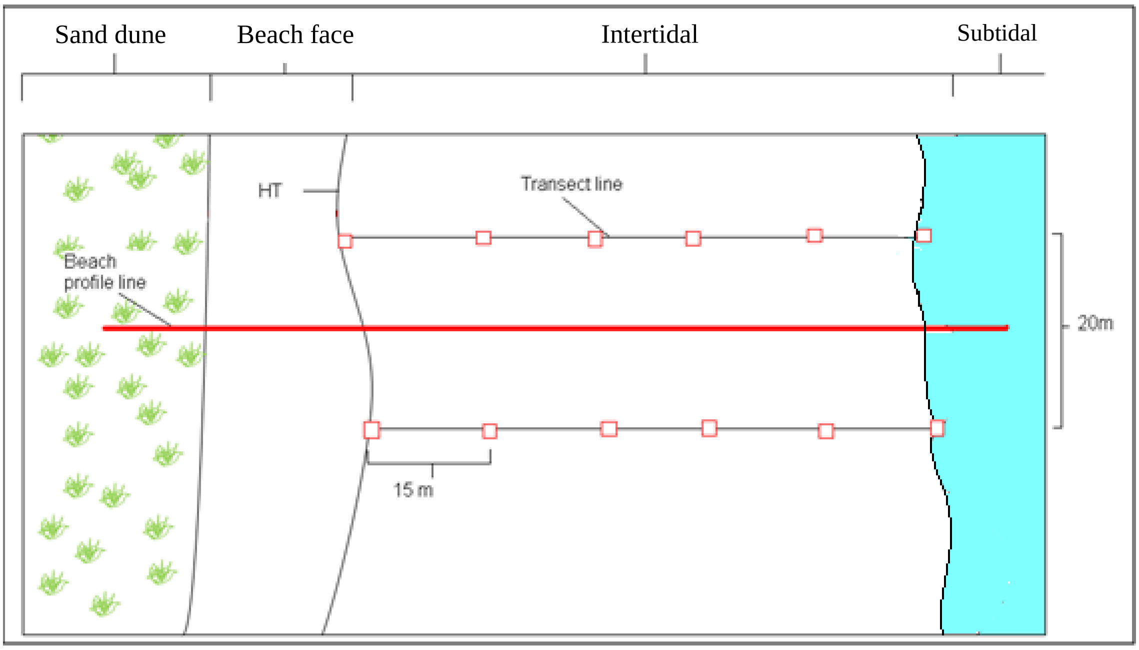


Figure 3.9: Diagram of the study setup at each site. The diagram shows the paired transect lines with the beach profile running parallel between the two.

3.3.4 Data and statistical analyses

All data were recorded in Microsoft Excel spreadsheets. Beach profiles were plotted in relation to the NZVD09. Measured horizontal excursions were calculated in relation to mean sea level and plotted. The sea level contour is approximately in line where juvenile tuatua are distributed, and so it provides the most relevant measure of beach profile changes which could affect tuatua populations. Sediment sizes were calculated for the average size (phi) and standard deviation (sorting value). For the shellfish distribution study, mean and standard error were calculated for each of the replicate samples. Regression analysis was used to investigate relationship between measured horizontal excursions and shellfish abundance, and temporal changes in measured horizontal excursion.

Statistical testing was carried out using ‘Statistica 7’. An Analysis of Variance (ANOVA) was conducted using ‘Statistica 7’ to test the relationship between average sediment size and season in the beach characterisation study. Repeated measures Analysis of Variance (ANOVA) and multi-factorial ANOVAs were used to determine if there were seasonal differences in abundance, tuatua shell length, and dispersal. ANOVAs were used in this instance because data was grouped into categorical formats (e.g. site names). Grouped data were found to be normal through distribution fitting. Repeated measures ANOVA was used for data where the same population was sampled over time (i.e. seasonal distribution). T-tests were used to determine if there were differences in shellfish between sampling times.

Additional tests were conducted to evaluate changes in sediment properties due to high earthquake activity in the Canterbury region starting on the 4th September 2010. T-tests were conducted to test the difference between sediment size and sorting pre- and post- earthquake (4th September 2010). ANOVAs were conducted to test if sediment properties changed between sites and season in light of earthquake activity.

3.4 Results

3.4.1 Characterisation of Pegasus Bay sand beaches

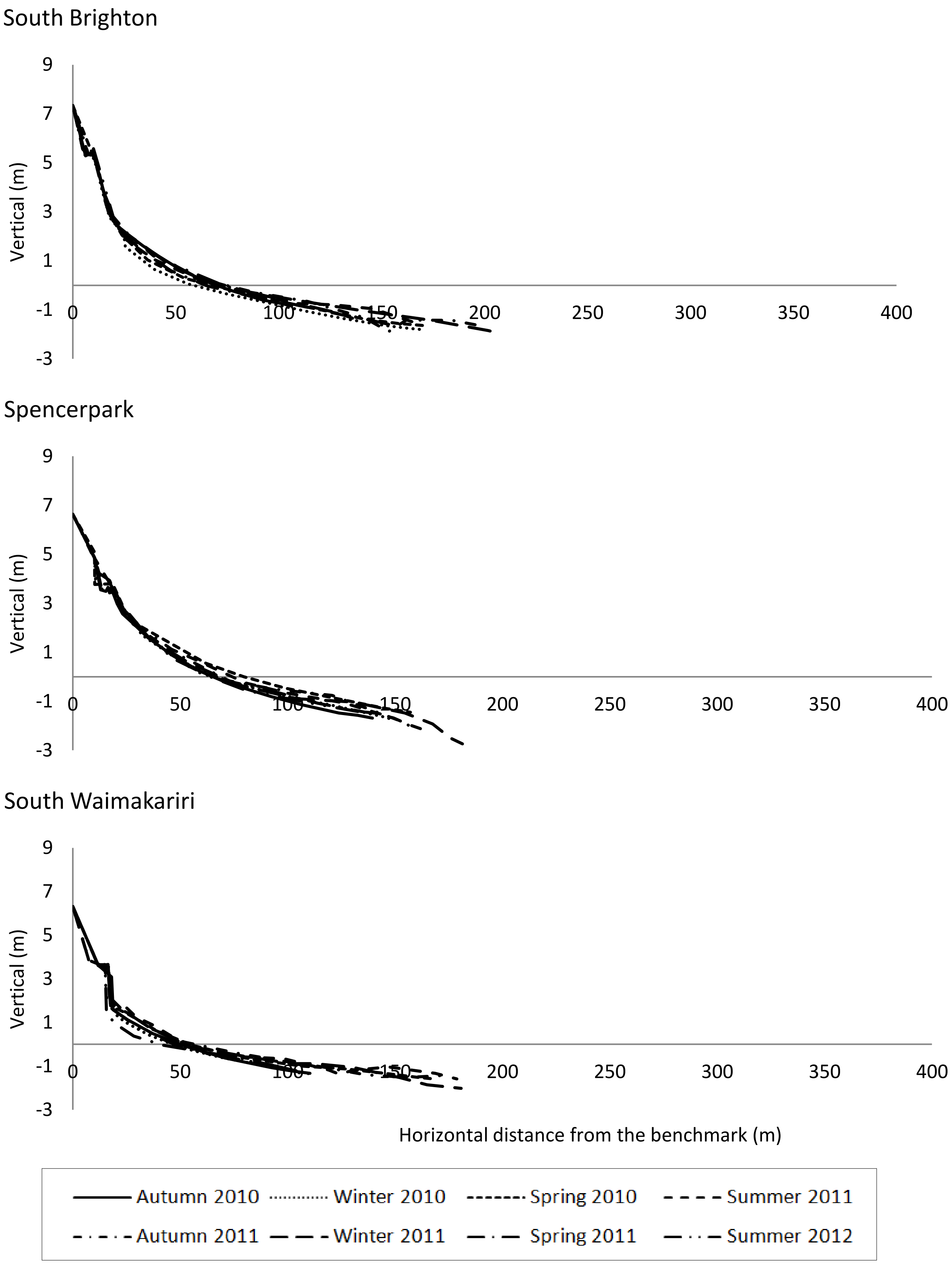
Beach Profile Dynamics

Over the two year study period, the study sites were found to be slightly accretional with exception to sites nearer to the Waimakariri River mouth, which showed variable dynamics. South Brighton was relatively stable over the period of the study. This site had a stable profile with a small envelope of change with the largest measured profile distance of 200 m.

Spencer Park showed similar stability to South Brighton with a slight period of building between August and November 2010 (Figure 3.11). The largest measured profile distance (i.e. horizontal beach width) was 181 m over this period. South Waimakariri Beach had a large scarp in existence for the duration of the study and appeared to be relatively stable, with only small amounts of erosion occurring (Figure 3.10). Kairaki exhibited the widest beach profile: 352 m from the benchmark on top of the most seaward sand dune to the subtidal zone. This site was found to be accreting at an average rate of approximately 20 myr^{-1} throughout the period of the study (Figure 3.11). Woodend was a stable site with no large erosion or accretion events and very little seasonality (Figure 3.10). Waikuku was also relatively stable over the two year study period. This site had small seasonality with periods of building between August and November and erosion during the rest of the year.

Overall, there appeared to be a degree of seasonal variation throughout the two year study period. In the winter months (June to August), some sites were eroded, subsequently undergoing accretion in the spring and summer months (e.g. Spencerpark and Waikuku). In the present study, the small amount of net annual beach profile change, despite the seasonal dynamics, supports the idea that most of the study sites experience relatively stable periods over longer time scales. The similar sizes in the beach envelopes of change amongst the measured beach profiles indicate that all sites were subject to comparable dynamics over the study period. The exception to this pattern was Kairaki beach, where there were pronounced patterns of long-term accretion and the mean sea level excursions over the same period showed similar dynamics (Figure 3.11).

Historically, the beaches of Pegasus Bay have been found to be relatively stable, with exception to those near to river mouths. For example, the Environment Canterbury bench mark at the south bank of the Waimakariri River mouth site, C2200, has exhibited large variations in beach width between seasons (Figure 3.11). This site was eroding at a rate of 2.26 myr^{-1} during the Environment Canterbury monitoring period (1991 to 2010), eventually being lost due to a large erosion event in 2010. At other sites, beach excursions showed a positive trend (accreting) with exceptions to site C2200 and C2300 where the Waimakariri River Mouth caused variation. Site C2545 (Woodend Beach) had a significant positive relationship (Figure 3.11). No other profile sites revealed a significant trend line relationship, due to the large variation caused between years and seasons.


South Brighton
Vertical (m)
9
7
5
3
1
-1
-3
0
50
100
150
200
250
300
350
400
Spencerpark
Vertical (m)
9
7
5
3
1
-1
-3
0
50
100
150
200
250
300
350
400
South Waimakariri
Vertical (m)
9
7
5
3
1
-1
-3
0
50
100
150
200
250
300
350
400
Horizontal distance from the benchmark (m)
Autumn 2010
Winter 2010
Spring 2010
Summer 2011
Autumn 2011
Winter 2011
Spring 2011
Summer 2012

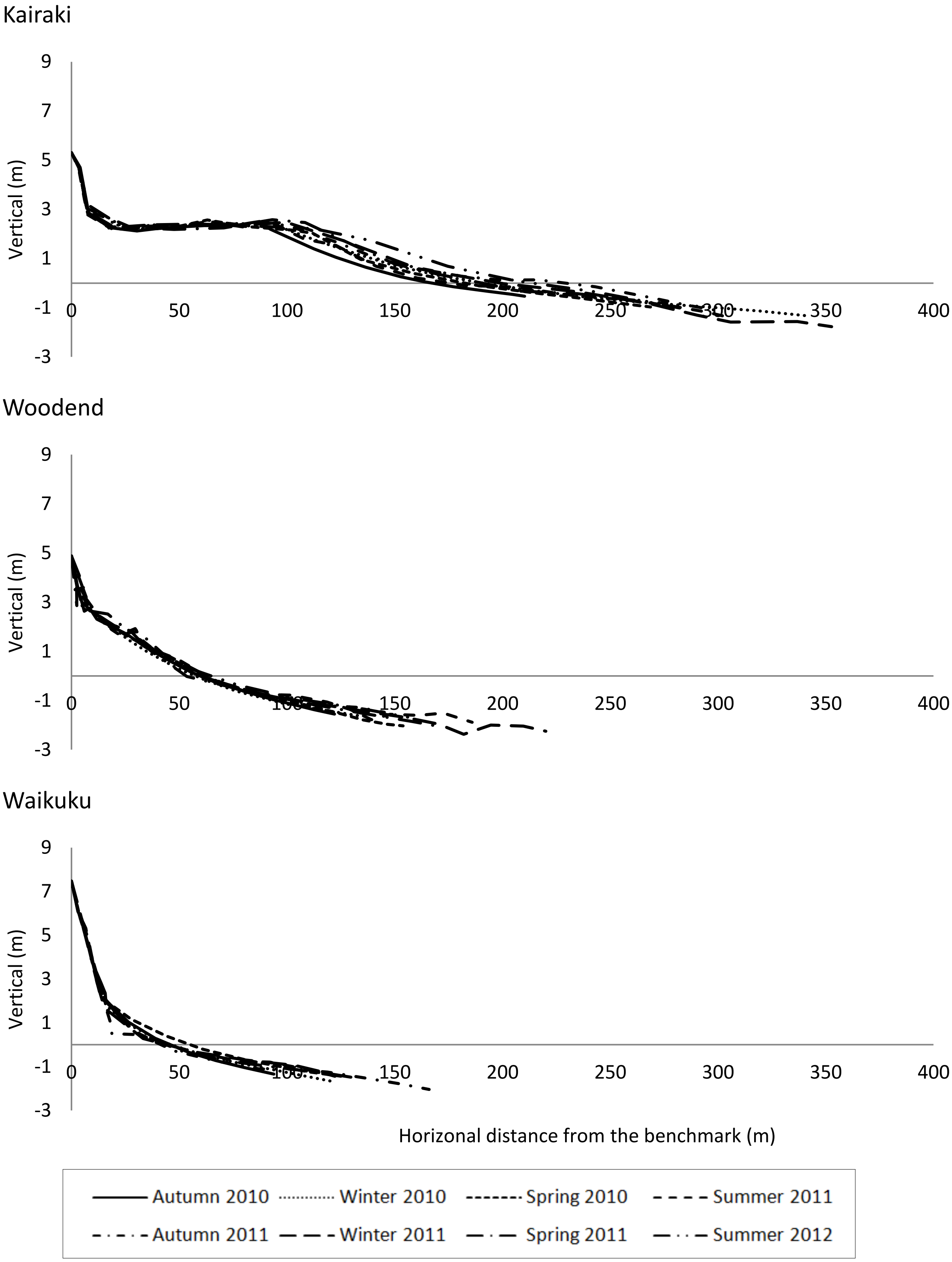
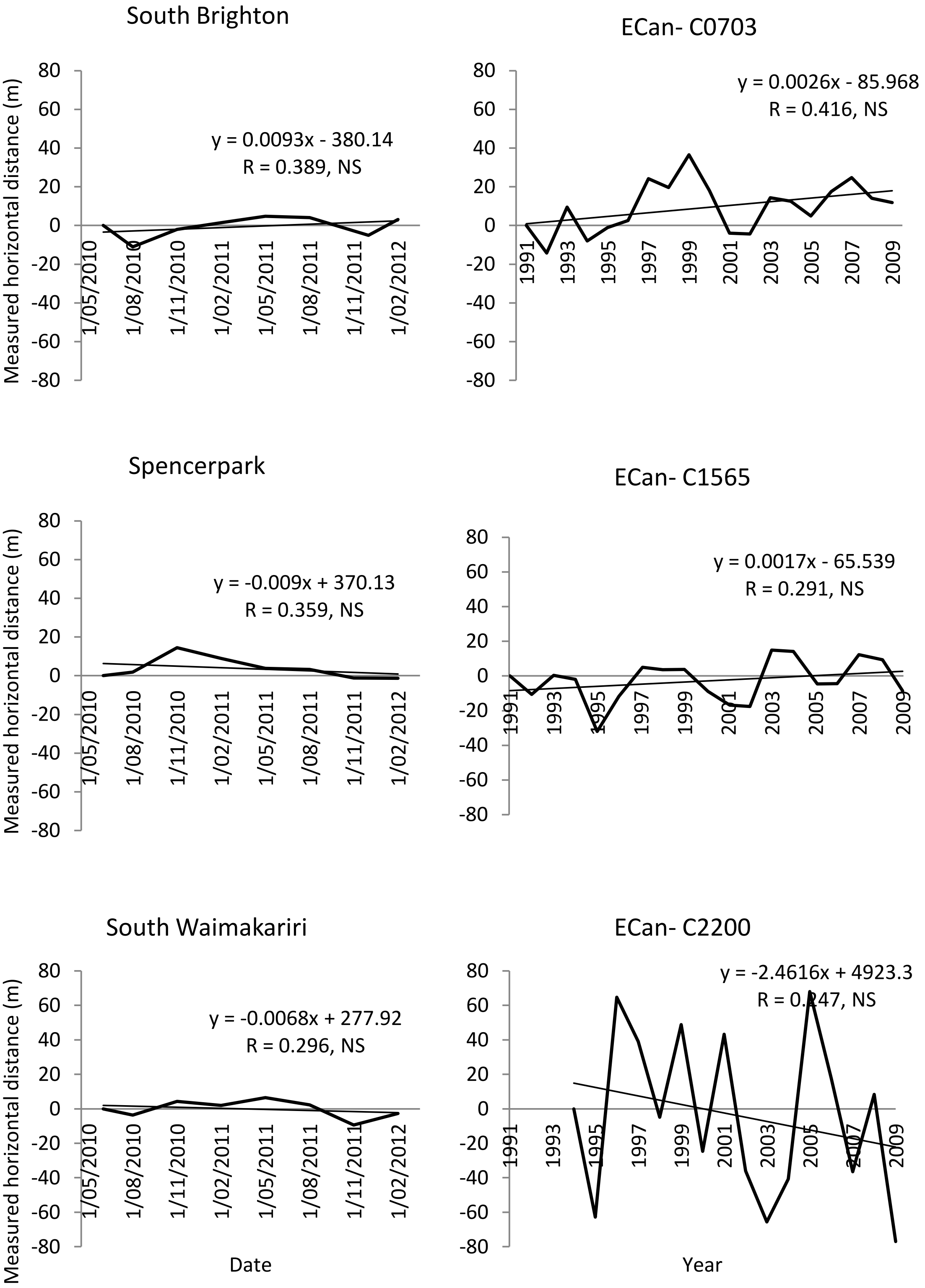


Figure 3.10: Temporal beach profiles for six selected sites in Pegasus Bay, Canterbury.


South Brighton
y = 0.0093x - 380.14
R = 0.389, NS
ECan- C0703
y = 0.0026x - 85.968
R = 0.416, NS
Spencerpark
y = -0.009x + 370.13
R = 0.359, NS
ECan- C1565
y = 0.0017x - 65.539
R = 0.291, NS
South Waimakariri
y = -0.0068x + 277.92
R = 0.296, NS
ECan- C2200
y = -2.4616x + 4923.3
R = 0.247, NS
Measured horizontal distance (m)
80
60
40
20
0
-20
-40
-60
-80
1/05/2010
1/08/2010
1/11/2010
1/02/2011
1/05/2011
1/08/2011
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1/02/2012
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
Date
Year

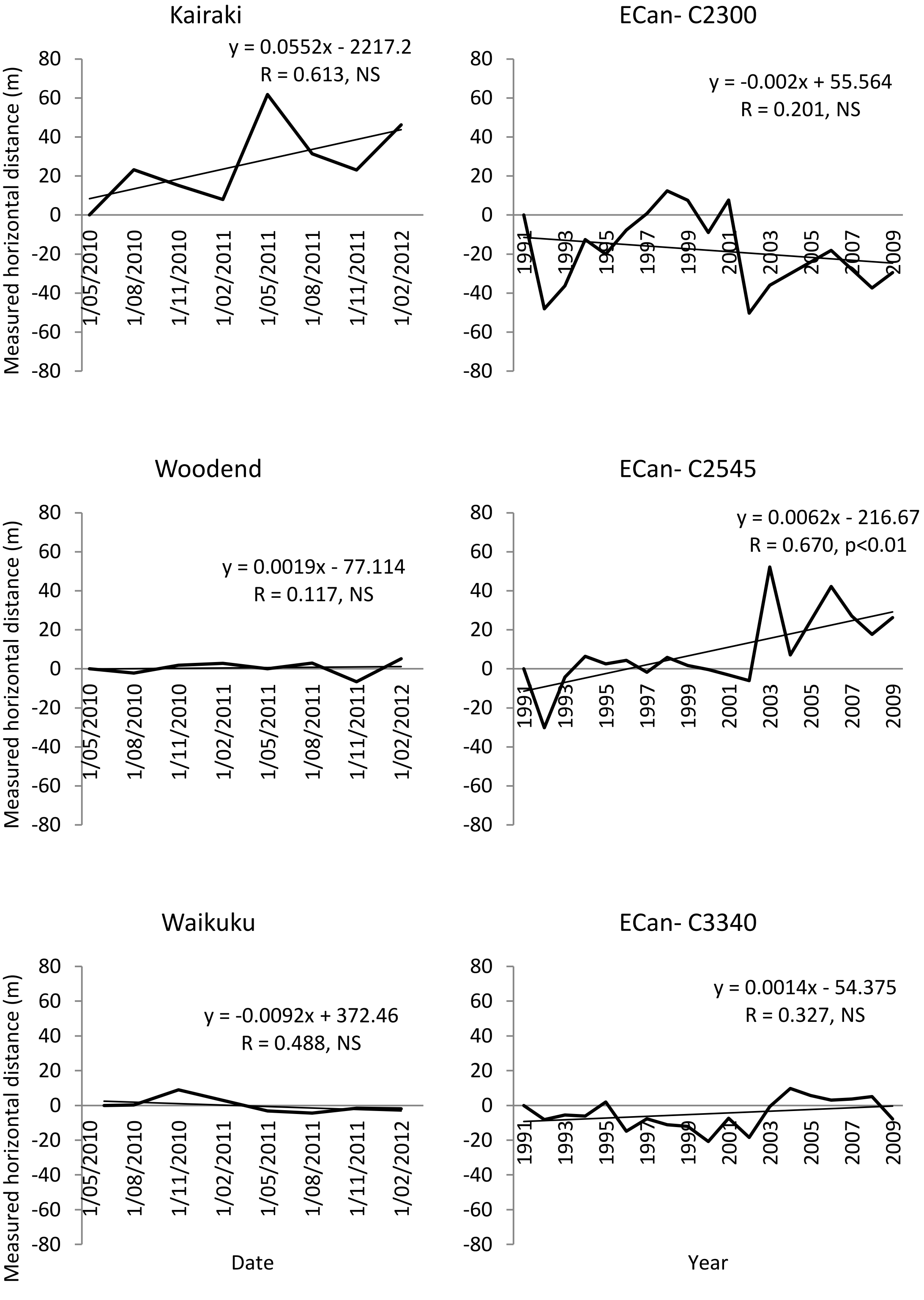

Figure 3.11: Temporal horizontal excursion graphs using the Mean Sea Level contour (NZVD09) for six sites in Pegasus Bay, Canterbury paired with the nearest Environment Canterbury beach profile record measured over approximately 20 years. Trend lines show the overall erosional (negative slope) or accretional (positive slope) trend throughout the study period (left column plots) and longer profile record period (right column plots).

Sediment size

Sediment samples included all the sand size classes (0 to 4 phi) (Figure 3.14) and were generally well sorted. Sediment grain size was coarser at sites closer to river mouths (~2.3 phi at river mouths and ~2.5 phi away from rivers). As the study period progressed, the mean sediment size became finer and sorting became poorer, and towards the completion of the study, these became more similar to values at the beginning of the study period. As will be discussed later in this chapter, this was likely an effect of earthquake-released sediment pulses working their way through the beach system.

Sediment from the earlier samples appeared to be unimodal (2.5 phi); however, samples became bimodal as the percentage of 3.5 phi sediment increased (Figure 3.14). The average size of sediment was significantly different between sites (ANOVA, $F(5,41)= 2.50$, $p<0.04$), and South Waimakariri Beach contained significantly larger sediment than South Brighton Beach (post-hoc Tukey's HSD test: $p=0.013$): 2.2 to 2.54 phi range at South Waimakariri compared to 2.57 to 2.79 phi range at South Brighton.

Table 3.2: The average sediment size (phi) and its sorting value (standard deviation) and class over eight seasons at six sites in Pegasus Bay, Canterbury. N.B. Waikuku summer 2011 is not available due to the February 22nd earthquake occurring that day disrupting field work before the sample could be obtained. Note that all of the average sediment sizes in this table fall within the fine sand category.

		Autumn 2010	**Winter 2010**	**Spring 2010**	**Summer 2011**	**Autumn 2011**	**Winter 2011**	**Spring 2011**	**Summer 2012**
South Brighton	Sediment size (Sorting)	2.57 (0.37)	2.61 (0.31)	2.65 (0.31)	2.66 (0.46)	2.67 (0.31)	2.79 (0.5)	2.58 (0.36)	2.58 (0.31)
	Sorting Class	Well Sorted	Very Well sorted	Very Well sorted	Well Sorted	Very Well sorted	Moderately well sorted	Well Sorted	Very Well sorted
Spencer Park	Sediment size (Sorting)	2.3 (0.36)	2.32 (0.34)	2.41 (0.34)	2.53 (0.58)	2.44 (0.39)	2.63 (0.58)	2.64 (0.53)	2.54 (0.56)
	Sorting Class	Well Sorted	Very Well sorted	Very Well sorted	Moderately well sorted	Well Sorted	Moderately well sorted	Moderately well sorted	Moderately well sorted
South Waimakariri	Sediment size (Sorting)	2.28 (0.38)	2.31 (0.37)	2.43 (0.34)	2.44 (0.64)	2.54 (0.53)	2.52 (0.51)	2.2 (0.35)	2.33 (0.36)
	Sorting Class	Well Sorted	Well Sorted	Very Well sorted	Moderately well sorted	Moderately well sorted	Moderately well sorted	Well Sorted	Well Sorted
Kairaki	Sediment size (Sorting)	2.27 (0.38)	2.37 (0.33)	2.65 (0.58)	2.66 (0.58)	2.55 (0.36)	2.54 (0.56)	2.48 (0.59)	2.55 (0.58)
	Sorting Class	Well Sorted	Very Well sorted	Moderately well sorted	Moderately well sorted	Well sorted	Moderately well sorted	Moderately well sorted	Moderately well sorted
Woodend	Sediment size (Sorting)	2.53 (0.34)	2.33 (0.38)	2.61 (0.6)	2.49 (0.62)	2.66 (0.58)	2.67 (0.5)	2.49 (0.37)	2.5 (0.34)
	Sorting Class	Very Well sorted	Well Sorted	Moderately well sorted	Moderately well sorted	Moderately well sorted	Moderately well sorted	Well Sorted	Very Well sorted
Waikuku	Sediment size (Sorting)	2.23 (0.37)	2.39 (0.41)	2.46 (0.37)	NA	2.54 (0.57)	2.66 (0.56)	2.55 (0.57)	2.69 (0.55)
	Sorting Class	Well Sorted	Well Sorted	Well Sorted		Moderately well sorted	Moderately well sorted	Moderately well sorted	Moderately well sorted

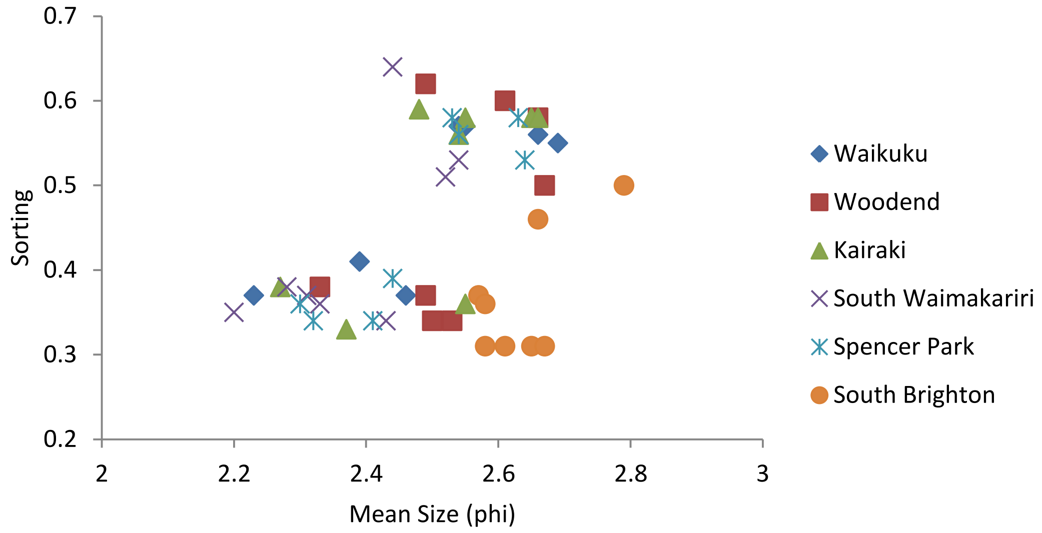

Figure 3.12: The relationship between sorting and mean sediment size at six locations in Pegasus Bay, Canterbury, with data take over eight seasons (Autumn 2010-Summer 2012).

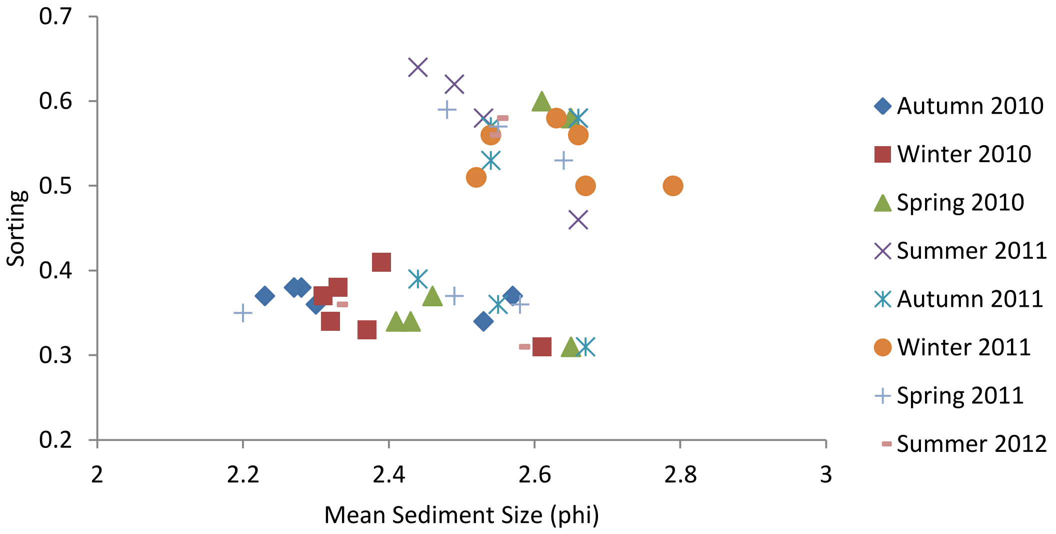

Figure 3.13: The relationship between sorting value and mean sediment size over eight seasons at six locations in Pegasus Bay, Canterbury. Note that the later samples are generally separated from earlier samples due to their poorer sorting (higher standard deviation) and finer sediment sizes.

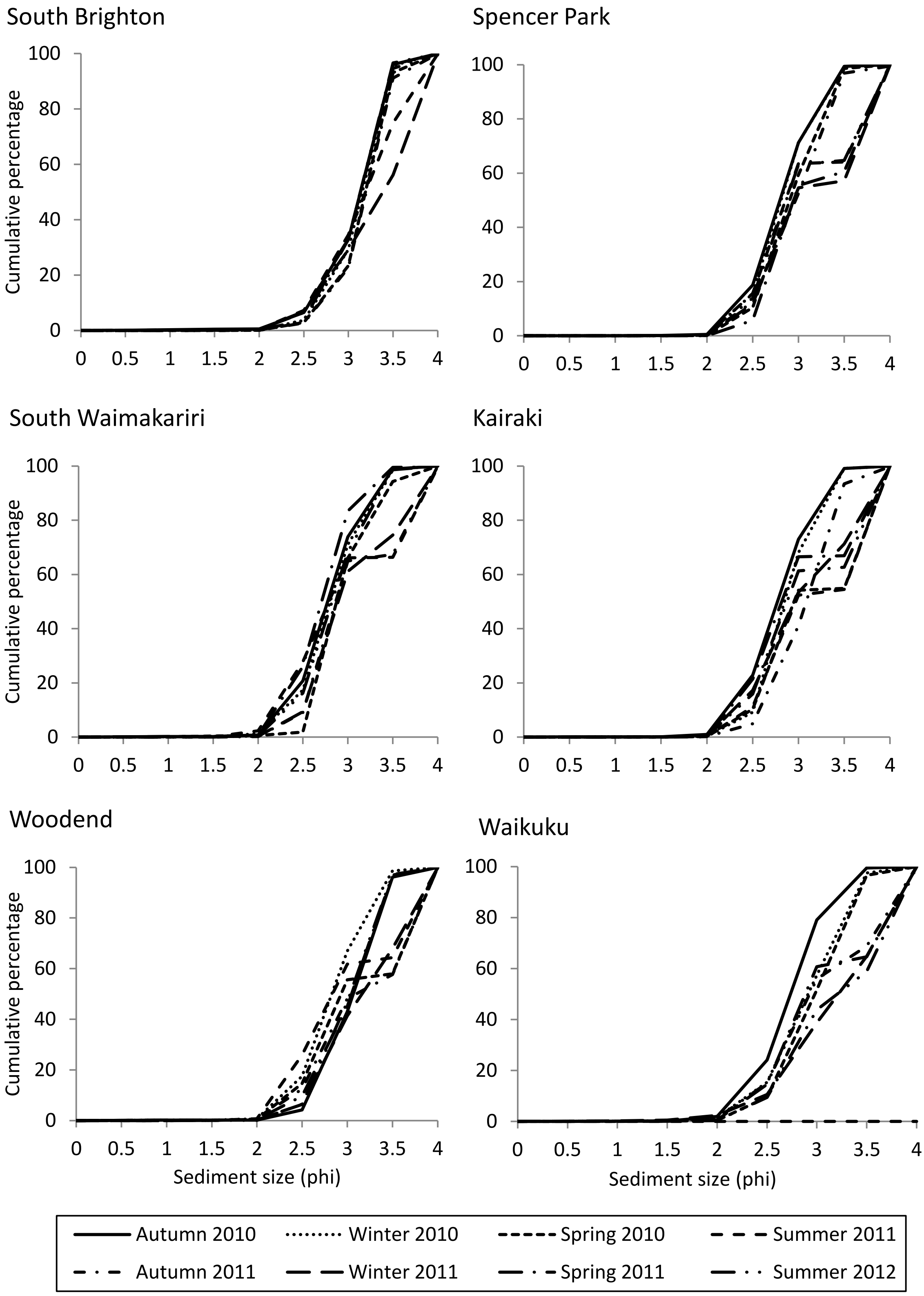

Figure 3.14: Cumulative frequency graphs of sediment cores taken from autumn 2010 to summer 2012 at six sites in Pegasus Bay, Canterbury.

Effects of the earthquake on sediment characteristics

There was an increase in 3.5 phi sediment from spring (November) 2011 onwards at most sites (Figure 3.15). Winter 2011 (post-quake) samples were significantly different from winter 2010 (pre-quake) ($F(5,41)=3.55$, $p=0.005$, tukey's HSD test). Sorting changed significantly between season but not site (site: $F(5,41)= 1.510$, $p=0.208$; season: $F(7,39)= 3.74$, $p=0.003$). Summer 2011 and winter 2011 had poorer sorting (higher standard deviations) than winter and autumn 2010, and winter 2010 respectively (Tukey's HSD test).

In light of the sediment changes identified, data were grouped into pre- and post-earthquake categories. The mean size of pre-quake sediment (2.38 phi) was coarser than post-quake (2.55 phi) ($t(45)= -4.49$, $p<0.001$). The mean post-quake sorting value was also was significantly higher (indicating poorer sorting) than the mean pre-quake sorting value (0.48 versus 0.36) ($t(43)= -5.88$, $p<0.001$), but both values remained within the well sorted class (Figure 3.16).

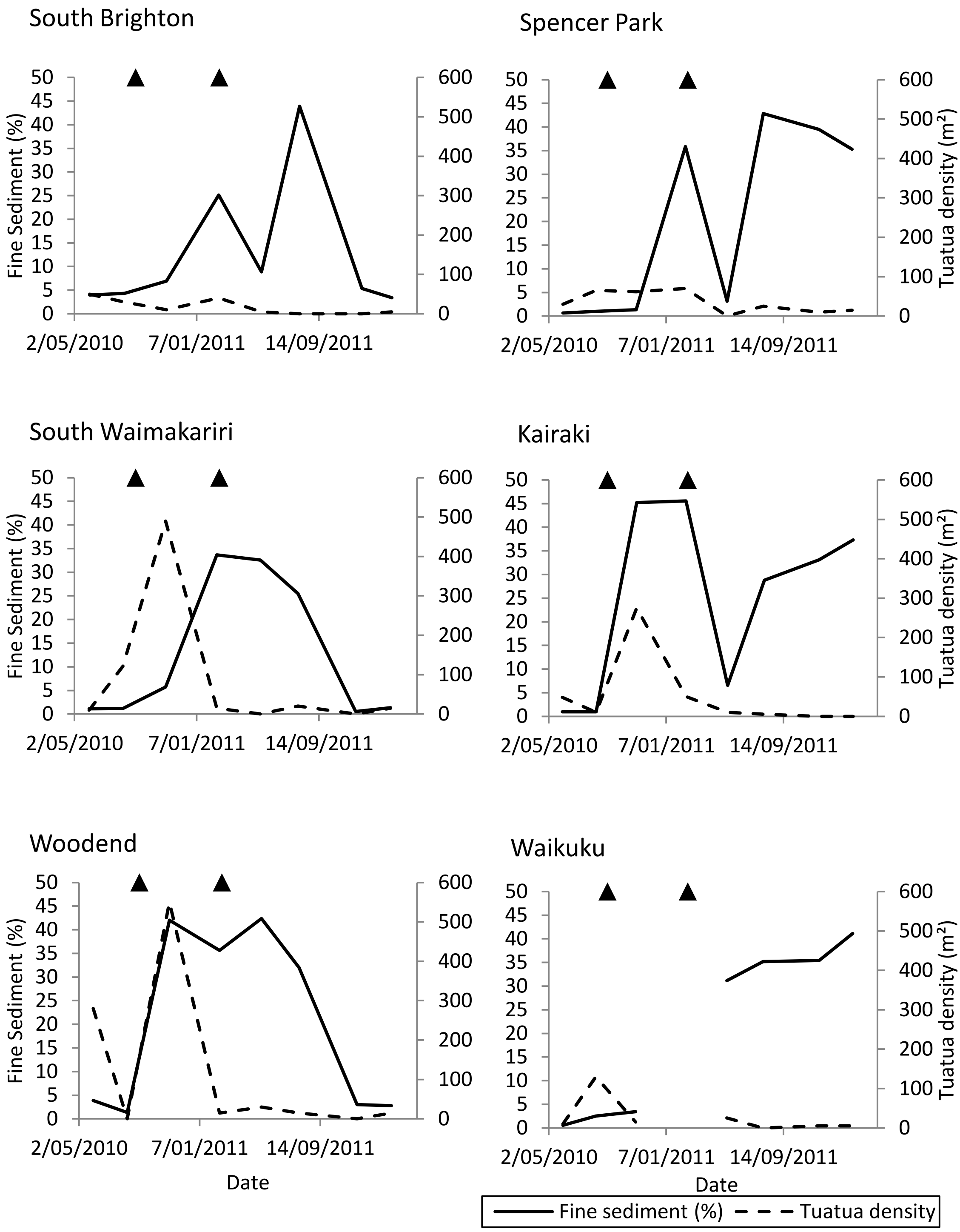

Figure 3.15: Fine sediment percentage and tuatua density at 30 m below the last high tide line sampled seasonally for two years in Pegasus Bay, Canterbury. Triangles denote significant liquefaction inducing earthquakes, a magnitude 7.1 on 4th September 2010 and a 6.5 on 22nd February 2011.

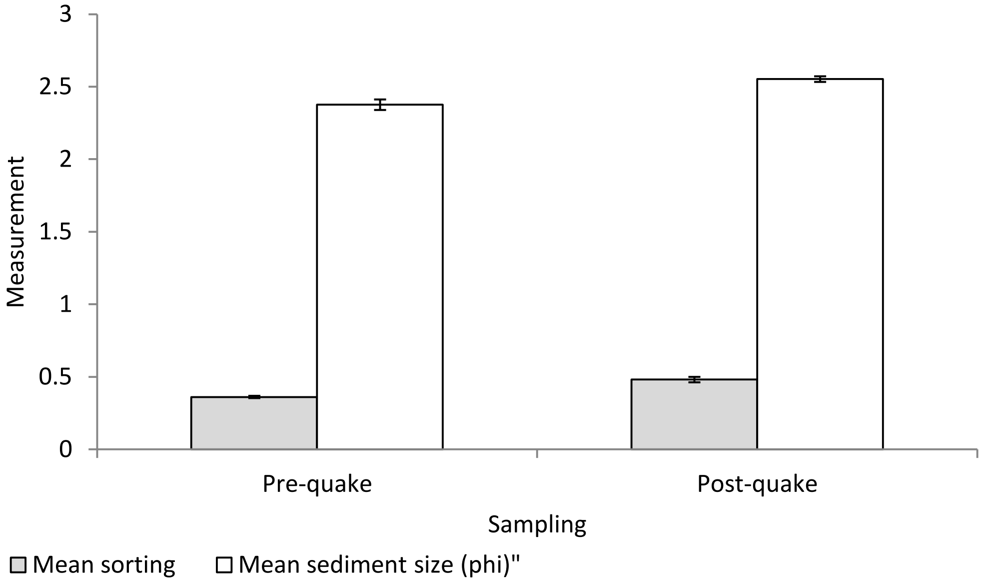

Figure 3.16: Mean size (phi) and sorting value of sediment cores taken from Pegasus Bay, Canterbury, pre- and post-earthquake (September, 2010).

3.4.2 Tuatua abundance and distribution

A total of 1008 shellfish were found during the study with higher abundances at the three northern sites (Kairaki, Woodend and Waikuku) (Figure 3.17). Using Richardson *et al.*'s (1982) identification key, these were all determined to be tuatua (*Paphies donacina*). The highest number of shellfish was found on Woodend Beach on the 5th November 2010 (spring 2010) with a total of 113 individuals. The greatest density of 550 individuals per m² was also found 30 m below the last high tide line at this time and location (Appendix 3). No tuatua were found at Spencer Park Beach on 17th May 2011 (autumn 2011).

Tuatua were found to be in a constant abundance between seasons and sites. An overall mean density of 11 shellfish per m^2 (SD= 13.8) was found; however, there were many quadrats where no shellfish were found lowering this value. The total number of individuals collected from samples spanning the intertidal zone at each site was not significantly different between seasons (ANOVA: $F(3,39)= 0.392$, $p=0.760$), or sites ($F(5,39)= 0.788$, $p=0.565$). From autumn 2010 to summer 2011 there were more tuatua present than between autumn 2011 and summer 2012 (t-test: $t(46)= 4.496$, $p<0.001$). When categorised into the prevalant use category (Horse, Vehicle, Pedestrian) of the site, an average density of 7 shellfish per m² (SE=1.4) was found on Pedestrian areas and 13 tuatua per m² on both vehicle (SE= 3.7) and horse (SE= 4.3) use areas, but this was not found to be signficantly different ($F(2, 44)= 0.930$, $p= 0.402$).

Table 3.3: Average density (tuatua per m²) (top) and standard deviation (bottom) of tuatua at each site and season and the number shellfish sampled (N) in Pegasus Bay, Canterbury.

		Autumn 2010	**Winter 2010**	**Spring 2010**	**Summer 2011**	**Autumn 2011**	**Winter 2011**	**Spring 2011**	**Summer 2012**
South Brighton	**Density (SE)**	5.5 (15.7)	9.0 (12.6)	1.5 (3.4)	13.0 (15.5)	10.0 (13.9)	4.0 (5.2)	6.5 (17.2)	3.0 (4.8)
	N	11	18	3	26	20	8	13	6
Spencer Park	**Density (SE)**	3.3 (10.0)	13.3 (23.2)	7.9 (20.5)	8.3 (23.2)	0.0	7.2 (8.3)	3.9 (7.0)	2.8 (5.1)
	N	6	24	16	17	0	13	7	5
South Waimakariri	**Density (SE)**	2.0 (3.5)	13.6 (37.9)	52.5 (153.8)	26.3 (34.6)	2.0 (4.8)	3.0 (6.3)	0.5 (1.6)	3.5 (6.3)
	N	4	27	105	52	4	6	1	7
Kairaki	**Density (SE)**	10.4 (20.0)	34.6 (96.4)	27.5 (79.0)	12.1 (15.3)	4.2 (5.6)	2.9 (4.0)	3.3 (6.2)	4.6 (9.2)
	N	25	83	66	29	10	7	8	11
Woodend	**Density (SE)**	34.4 (92.4)	36.7 (97.2)	62.8 (182.8)	4.4 (5.3)	5.6 (9.8)	5.0 (6.1)	2.2 (4.4)	3.9 (6.5)
	N	62	66	113	8	10	9	4	7
Waikuku	**Density (SE)**	18.9 (53.0)	15.6 (43.0)	4.4 (7.7)	NA	3.9 (8.2)	3.3 (5.6)	2.8 (6.7)	1.1 (2.2)
	N	34	28	8	NA	7	6	5	2

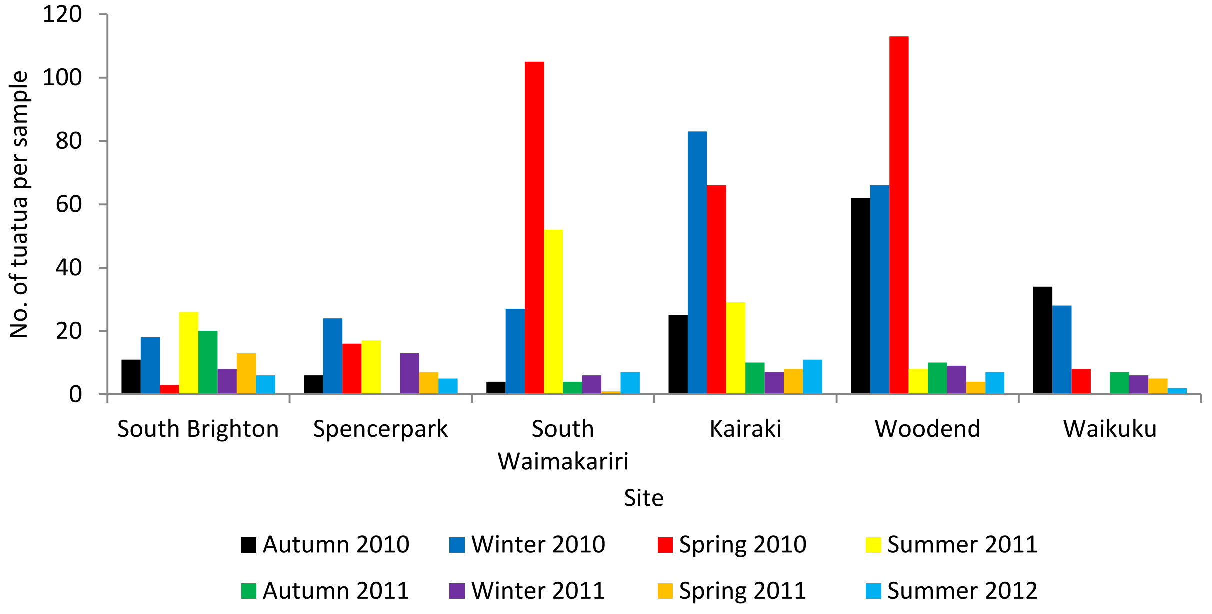

Figure 3.17: The total number of tuatua (*Paphies donacina*) at each site in Pegasus Bay, Canterbury, for each season from Autumn 2010 (May) to Summer 2012 (February).

Tuatua had a similar dispersal patterns at each site for the duration of the study. The position of individuals on the shore did not change between sites and seasons (ANOVA: site- *F*(5,353)= 0.374, *p*= 0.867; season- *F*(5,353)= 0.029, *p*= 0.994). A distinct banding, where shellfish were found at a maximum density within the transect, was observed at all sites (Appendix 2). A significantly higher percentage of individuals was found at the 30 m mark than any other position on the shore (ANOVA: *F*(11,353)= 10.895, *p*<0.001, Tukey's HSD test) (Figure 3.18).

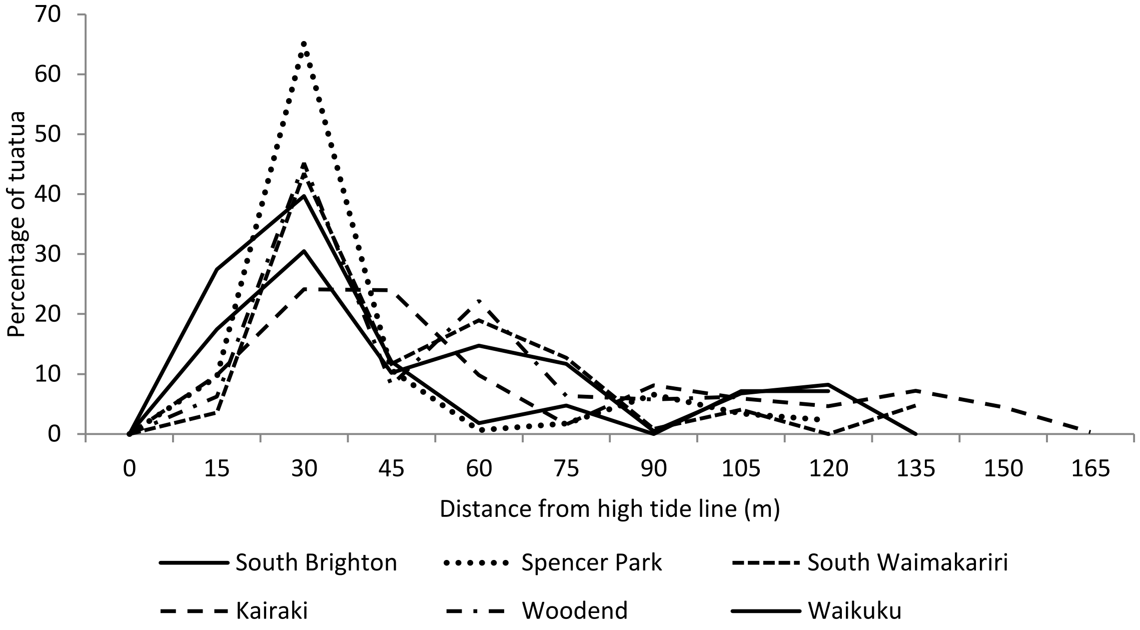

Figure 3.18: The combined seasonal spatial distribution of tuatua on six beaches in Pegasus Bay, Canterbury.

Physical beach characteristics as an indicator of abundance

The total number of tuatua found at each site and season was plotted against the change in horizontal beach excursion (Figure 3.19) but no correlation was found using regression analysis. With the increase in fine sediment a change in tuatua abundance was not shown in the data (Figure 3.20). Regression analysis testing other variables including mean sediment size and sorting, percentage of fine sediment, and pore water content (%) also failed to yield a significant result.

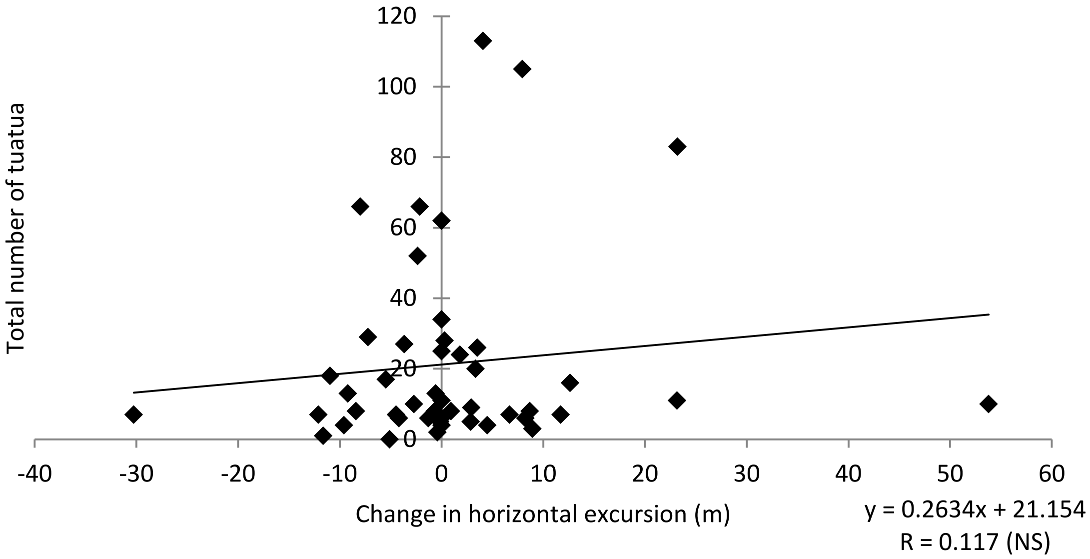

Figure 3.19: The relationship between total number of tuatua (*Paphies donacina*) and the change in horizontal excursion between sampling times at mean sea level of beach profiles in Pegasus Bay study sites, Canterbury. Also included is the line equation and regression R. NS= not significant.

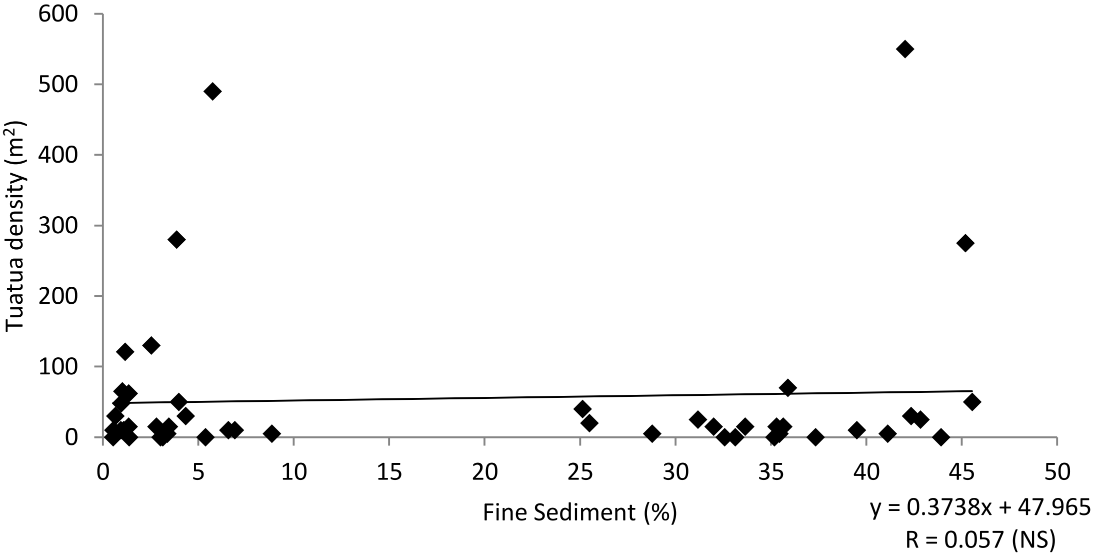

Figure 3.20: The relationship between percentage of fine sediment (>3.5 phi) and tuatua density at mean sea level within the Pegasus Bay study sites, Canterbury. Also included is the line equation and regression R. NS= not significant.

3.5 Discussion

The ability to use physical environmental data to predict ecological information could be a useful tool for sand beach managers. The present data confirms findings of earlier studies by Gabites (2006) and Allan (1999) that beaches in Pegasus Bay are very slightly accretional over decadal time scales. As with the genus *Donax* found on beaches in South Africa (Ansell, 1983), tuatua in Pegasus Bay were the dominant surfclam in the intertidal zone. However, there was high spatial and temporal variation in the abundance of tuatua during the study period which could be due to a wide range of factors such as El Nino and La Nina oscillations, human impacts and high earthquake activity. The latter is not directly from the ground shaking, but rather the pulsed increase of finer sediment in the beach deposit which is known to have adverse effects on bivalve species (Nel *et al.*, 2001). Understanding and acting based on the interrelatedness between the environment and the fauna is encouraged in ecosystem-based management. It is very difficult to clearly and quantitatively attribute environmental variables to shellfish populations, but if successful, doing so will provide information on the expected abundance of biota as result of measured physical variables.

3.5.1 Characterisation of Pegasus Bay beaches

The present study found that the majority of beach sites exhibited patterns of accretion; however, the two sites (South Waimakariri and Kairaki) in close proximity to the Waimakariri River were erosional. Further comparisons with Environment Canterbury’s twenty year cross-sectional surveys, measured on a yearly (or biannual in some areas) basis, indicate most sites have been relatively stable over an extended period (Figure 3.11). There was some variation from year to year, especially at site C2200 which is situated on the south side of the Waimakariri River mouth. A possible reason for this is the general variability of physical processes near to such areas. Instability created by the Waimakariri River mouth makes these areas unsuitable to sustain populations of intertidal shellfish, but most other areas of Pegasus Bay are likely to be highly suitable habitats due to their relative stability. In addition to instability created by the Waimakariri River mouth, earthquake activity changed the sediment composition of some sites which could have affected shellfish populations in Pegasus Bay.

Historically, the Waimakariri River mouth flowed out of Brooklands Lagoon, with the inlet travelling up and down the coast to its southern end. An artificial cut was made through the beach in 1930 to locate the mouth opposite the main river channel, bypassing the lagoon

(Christchurch City Council 2010; Christchurch City Council, 2011). Since then, it has been observed that the Waimakariri River mouth has slowly migrated towards the south again from the main river channel cut. This process has eaten away at the sand dunes and uprooted large trees (Figure 3.21). The migration to the south and subsequent erosion is evidenced in the measured beach profile record, which shows that Kairaki Beach (north side of Waimakariri) has been consistently accreting, whereas South Waimakariri Beach has been eroding over the profile record period since 1994 (Figure 3.10). Gabites (2006) suggested this trend was not truly indicative of the area due to the short period of the study. However, the subsequent loss of this site, due to a large erosion event in 2011, suggests that this trend has persisted. In the present study, however, the South Waimakariri profile did not show an erosional trend from 2010 to 2012. A key reason may be because the site was far enough away from the shifting river mouth for it not to be subject to erosion caused by riverine processes.

Gradual accretion was found at the majority of the sites sampled in the present study, conforming with the findings of Gabites (2006) who noted that the sand beach areas, that is the southern 40 km of Pegasus Bay, were moving seawards. Allan *et al.* (1999) also concluded that beaches were accreting in their study of the southern spit area of Pegasus Bay. In contrast, an erosional trend at the mixed sand and gravel beaches (north of Leithfield Beach) was found in Gabites' study.

Throughout the period of the present study (May 2010 – February 2012) it was observed that the Waimakariri River Mouth was moving south. A range of process variables could be responsible for this but the most likely are coastal storm events in combination with long-shore processes. The predominant current system along the east coast of the South Island is northward moving, driven by swell waves moving up the coast of New Zealand from the Southern Ocean (Hart *et al.*, 2008). Banks Peninsula interrupts this flow, resulting in a reverse eddy in the lee of the Peninsula. Reynolds-Fleming and Fleming (2005) established that the predominant current in Pegasus Bay is southward moving, with an average velocity of 2 cms^{-1} in the nearshore. This current system could be a large driver for the Waimakariri River migrating south. It is assisting the movement of sediment along the coastline past the river mouth as bars are formed before being deposited on the beach face. I observed a large bar of sediment had built up on the north side of the mouth in November 2010. The Waimakariri River mouth interrupts the current flow and associated southward sediment transport to the south close in the nearshore. When large storms driving swell from the north occur, the bar would be broken and the sediment could bypass the mouth and continue moving south along the coastline. In between storms this area would continue to build if the present conditions permitted.

Figure 3.21: Trees uprooted on the southern side of the Waimakariri River mouth from the river mouth shifting south and eroding the sand dunes. Photo taken in November 2010.

3.5.2 Earthquake influences on beach characteristics

During the period of the study (May 2010 to February 2012) there were 40 earthquakes over a magnitude five (M_L) (Geonet, 2012). In the event of earthquakes with larger ground accelerations, volcanoes of liquefied sediment were produced from the ground (see Table 3.4 for a list of these events). This not only occurred on land, but in waterways and coastal regions (author observations). Zeldis *et al.* (2011) found mounds to cover 35 – 65% of the estuary surface depending on the site sampled. The highest cover was found at the eastern edges of the estuary. In the present study, the data did not show a change in the open coast beach deposit sediment properties until four months after the September 4th earthquake. Such a time lag would be expected between the surface and waterway release of sediments and their reaching the study site beach deposits, particularly because the 4/09/2010 earthquake was centred west of Christchurch in the Darfield area (Table 3.4). The later earthquakes, from February 22nd 2011 onwards, were centred in or close to the coastal areas as the epicentres generally tracked eastward, so fine sediment may have been pushed up closer to the beach zones, both in the coastal reaches of rivers and across the terrestrial surfaces of the coastal suburbs with high water tables, resulting in a shorter time for the released sediments to reach the open coast environments.

Table 3.4: A summary of large (>6.0 M_L) earthquake activity in the Canterbury region during the study period (data taken from GNS, 26/01/12)

Approximate epicentre location (town or suburb)	**Epicentre coordinates (longitude, latitude)**	**Date**	**Magnitude (M_L)**	**Epicentre depth (km)**	**Approximate distance from open-coast shoreline (km)**
Darfield	43.55°S 172.18°E	4th September 2010	7.1	11.04	45
Hillsborough	43.5834°S 172.7012°E	22nd February 2011	6.3	5.92	5
Redcliffs	43.56°S 172.74°E	13th June 2011	6.3	6.92	2

In the present study, mean sorting values increased by 33% post earthquake (indicating relatively poorer sorting) and mean sediment size decreased by 7%, but the mean values remained within the well-sorted fine sand classes. Such sudden changes in the sediment deposit have not been recorded for this coast under non-earthquake conditions. Unpublished data made available by Environment Canterbury, showed that sediment of a mean size of 2.31 phi was found on the beaches of Pegasus Bay in 1997. This sediment size is very similar to that found at the start of the present study. In addition, Duns (2005) also found sediment to be similar in size and sorting to that found at all sites at the beginning of the present study. There was a notable increase in fine sand (3.5 phi) during the period of the study. Such a sudden and pronounced increase in fines is unprecedented when compared to three decades of previous records and studies. It was, therefore, not likely to have been produced by wave climate variations in season or yearly processes, but is rather more likely to have been an outcome associated with the large amount of earthquake activity in the Canterbury region.

Typically, sediment sizes and sorting can be associated with physical processes (Thrush *et al.,* 2005). Furthermore, species assemblages can also be predicted through associations with sediment types and the process associated with them (Compton *et al.,* 2008). However, these processes are relatively regular and predictable (operating over sub-annual to inter-decadal cycles) compared to the release of fine sediments from large earthquakes (e.g. the Canterbury earthquakes had return intervals in the tens of thousands of years). The addition of new sediment and changes to sorting value can influence bivalve biodiversity by creating higher habitat heterogeneity (Compton *et al.,* 2008). However, any effects of these deposit changes may be less pronounced where shellfish species are concentrated in the surf zones due to rapid mixing, disturbance and transport of sediment in this high-energy part of the beach – compared to lower energy nearshore areas where extra pulses of fines released to the coast would be more likely to settle and remain for extended time periods. For tuatua, this means that both the subtidal adult and intertidal juvenile populations would have been less vulnerable to earthquake releases of fines compared to deeper, nearshore species.

3.5.3 Tuatua abundance and distribution

Tuatua abundances varied dramatically from year to year. For example, in spring Woodend Beach went from a total of 113 to just nine tuatua the following year. Marsden (2010) found denser populations in southern areas of Pegasus Bay compared to northern sites. Juvenile recruitment occurs from the subtidal adult population, but relating these intertidal densities to the offshore population is difficult. This is due to the planktonic dispersal of juveniles and also some juveniles remain subtidal (Cranfield *et al.,* 2002). Anecdotal evidence suggests this distribution was not always the case in Pegasus Bay. Members of the public have mentioned that as children they could dig up adult tuatua everywhere in the lower shore. During the present study very few or no adult tuatua were found in the intertidal at study sites.

Juvenile tuatua were located in a distinct band 30 m below the last high tide mark at all sites sampled. This pattern did not vary between seasons or site and indicates that constant zonation occurs for intertidal tuatua. Studies by other authors for tuatua populations in Pegasus Bay have also identified these high density bands (Cranfield *et al.,* 2002; Kingett Mitchell Ltd., 2003; Marsden, 2010). In Marsden (2010), highest tuatua densities were found in a band 20 m below the last high tide line, and Kingett Mitchell Ltd. (2003) determined the band to be in the upper 40 m of the shore. Therefore, the band found in the present study is within the parameters identified by other studies, but it may move vertically over a longer time period (e.g. year to year).

The banding distribution identified for tuatua in the present study is likely to occur with a range of environmental tradeoffs. For example, banding low in the intertidal zone allows individuals to be submerged for longer duration to feed and grow but are more at vulnerable to predation; whereas, banding high results in less feeding time but lower predation risk. Banding patterns also have the potential to maximize damage to populations if damaging activities are focused at this tidal level. Banding distributions have been found in other New Zealand surfclam species such as toheroa (*P. ventricosa*); however, this species also has adult individuals found intertidally and has been found to be concentrated 20 m below the last high tide (Akroyd *et al.*, 2002). Overseas species, such as *Donax variablis* in U.S.A, exhibit banding patterns within the intertidal zone (Wilson, 1999).

Using evidence from previous studies of tuatua in Pegasus Bay- the tuatua band being 20 m below last high tide (Marsden, 2010), and in the top 40 m (Kingett Mitchell Ltd., 2003) - in combination with the present study, it could be estimated that the band may be approximately 20 m wide and centred on the 30 m below last high tide mark. Therefore it would be appropriate to keep detrimental activities out of this zone; however, one must also keep in mind other biota is surrounding this area also. For example, polychaete holes were observed below the shellfish band during the study. Permitting traffic to this zone would simply created issues for other species. In all, this requires management which aims to limit the impact of heavy users for the entire beach ecosystem. Identifying and protecting vulnerable biota in certain areas allows for alternative areas which can be used for recreation where damage is negligible.

Factors affecting abundance and distribution

Juvenile tuatua densities were found to be highest 30 m below the last high tide line and abundances were generally higher at the northern sites. Attributing or correlating tuatua distribution patterns to environmental variables would be a useful tool if successful. It would allow beach managers to infer what the shellfish status should be through assessing physical environmental variables. The present study was unable to attribute shellfish abundance or density to any particular variable which suggests that a range of factors was influencing dispersal of tuatua in Pegasus Bay. The beaches are all relatively similar in terms of sediment size, profile and physical processes, so beaches which contrast one another may reveal shellfish abundance-environmental factor relationships unable to be found in the present study.

For the duration of the study, the abundances and distribution of tuatua were found to be highly variable and no physical property of the sand beaches was found to influence tuatua abundance. This is despite rapid changes in the population. For example, between winter and spring, 2010, there was a large increase in tuatua numbers at the three northern sites (Kairaki, Woodend and Waikuku) and this was not found the subsequent year. Such changes are not likely to be solely down to dispersal dynamics of tuatua, but could be due to environmental conditions.

Three major environmental factors may have influenced the tuatua population: climatic patterns, high earthquake activity, and artificial extrogenous forces (i.e. the operation of a hydraulic shellfish dredge). If climatic conditions are not suitable for tuatua to grow and reproduce the subsequent recruitment will be affected negatively. Tuatua are subjected to a range of environmental conditions, such as high wave forces and changing water temperatures, which could influence reproduction and Dawson (1954) found that missing year classes indicated inter-annual differences in reproduction of tuatua. If this is the case for tuatua, reproduction may not occur at all one year, but large amounts of gametes could be produced the following year.

Mast seeding is a term used largely by plant ecologists; however, the notion of this theory could be applied to shellfish populations, and could explain the differences in recruitment from year to year. Mast seeding is defined as the variable and synchronous production of seeds by a population of plants from year to year for either pollination or predator satiation benefits (Buonaccorsi *et al.*, 2003). The reproductive cycles of shellfish can be compared to that of plants as they both spawn by releasing gametes and are synchronized by environmental cues (Marsden, 1999a). If mast seeding occurs in shellfish populations then it would be assumed that some years may have little or no recruitment but other years would have large amounts of recruitment when conditions are more favourable.

Environmental conditions were warmer in 2010 and may have been more favourable for gonad production which could have resulted in higher levels of recruitment compared to in 2011 (NIWA, 2011a). For example, temperatures were higher than average in Christchurch during the summer of 2010/11 (NIWA, 2011a) which is likely to cause higher reproductive outputs in tuatua populations (Marsden, 2002). This would reflect in the following year's recruitment which takes place approximately two months after gonad maturation (Marsden, 2002). Furthermore, winter temperatures are usually cooler resulting in shellfish retaining tissue through a shutdown period for the following reproductive season. The 2011/12 summer was a lot cooler due to La Nina climate patterns and not as favourable for reproduction (NIWA, 2012). The pattern found during the present study had high levels of recruitment during the warmer months which was also identified by Marsden (2002).

High earthquake activity occurred in the Canterbury area from 4th of September 2010; these events included ground shaking, sediment movement and contamination of nearshore areas with sewerage pollutants as a consequence of damaged infrastructure. This may have caused large numbers of the populations to move, or large amounts of mortalities reducing reproduction the following year (2011). The effects of the earthquakes were felt throughout Canterbury and included ecological damage, especially in estuarine environments where organisms were smothered by introduced sediment (Author observations). The finer sediment deposits occurred in the warmer months when important life stages; when reproduction and recruitment occurs in Pegasus Bay tuatua (Marsden, 2002). The capacity of such processes may decrease as a result (i.e. reproductive outputs would be reduced).

The ecological implications of introducing large quantities of sediment to an intertidal area can have a significant impact on communities. The immediate cause for concern is smothering, which occurs when sediment is rapidly deposited and settles on top of the existing substrate surface (Thrush *et al.*, 2004). In surfclams, increased fine sediment can clog the gills and reduce feeding capability. It does not take a large amount of sediment for a population to be significantly affected. For example, Zajac and Whitlach (2003) deposited 1 m^2 areas of sand 15 cm deep on the surface of infaunal communities and found that it took 2.5 months for recovery to occur. Therefore deposition of foreign sediment over the entire coastal zone may cause recovery to take several months. In the long term it could result in reduced reproduction and ecological functioning of infaunal populations. This may result in other species, reliant on bivalve facilitation, decreasing in abundance. Overall, this could reduce the stability and resilience of the ecosystem until full recovery occurs.

In regard to intertidal tuatua, this particular zone is highly disturbed by wave processes so sediment would not be likely to smother individuals in this zone. The subtidal zones (below the MLWS) of surf beaches are observably less impacted by wave forces. Sediment would settle for longer and may cause smothering to the adult population in the area. This may cause disruption to behaviour by individuals of the population. For example, Nel *et al.* (2001) found that shellfish (*Donax sordidus* and *D. serra*) had longer burial times in finer sediment (≥ 3.5 phi). This response is likely to influence the overall success of the population. In a physically dynamic environment, such as the swash zone, an increase in burial time would result in individuals being exposed to stressors, such as desiccation, for longer.

Fine sediment introduction has also been shown to adversely affect feeding by clogging of the feeding structures (Lohrer *et al.*, 2006). This may have occurred for tuatua and would result in movement out of the affected area. Hull *et al*. (1998) found that a related species, *Paphies australis,* was able to resurface and resume feeding when covered by up to 10 cm of sediment. The fine sand deposits in Pegasus Bay would be likely to be shallower than this, so it would be expected that most tuatua would successfully able to resurface and disperse from the affected area.

"Tuatua are known to strictly avoid silt" (Morton & Miller, 1973) and may have moved away from affected areas as a result. Norkko *et al.* (2001) found small bivalves (*Macomona liliana* and *Austrovenus stutchburyi*) to have slower fall velocities and to be able to disperse significantly differently than sediment bed loads. This finding indicates that surfclams can actively disperse. Moreover, when new sediment enters the ecosystem affected individuals can move away from the area. The success of this dispersal will relate to fall velocities. As smaller individuals fall slower they would be predicted to disperse further than large faster falling shellfish. In addition surfclams, such as *Donax variablis,* can increase their surface area, reduce fall velocities, by extending siphons and its foot to swash ride using wave energy (Ellers, 1995). The level of increase in fine sediment was significant (Section 3.4.1), and if Morton & Miller are correct, energy may have been put into movement away from the new silty sediment. This could explain the reduction in shellfish densities between these years.

Following disturbances, it may be beneficial to implement increased controls to protect the ecosystem. After the earthquakes, contamination, which could have toxic effects on marine biota, was released into waterways due to broken and blocked infrastructure. Protecting ecosystems during this period would result in a reduction of additional stress and decrease the toxicity of other contaminants (Holmstrup *et al.*, 2010). This is because organisms will be more likely to remain in homeostasis and increase chances of survival compared to those stressed before contamination.

Additional extrogenous forces from humans could have altered shellfish distribution so that tuatua were in lower than usual abundances the second year. The earthquake activity resulted in damaged infrastructure which resulted in the release of untreated sewerage to the coastal zones (Environment Canterbury, 26/01/2013). This also disrupted many coastal activities both detrimental and beneficial to tuatua, which could further influence abundance and distribution.

Raw sewerage was released as a result of damaged infrastructure which caused faecal contamination to rise to anthropogenically unsafe levels. In normal operation, tertiary treated effluent is released from two pipes. The largest of which is located in South Brighton and releases Christchurch City's effluent 3 km offshore. The other is located at Woodend Beach and releases Waimakariri Districts effluent 1.5 km offshore (Waimakariri District Council, 2012).

The water from effluent outfalls has been shown to significantly alter marine communities (Reopanichkul *et al.*, 2009; Smith, 1997). A key indication of community change is that polychaete and detritus feeders become more abundant (Hayward *et al.*, 1997). This is often a result of increased nutrient and subsequent phytoplankton blooms. For bivalve species, water from outfalls also alters distribution and abundance. Provided waters are well mixed and sediments do not become anoxic, the increased abundance of phytoplankton could result of more food for shellfish and higher abundances as a result.

Armstrong *et al.* (1980-81) found that abundance of such species was lower at an effluent outfall in Puget Sound, U.S.A., and increased rapidly with distance from the discharge. This was likely to be due to the increased biological oxygen demand as bacteria break down the sewerage. A study by de la Ossa Carretero *et al.* (2008) on *Spisula subtruncata* also found rapid increases in population numbers further from outfalls on the Castellon coast, Mediterranean Sea, with high abundances 1000 m from the outfall. It was also noted that the type of treatment could result in changes in abundance. Generally these findings are for shallow benthic communities. These effluent outfalls are likely to have minimal effects on the distribution of tuatua in Pegasus Bay because modelling has shown that the distance and depth of the pipes and the resultant effluent plumes are unlikely to reach the shore at sufficient concentrations to cause significant changes (Miller, 2011).

Prior to the earthquakes, water quality at beaches in Pegasus Bay was at safe swimming levels. However after the earthquakes, water quality was degraded from contaminants entering the waterways. For example, on the 3rd of March 2011, Kairaki Beach was found to contain 1515 *E. coli*/100ml, with the safe swimming water value being below 260 *E.coli*/100ml (Environment Canterbury, 2012). This level of contamination caused all beaches to be closed for swimming, fishing and whitebaiting.

In regular use, the beaches of Pegasus Bay are also commercially fished for shellfish using a hydraulic dredge operated from a boat in the surf zone. This could artificially loosen juvenile tuatua from the sediment and cause them to wash up and survivors to inhabit the intertidal zone. This would explain the higher numbers on the northern beaches, where the dredge operator frequently fishes. This commercial operator had to stop harvesting following the earthquakes until water quality increased. The possible impacts of this dredge on the tuatua population came to light when a member of the public submitted photos to me and a member of Environment Canterbury showing large amounts of juvenile tuatua stranded on the swash line after dredging had occurred (Figure 3.22). These were all dead, but other shellfish may have survived and re-buried into the intertidal zone after being loosened from the sediment by the dredge. The high abundance of juvenile tuatua as sites become closer to the Waimakariri River mouth from Waikuku found in the present study suggests that the dredge could have contributed to this finding (Figure 3.17). Loosened juvenile tuatua may not have dispersed pass the Waimakariri River mouth because it acts as a geographic barrier by interrupting the predominant southerly current flow (see Chapter 1 section 1.7).

Figure 3.22: Stranded tuatua at Waikuku Beach shortly after the commercial dredge had been operating in the area (Photo courtesy of Tania Brill, 13/07/2010).

The dredge has not been in operation in Pegasus Bay since the September 4th 2010 earthquake (*Pers coms.* Cloudy Bay Clams, 2012). The absence of dredge activity could have resulted in an increase of intertidal tuatua densities in the first round of sampling (i.e. the dredge artificially washed juvenile tuatua onto the intertidal zone of the beach). This is not beneficial for shellfish due to individuals being loosened from their natural area and being artificially moved out of the preferred habitat. Decreased feeding would result from reduced submerging times in the intertidal area. Further information on the exact dates of operation would be needed to allow a more informed decision to be made. Information of this type was difficult to access due to the Ministry of Primary Industries (formerly Ministry of Fisheries) not being able to legally disclose this data without permission from the dredging company.

Suitability of sites for intertidal tuatua

The beaches of Pegasus Bay were shown to be relatively stable intermediate beaches with well sorted sediment. Such properties make these beaches ideal habitat for shellfish species, such as tuatua (McLachlan *et al.*, 1995). If undisturbed, tuatua would be expected to be in high abundance along the sandy parts of the bay. However, Dawson (1954) suggested that unstable parts of Pegasus Bay would be likely to have reduced populations. The profiles from the present study indicate variability around the Waimakariri River Mouth, so it would be expected that areas near to river mouths could have unstable populations which can change drastically between years (Figure 3.11). Whilst such areas may be able to temporarily contain tuatua, it is unlikely these will be sustained for long periods of time due to the high amount of physical processes acting on these beaches. These areas are extensively disturbed, being influenced by inland storms discharging though the river, and coastal storms immediately in the vicinity of this environment.

Shellfish are usually found in association with particular types of sediment (Compton *et al.,* 2009), and so it would be expected that tuatua would be found in association with sediment sized approximately 2.5 phi (fine sand). With the recent increase of 3.5 phi sediment, spatial changes in tuatua distribution may occur as a response. It would be likely that less shellfish would be found in areas higher in fine sediment. As a result of the earthquake activity and the introduction of finer sediments it may be that shellfish have moved away from affected beaches and into areas containing unchanged sediments. Overall, the introduction of fine sediment to the coastal environment is likely to have some adverse effects on shellfish. Active dispersal will mitigate such effects, so this sediment addition will not be detrimental in the long-term if sufficient unaltered space is available.

3.5.4 Vulnerability of tuatua to physical human impacts

Tuatua had highest abundances approximately 30 m from the last high tide line, where sand is hardened and vehicle and horse traffic occurs. This distribution pattern makes tuatua vulnerable to being crushed by users, especially when traffic is high. The band of distribution moves vertically by small amounts from year to year. This is likely to be attributed to outside environmental factors, such as when a beach is accreting or eroding.

Tuatua were not found exclusively within this band. During certain time periods individuals were spread throughout the intertidal zone. Changes in tuatua distribution pattern may make mitigation of vehicles difficult because evaluating tuatua densities is time consuming and labour intensive. Therefore, exclusion of vehicle and horse users from the intertidal zone would make it unnecessary to carry out monitoring of tuatua distribution and would be the most cost effective way to protect tuatua.

Recruitment of juvenile tuatua on the shore occurred two months after gonad maturation (Marsden, 2002). For tuatua in Pegasus Bay this only occurs in the warmer months, unlike the related species *P. subtriangulata* in the North Island which can breed all-year-round

(Grant & Creese, 1995). The disadvantage of the recruitment pattern for shellfish in Pegasus Bay is that heavy vehicle use occurs at this time. Horse users use the beach all year round so shellfish are equally vulnerable to these users throughout the year. The main issue associated with this is that tuatua wash up on the beach where they are vulnerable to trampling. When higher numbers of vehicles are present, the risk of individual tuatua being injured increases. The tuatua which bury successfully may still be vulnerable due to having weaker shells and shallower burial depths than larger individuals (see Chapter 4).

3.6 Conclusion

Over the study period, the beaches of Pegasus Bay were stable with low rates of accretion, except for areas near to the Waimakariri River mouth. Dynamics of the river mouth makes these latter sites variable and less suitable for tuatua to inhabit. Sediment composition of Pegasus Bay was generally in the well sorted category, but finer sediment was found to enter the system as a result of the earthquake activity in the Canterbury region. The most likely vector of this sediment was the Waimakariri River mouth and upwelling in the coastal zone. Further investigation into the ecological effects of the earthquake-derived sediment in the coastal environment is needed to understand the subsequent impacts on sand beach biota.

Juvenile tuatua were variable in abundance on both temporal and spatial scales; however, no relationship could be found in the data between tuatua abundance and physical beach characteristics. Further research into the beach erosion and accretion and other physical processes and their effects on shellfish populations is needed. This requires stable populations of shellfish and more intensive sampling to establish if such a relationship exists. A distinct banding pattern was found 30 m below the last high tide which indicates tuatua have a zonation preference. The exhibited banding pattern could cause additional vulnerability to vehicles and horses as this area is a preferred area for such users. It is most likely that tuatua dispersal and abundances are a result of a combination of active dispersal and physical beach dynamics; the former of which is yet to be evaluated. Understanding tuatua reproductive patterns will be likely to aid in understanding how abundances can be affected.

Chapter 4 Using shell-length to identify recruitment, burial depth and shell strength of tuatua (*Paphies donacina*) in Pegasus Bay.

4.1 Introduction

Sand beaches are one of the most predominant coastal ecosystems in the world and are subjected to a large range of physical dynamics (Mclachlan, 1990). The biota that are present on such beaches are unique; requiring specific adaptations to live in such physically disturbed habitats. In New Zealand, the surfclam *Paphies donacina* (tuatua) makes up a large biomass of biota in the sand beaches it inhabits (Morrison *et al.*, 2009). Despite this, little is known of the biology of tuatua. By examining the size distribution of shellfish, population dynamics can be understood through evaluating changes over extended time periods. Size data can be used to determine the age of individuals (Cranfield *et al.*, 1996) and identify recruitment periods (Dawson, 1954). In addition, shell size is likely to be a key attribute in determining the potential impact of damage inflicted from human activities because it is known to be a key predictor of shell strength (Garden, 1999; Grefsrud & Strand, 2006; Nagarajan *et al.*, 2006) and burial depth (Zwarts *et al.*, 1994; McLachlan *et al.*, 1995).

Tuatua (*P. donacina*) are a highly mobile and important member of sand beach ecosystems. A complex set of abiotic and biotic interactions occur, which dictate where individual shellfish may distribute at any time. For example, wave forces can move individuals within the surf zone and predation may reduce population abundance. As a result, the mean size of shellfish populations also has the potential to vary from day to day. Understanding this variation is necessary in order to identify the overall dynamics of a tuatua population. On the population level, spatial and temporal size data can be used to identify important events.

Tuatua of a wide range of shell lengths are found on the beaches in Pegasus Bay, but more juveniles are present in the intertidal zone (Cranfield *et al.*, 2002). Adults are distributed in the subtidal zone, but can also be found in the low tide swash during spring tides. Dawson (1954) used shell lengths to predict the age of tuatua populations in Pegasus Bay, and more importantly to infer when recruitment had occurred. Dawson (1954) found that recruitment in tuatua was not consistent between years, but occurs when environmental variables were suitable. With the exception of Marsden (2002) and Dawson (1954), tuatua (*P. donacina*) in

Pegasus Bay have had population surveys conducted at a single time period (Cranfield *et al.*, 2002; Kingett Mitchell, 2003; Marsden 2010). The present study sampled shellfish seasonally over a two year period providing replicated data to identify population changes during this time.

Burying into the sediment is a vital adaptation for the survival of sand beach bivalves such as tuatua. The sediment provides sheltered moist conditions which protects individuals from desiccation during the low tide and from predators (Zwarts & Wanink, 1989). Humans are using sand beaches in higher numbers, so the sediment provides much needed cushioning when recreational activities take place on the sediment surface. Deeper burial within this sediment gives shellfish a buffer zone where forces can be dissipated before impacting on individuals. As a result, shellfish are more likely to survive being driven over by heavy beach users (i.e. vehicle and horse users).

Schlacher *et al.* (2008b) found that when driven over by a vehicle there were more shellfish fatalities in softer sediment than compacted sediment. This is likely to be because vehicle tyres penetrate deeper in less compacted sediment. The deeper an individual is buried, the less likely it would be affected by forces exerted from vehicle and horse users. This is because the forces weaken as they are spread over and down through the sediment column.

Generally, sand beach bivalves bury shallowly in the sediment. Sassa *et al.* (2011) found that sediment characteristics also influence the depth and angle at which shellfish bury. The findings of that study using *Ruditapes philippinarum* and *Donax semigranosus* indicated that compact sediment resulted in a reduced burrowing angle and overall depth. This reduction of depth with angle is of little surprise. After all, trigonometry highlights that to bury deeper below the surface at a lower angle you would have to move further on this angle to do so. However, these findings highlight that different sediment characteristics between locations will influence the depth and orientation of shellfish; both of which may influence the vulnerability of individuals to outside forces.

To be successfully protected from forces above the sediment shellfish also have another asset that helps to reduce the damage inflicted; a shell. The development of a robust shell has important benefits for bivalves: increasing defence capability would be the largest benefit of this feature. Tuatua (*P. donacina*) are a major food source for many predators in sand beach ecosystems of Pegasus Bay, including crabs, birds, and fish (Williams, 1969). The main method of defence from these predators is use of a hard calcareous shell which encloses the individual (Smith & Jennings, 2000). If applying ‘Optimal Foraging Theory’, strong shells increase predator handling time of an individual, making it less desirable to predators (Hughes, 1980).

In the intertidal zone there are many activities that can result in shellfish mortality; these include vehicle traffic, horse riding, and general recreation, such as sporting activities. Juvenile tuatua are spread in the top 10 cm of sediment throughout the intertidal zone of New Zealand’s sand beaches, and are vulnerable to many stressors including human activity (Cranfield *et al.*, 2002; Marsden, 2010). Therefore, it is very important for bivalve species to develop a strong shell to prevent damage and subsequent mortality. In addition, knowledge of the force that it takes to break these shells can be used in management as background information for a new activity to take place. For example, if a proposed activity includes using heavy equipment then the potential impacts on shellfish can be assessed.

Testing of shell strength has been carried out on other bivalve species using a range of methods. Some provide direct measurements of shell strength (Garden, 1998; Grefsrud & Strand, 2006), while others give indirect measurements, such as the height taken to break the shell when dropped (Nagarajan *et al.*, 2006). These experiments have calculated the force required to damage the shell but the orientation was not considered.

Most experiments tested the shell when positioned so that the margin of the valves was horizontally aligned. However, orientation of the shell in its normal vertical position in a beach could produce differing results. Testing both axes is relevant for tuatua because when buried in the sediment tuatua are almost always aligned vertically, as shown in Figure 1.11. Despite this, testing shell strength for horizontal alignment was also performed because when tuatua are removed from the sediment from bird predation, or washed onto the shore, they are in this position. It has been observed in Donax spp., which has similar characteristics to tuatua, that individuals can actively surface and move across the sediment by leaping (Ansell, 1983). As such, any force which is imposed on individuals will be of this nature. Horizontal tests are also comparable with previous work which performed tests on this axis of bivalve shell.

4.2 Aims

This study had three key aims which were, firstly, to describe the changes of individual size of a tuatua population at six selected sites within Pegasus Bay, Canterbury. Secondly, to establish whether the burial depth of tuatua (*P. donacina*) changed with shell length, and, thirdly, to assess the effects of shell length and orientation on the shell strength of tuatua.

It was expected that the population structure of tuatua would be similar between sites due to being in close proximity and undergoing similar dynamics. Tuatua were expected recruit over a single time period and remain on the beach resulting in an increase in mean size throughout the study period. A positive relationship between and shell length and burial depth was expected, as was a positive trend between shell length and strength.

4.3 Methods

4.3.1 Size distributions

The shell lengths of all individual tuatua were recorded during abundance sampling conducted in Chapter 3. This took place in every three months from May 2010 to February 2012. Shell length was measured to the nearest millimetre using vernier callipers at the maximum distance across one side of the tuatua shell (Figure 4.1).

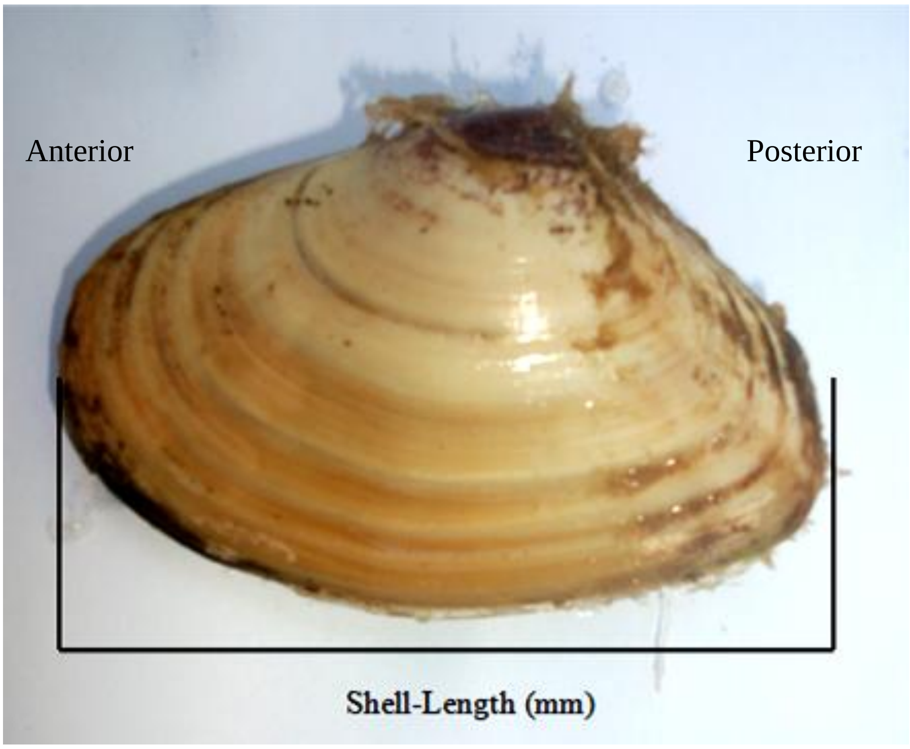

Figure 4.1: The measurement of shell-length for tuatua.

4.3.2 Burial depth

On the 1st and 2nd of August 2011, three beaches in Pegasus Bay, Canterbury (Waikuku, Spencer Park and Woodend) were sampled for this study because they contained high densities of tuatua (*P. donacina*). The other sites (Kairaki, South Waimakariri and South Brighton) were sampled but did not contain sufficient tuatua. The depth at which individuals were buried at the low-tide mark (0.2 m) was measured in the intertidal zone (approximately 30 m below the high tide drift line). This was done like an archaeological dig - using a spade to lightly scrape away sediment until an individual was uncovered, but in its original position. The burial depth was measured for each individual. Depth was measured from the sediment surface down to the top edge of the shell. The individual was then removed and its shell length recorded. This was repeated until at least 15 individuals were found at each site.

4.3.3 Shell strength

The strength of the shell was tested on both the horizontal and vertical axis to examine if the force needed to cause a fatal breakage (i.e. a large crack through the shell) differed in relation to orientation. Tuatua of a range of shell lengths were collected from South Shore Beach, Canterbury, but tuatua greater than 80 mm were only found in the shallow subtidal zone at Taylors Mistake Beach, Canterbury (Figure 4.2). Shellfish were gathered three days before testing that took place on the 9th of March and the 6th of April, 2010. All individuals were kept in an aquarium with fresh running sea water at a temperature of 15°C. Only healthy individuals were used, those which, when undisturbed, had siphons protruding from the shell, and withdrew siphons and closed their shell when physically disturbed.

Figure 4.2: Map of showing sites where tuatua were gathered for compression experiments.

Testing apparatus

A textile compression machine (‘MTS 858’ with a 25 kN load cell) was adapted for use on tuatua shells. The smallest tuatua that could be assessed was 8 mm in shell length because the load cell was insensitive to force exerted on individuals below this shell length. This machine works by using two metal plates that exert a force for a given displacement. As displacement increases, so too does the force until the object breaks. For each tuatua tested, the plates were set so that they touched the shell then the machine was started.

Horizontal axis experimental procedure

Forces along the horizontal axis of the tuatua were measured when the shell was orientated with the valves margin lying horizontally. Tuatua were put in sealed plastic bags and laid between the two metal plates of the machine so that the widest part of the shell was touching the plates and sitting level. The machine compressed at a rate of 2 mms^{-1} until the shell cracked. The cracking point was determined by watching the force exerted on the shell which was stopped when force fell suddenly, for example, when the force exerted dropped from 300 N to 50 N.

Vertical axis experimental procedure

It was necessary to determine the force required to damage a vertically aligned shell because this is the orientation of tuatua when buried in its natural environment. Testing this orientation could not be done using the same method as for the horizontal axis due to the instability created by compression of the animal on this plane if unsupported. To provide support, three different sized holders were constructed to hold the animal in place at its posterior end. The holders were made from plastic plates that had openings cut in the middle and were filled with Plasticene™ to hold the individual. The dimensions of the gaps were; large- 70 mm x 40 mm, medium- 70 mm x 20 mm, small- 20 mm x 10 mm (Figure 4.3). The shell length class of tuatua put into each plate was; large- > 40 mm, medium- 21 mm to 40 mm, small- 5 mm to 20 mm. In all 33 individual shellfish were tested with 14 in large holders, eight in medium and 11 in small. In the field, shell lengths were between 4 mm and 30 mm.

The individual tuatua and holder was put into the compression machine with the longest length of the shell touching the two plates. The rate of compression was 4 mms^{-1} for this series of testing. This was to increase the speed of the testing but still be at a rate that compression can be measured reliably, as shown by Garden (1998). The plates were adjusted so that they were touching the anterior and posterior end of the shell. The machine was started and was stopped when forces exerted reached a maximum, as done for the horizontal testing. Unlike the horizontal testing, sometimes the break would not be fatal (small crushed areas), so the compression was continued until deemed fatal (e.g. cracked through the shell, see Chapter 5).

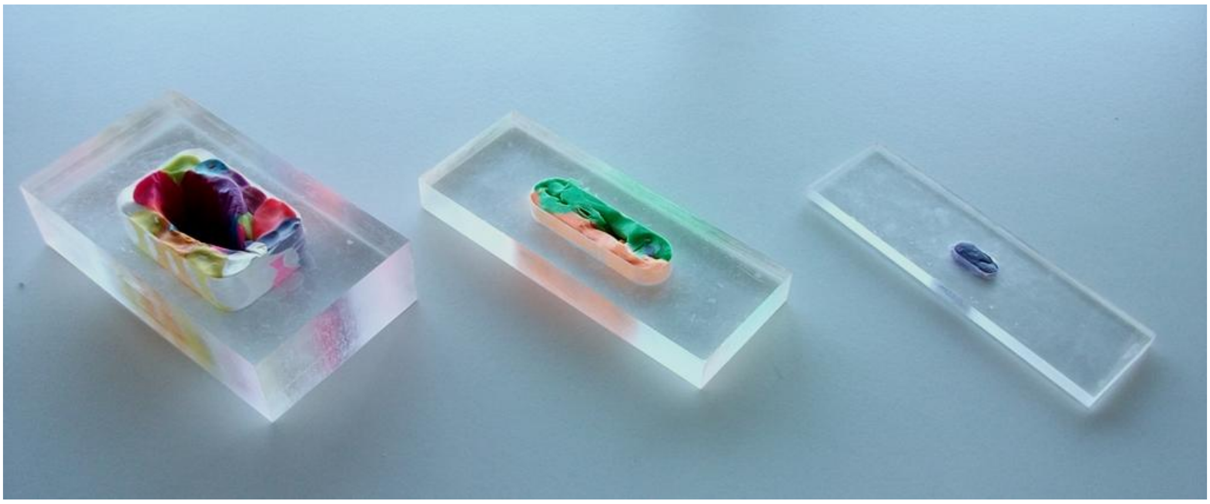

Figure 4.3: The three tuatua holders that were used for vertical compression testing.

4.3.4 Data and analysis

All data were recorded in Microsoft Excel. All statistical analyses were carried out using 'Statistica 7'. Analysis of Variance (ANOVA) was used to test differences in shell length between sites, season and position on the shore.

The relationship between shell length and burial depth was tested using linear regression analysis. A one-way ANOVA was used to test if the shell lengths and burial depths at sites were significantly different. An Analysis of Covariance (ANCOVA) was carried out to test if the shell length and burial depth relationship was different between sites.

For shell strength testing, displacement and force readings were recorded. Regression analysis was carried out to determine the relationships between variables. An ANCOVA was used to test the relationship between shell lengths and break force with different shell orientations.

4.4 Results

4.4.1 Spatial and temporal changes in tuatua size

Individual shell length

During the period of the study, tuatua in a range of sizes from 4 mm up to 61 mm were collected. All sites appeared to contain similar lengthed individuals at each time period of sampling. Shell length of individuals had an overall mean of 16.9 mm (SE= 0.27) and rarely exceeded 30 mm. The largest individual found was 61 mm on in the near the swash zone of South Waimakariri Beach, and the smallest was 4 mm found at every site during the period of the study.

At each site the mean shell length was significantly different between seasons and reduced between spring and summer of each year (Table 4.1). Generally most sites had larger individuals in the spring and summer months than in autumn and winter (Figure 4.5). When seasonal data were grouped, tuatua were significantly smaller at South Brighton compared to other sites ($F(5,1002)=23.000$, $p<0.001$) (Table 4.1).

Between the sampling periods (three months), tuatua of a starting length of 11 mm had a mean increase of 4.28 mm. This was extrapolated to a mean shell length increase of 17.1 mm yr^{-1}. Where found, shellfish were a similar length within the sampling area ($F(9,30)=0.954$, $p=0.496$). The high tide line was not included in this analysis due to no tuatua being found at this location for the duration of the study.

Figure 4.4: Juvenile tuatua caught during sampling.

Table 4.1: Table of mean tuatua shell length at each site and season and the ANOVA *p* value (* *p*<0.001; NS, *p*>0.05). Use type at each site also noted, NVH, no vehicle or horse use; H, horse; V, vehicle.

			South Brighton (NVH)	**Spencer Park** (H)	**South Waimakariri** (V)	**Kairaki** (V)	**Woodend** (H)	**Waikuku** (NVH)	***ANOVA Result***
2010	**Autumn**	**Mean shell length (SE)**	10.5 (1.9)	10.5 (1.1)	15.7 (3.5)	12.6 (0.8)	10.3 (0.4)	12.6 (0.4)	*p*= 0.028
		N	11	6	4	25	62	34	
	Winter	**Mean shell length (SE)**	8.2 (1.0)	11.2 (1.1)	16.6 (0.5)	17.3 (0.4)	17.2 (0.6)	17.8 (0.9)	*
		N	18	24	27	83	66	28	
	Spring	**Mean shell length (SE)**	22.7 (0.7)	16.8 (1.1)	19.2 (0.4)	20.6 (0.4)	22.9 (0.4)	18.0 (2.0)	*
		N	3	16	105	66	113	8	
2011	**Summer**	**Mean shell length (SE)**	7.5 (1.2)	27.3 (2.2)	21.1 (2.2)	22.5 (2.1)	22.5 (5.1)	-	*
		N	26	17	52	29	8	-	
	Autumn	**Mean shell length (SE)**	7.1 (0.8)	-	7.3 (1.3)	7.9 (1.0)	12.1 (3.1)	7.4 (1.1)	*p*= 0.165
		N	20	0	4	10	10	7	
	Winter	**Mean shell length (SE)**	10.1 (2.4)	14.3 (3.7)	10.8 (0.7)	12.0 (1.7)	10.2 (2.0)	27.2 (13.7)	NS
		N	8	13	6	7	9	6	
	Spring	**Mean shell length (SE)**	14.5 (1.7)	13.7 (2.0)	61.0 (NA)	18.0 (4.5)	31.5 (11.5)	13.6 (1.5)	*
		N	13	7	1	8	4	5	
2012	**Summer**	**Mean shell length (SE)**	7.3 (1.8)	19.0 (8.5)	11.3 (3.5)	9.3 (2.0)	11.4 (3.5)	7.5 (0.5)	NS
		N	6	5	7	11	7	2	
		ANOVA Result	*	*	*	*	*	*p*= 0.005	

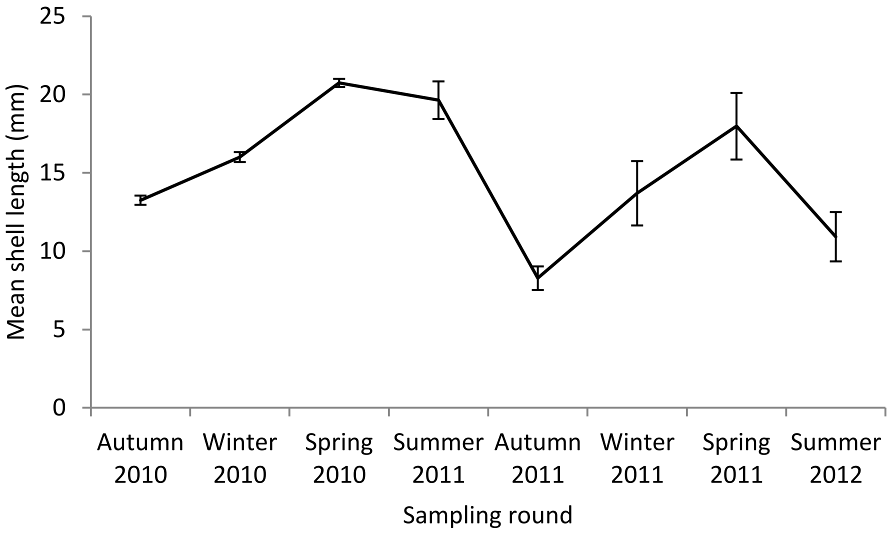

Figure 4.5: Seasonal variation in the mean shell length of tuatua in Pegasus Bay, Canterbury, error bars denote standard error of mean values.

Size distributions

When size frequency data were collated into seasons, the size of tuatua populations was multimodal during most seasons (Figure 4.6). The data for each season was not normally distributed. Due to the multimodal distribution of the first round of sampling (autumn 2010-summer 2011) individuals were likely to be from more than one recruitment event. The shell length increased at a low rate over time which suggests that the same length cohort remained on the intertidal beach.

Chapter 3 found that tuatua abundance varied between years; however, the modal shell lengths were similar to the previous year for each corresponding season (Figure 4.6). Again, the distribution appeared multimodal with a peak mode suggesting individuals were all of the same year class; most likely less than one year old. This distribution of sizes changed in the warmer months when smaller individuals were present in the sample.

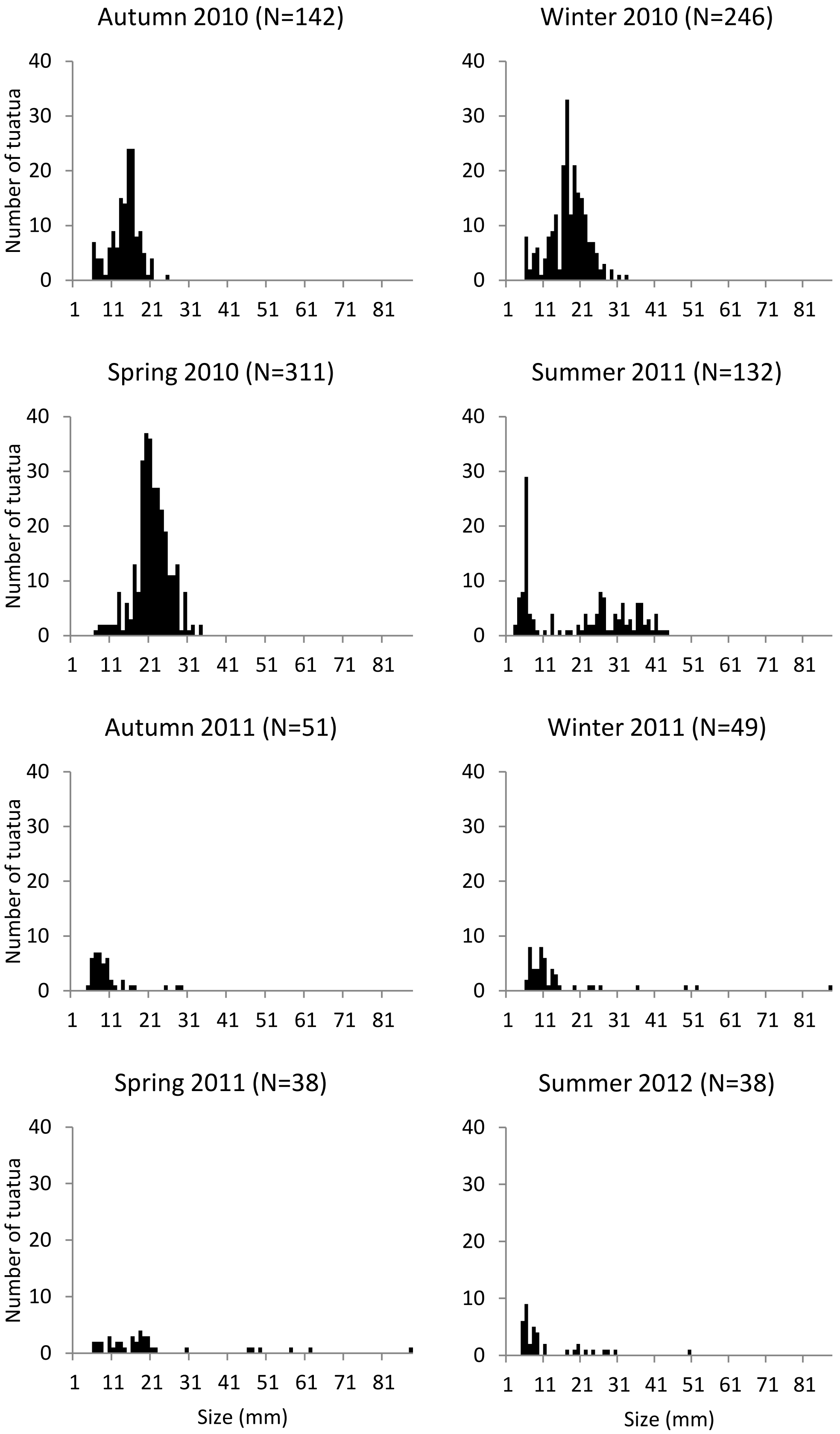

Figure 4.6: Seasonal variation in size frequency distributions of tuatua in Pegasus Bay, Canterbury with all sites combined.

Vehicle and horse user effects

When sites were grouped into prevalent use categories (no vehicle or horse, vehicle use and horse use) (Table 4.1), a significant difference in shell length was found between sites (*F*(2, 1005)= 37.8, *p*<0.001). The sites used by horses and vehicles had significantly larger shellfish than sites without these users (Figure 4.7) (Tukey's HSD test).

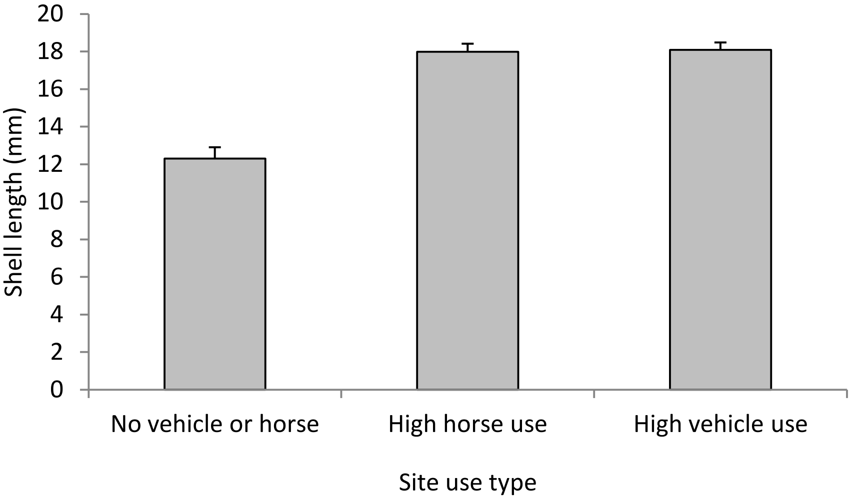

Figure 4.7: Mean shell length of tuatua in areas of Pegasus Bay with differing users. Error bars denote standard error. See Table 4.1 for categorisation of sites.

4.4.2 Burial depth

Tuatua burial depth ranged from 8 mm to 40 mm and increased with shell length. At each location, tuatua were significantly different in mean shell length and burial depths (ANOVA: Shell length, *F*(2, 42) = 4.960, *p*<0.012; Depth, *F*(2, 42) = 25.454, *p*<0.001). At Waikuku, tuatua were largest and deepest buried, whereas at Woodend individuals were small and shallowly buried. The average shell length (size) of tuatua collected from the mid tide sites at Waikuku Beach was 46.7 mm (SE=3.6), Spencer Park Beach was 39.6 mm (SE=1.1) and Woodend was 36.4 mm (SE=1.6). Burial depth of tuatua was 27.9 mm (SE=1.6), 19.2 mm (SE=1.4), and 13.9 mm (SE=1.3) at each location respectively (Figure 4.8). Tuatua from all sites had the same positive relationship between shell length and burial depth (ANCOVA: *F*-Slope(2, 39)= 1.408, *p*=0.257; *F*-Elevation(1, 41) = 2.956, *p*=0.093), as shown in Figure 4.9.

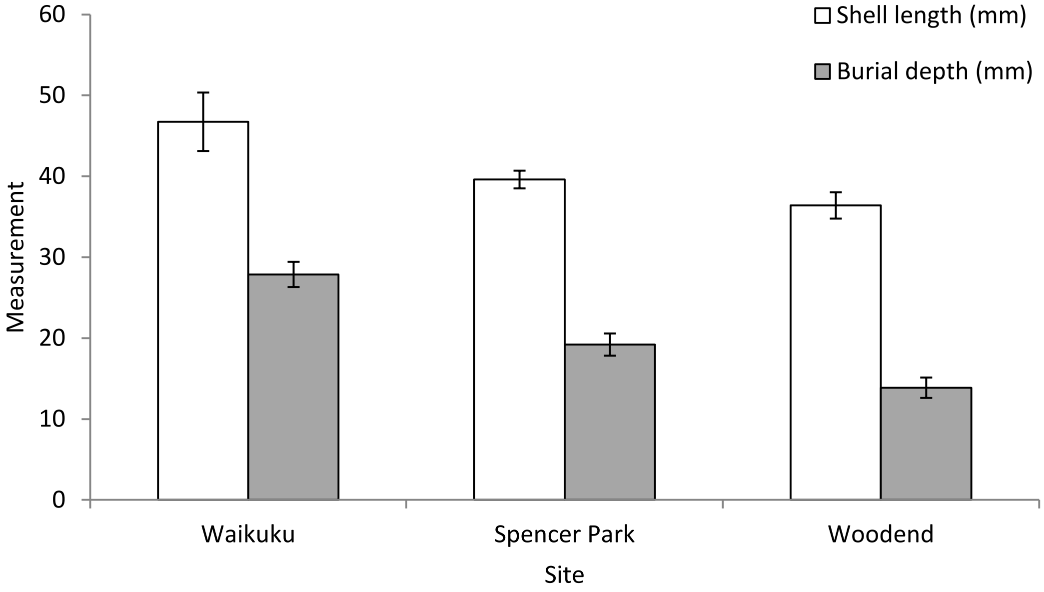

Figure 4.8: The shell length and burial depth of individual tuatua (*Paphies donacina*) at Waikuku, Spencer Park and Woodend Beaches.

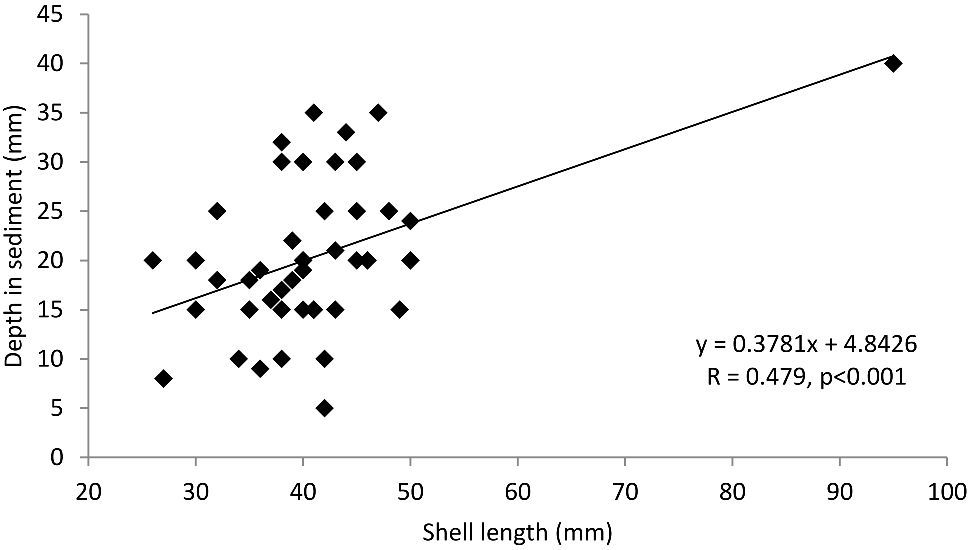

Figure 4.9: The relationship between tuatua shell length and burial depth (mm) of individuals in the sediment (mm).

4.4.3 Shell strength

The characteristics of the break type were similar to observed field breakages due to vehicles and horses (Chapter 5 and Chapter 6). That is, either a slip or a complete break in the shell was observed.

Horizontal axis

On the horizontal axis, a single break profile, ‘break’, occurred at a force when the shell broke with a single large crack. The compression force built exponentially prior to breaking the shell in this way. There was a significant logarithmic relationship between shell length and force required to break an individual (*R* = 0.91, *p*< 0.001, N=26) (Figure 4.10). All shells broke uniformly with a single fatal break through the middle.

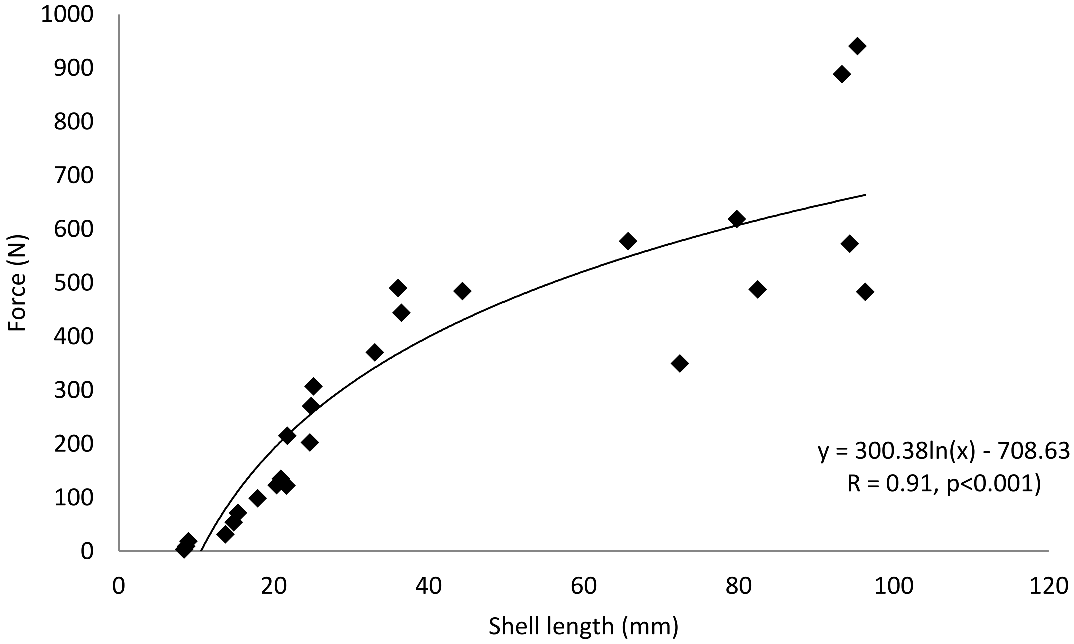

Figure 4.10: The relationship between shell length (mm) and force (N) required to break the shell of the southern tuatua (*P. donacina*) on its horizontal plane (*R* = 0.91, *p*< 0.001, N=26).

Vertical Axis

There were two types of breakages, which were characterised as in Garden (1998), as ‘crush’ or ‘break’. These two breakage types occurred at all shell lengths. A ‘crush’ occurred on weaker shells that did not require as much force to crack. Stronger shells had a ‘break’ type crack where the force built and a single sudden break would occur (Figure 4.12). The ‘crush’ profile increased in force at a constant rate as the shell continuously broke in multiple areas throughout testing. In contrast, a ‘break’ type individual withstood the force applied which caused it to build exponentially until a single break occurred. There was a significant positive linear relationship ($R = 0.96$, $p < 0.001$, N=33) between the shell length of the individual and the vertical force required to break its shell (Figure 4.11).

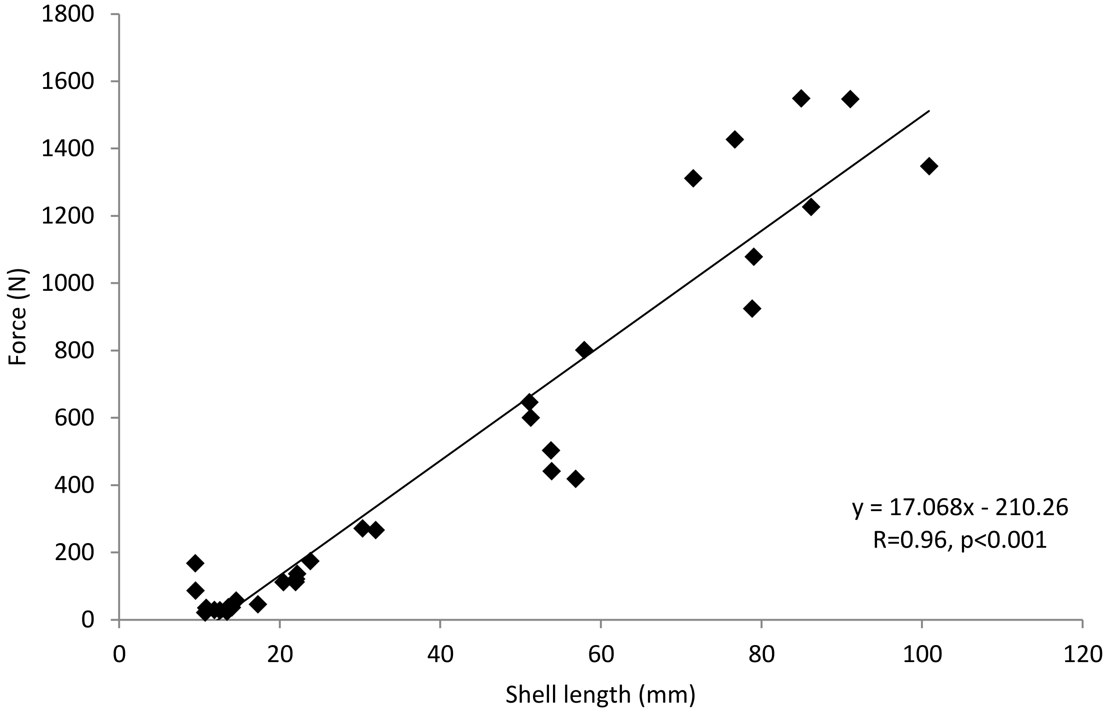

Figure 4.11: The relationship between shell length (mm) and force (N) required to break the shell of the southern tuatua (*P. donacina*) on its vertical plane ($R = 0.96$, $p < 0.001$, N=33).

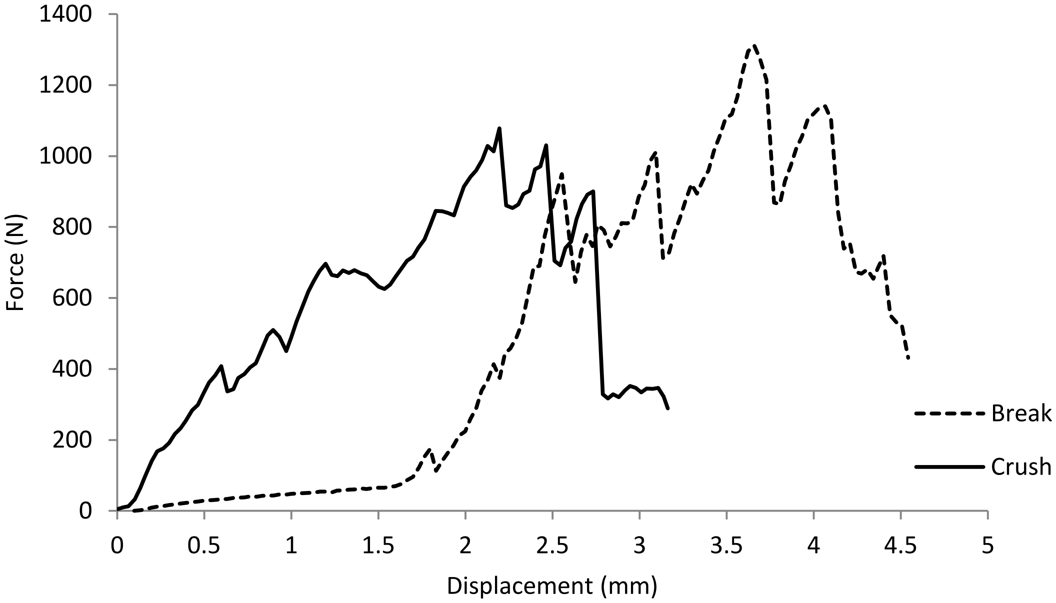

Figure 4.12: Two different profiles from breakage testing on the vertical axis of a tuatua (*Paphies donacina*) shell for individuals of similar shell length. This gives the force (N) and the shell displacement (mm). Profile titles are adapted from Garden (1998).

Effects of shell orientation potential shell damage

Both axes of orientation appeared to have similar strengths; however, the vertical axis was found to have two distinct break profiles (Figure 4.12). For the purpose of shell orientation comparisons, only the results of individuals that broke with the 'break' profile were used. This is because the 'crush' break profile, observed for some vertically aligned individuals, was not as strong (Figure 4.13). With 'crush' individuals removed from the vertical axis data, there was a positive relationship between shell length and strength of R = 0.95 (p< 0.001, N=21). The horizontal axis had a logarithmic relationship between shell length and strength, whereas the vertical axis had a linear relationship. On the horizontal axis smaller individuals were slightly stronger; however, shell strength was higher for vertically orientated individuals as lengths increased (Figure 4.13).

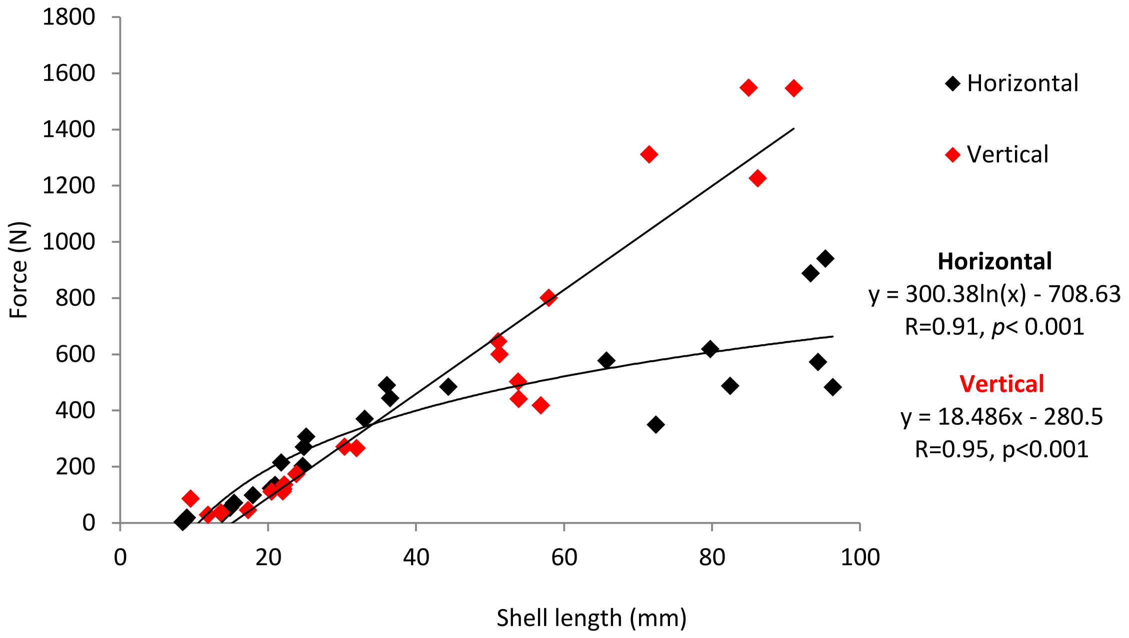

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Figure 4.13: The relationship between shell length of an individual (mm) and force (N) taken to break the shell on the horizontal (diamonds) and vertical (squares) axis of southern tuatua (*P. donacina*) with 'crushed' individuals removed. Horizontal line, $R = 0.91$, $p< 0.001$, N=26. Vertical line, $R = 0.95$, $p< 0.001$, N=21.

4.5 Discussion

Intertidal surfclams of Pegasus Bay are vulnerable to selection pressures due to being small, which correlated with shallow burial depth and low shell strength; two key attributes which influence survival. Species on other continents filling a similar niche may also have such relationships. The intertidal zone of Pegasus Bay was found to be inhabited exclusively by juvenile tuatua. Such separation between adult and juvenile individuals is common in many species of surf clams (McLachlan *et al.*, 1996). A similar species of New Zealand surfclam, toheroa (*Paphies ventricosa*) exhibits a similar separation; however, all ages of individuals of this species can be found in the intertidal zone, but juveniles are in high densities further up the shore (< 40 mm) and adults lower on the shore (Beentjes *et al.*, 2006). Similar patterns are also found in the South African bivalve *D. serra*, with large individuals low on the shore and small individuals higher on the shore (Donn, 1990).

In the present study, tuatua recruitment took place in the warmer months which was also found in Marsden's (2002) findings. The results of the present research indicate that due to intertidal tuatua being small, shallowly buried and possessing weak shells they are highly vulnerable to vehicle and horse users in Pegasus Bay. Furthermore, sediment characteristics may also increase vulnerability (Sassa *et al.*, 2011).

Consistent with findings of Cranfield (2002), who found only small tuatua in the intertidal zone, individuals caught in the present study were also small and very few exceeded 30 mm in shell length. Using age estimates from Cranfield *et al.* (1996), the shellfish were typically less than one year old (< 25 mm shell length) with some individuals over one year old.

South Brighton Beach had significantly smaller tuatua than other sites, indicating that this area may be influenced by different environmental conditions. James (1999) found that sizes of the bivalve *Donax deltoides* changed over relatively small spatial scales at Catherine Hill Bay, New South Wales, Australia. His study found smaller individuals were present in bays compared to cusp horns. Presumably this was due to smaller individuals being more exposed to water currents than larger shellfish and being deposited where currents are weaker. This could be a possible explanation for the present study's findings of smaller sized tuatua on South Brighton Beach. The prevailing currents in Pegasus Bay move southwards (Reynolds-Fleming & Fleming, 2005), so smaller individuals would be transported further hence, a smaller population would exist.

Dawson (1954) found that intertidal tuatua got larger towards the southern end of Pegasus Bay. This finding was not supported in the present study, where no such relationship was found with latitude (Figure 4.14). In addition, in Dawson's study the mean shell lengths of shellfish in the intertidal zone ranged from 25 to 55 mm. This was larger than found in the present study where the mean shell lengths ranged from 7 to 31 mm. A population made up of small sized individuals are of concern in the long-term because it could have reduced reproductive outputs (Haag & Staton, 2003). Reduced reproductive outputs will influence the success of the population by not supplying recruitment demand. This will eventually mean reduced adult tuatua and may require closure of the fishery. Smaller individuals are also more prone to predation (Boulding, 1984) and other physical forces.

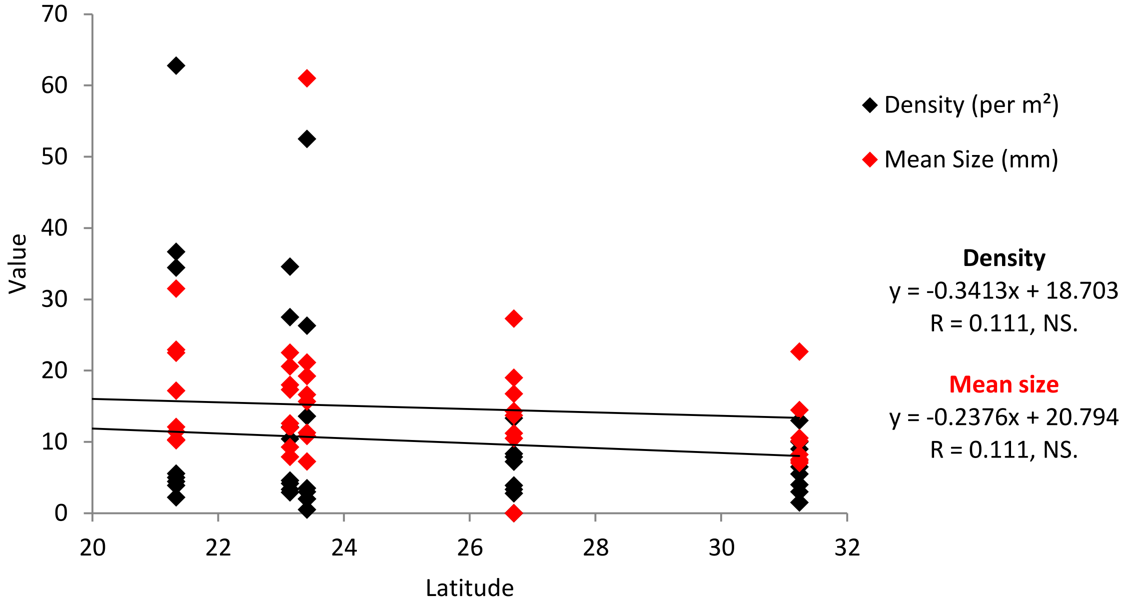


Figure 4.14: The relationship between mean tuatua (*P. donacina*) shell length and density with latitude in Pegasus Bay, Canterbury. Also included is the line equation and regression *R*. NS= not significant.

In surf clams, reproduction relies on environmental cues. Reproduction and subsequent recruitment occurred over the warmer months of the year in Pegasus Bay and Marsden (1999) suggested that this relies on warm sea temperatures, which also correlates with increased food sources. Size frequency data for the current population appeared as if the same cohorts remained throughout most of the year; however, this changed in the warmer months (between spring and summer) for each year.

Mean shell length of individuals changed seasonally; which was expected from species which breed periodically such as tuatua (Dawson, 1954; Marsden 2002). The tuatua in Pegasus Bay had a multimodal size distribution in most seasons and included smaller individuals in the summer period. Marsden (1999) suggested that reproduction was continuous in the warmer summer months and followed by inactivity over the winter. The offspring then recruit onto the beach and remain until environmental events take place which move the individuals offshore to be replaced by new juvenile recruits. Similar reproductive mechanisms occur in many species of bivalves worldwide including the oyster, *Crassotrea gigas*, in France (Costil *et al.*, 2005), the mussel, *Atrina seminuda*, in Venezuela (Freites *et al.*, 2010), and the clam, *Meretrix lusoria*, in Japan (Nakamura *et al.*, 2010). Utilising environmental cues to begin reproduction is an important adaptation for exploitive reproducers, such as tuatua (Marsden, 1999a), because it ensures that gamete concentrations will be high, increasing the chances of successful reproduction. Environmental cues are essential for the timing of these events and can range from small events, such as changes in water temperature (Minchin, 1992), to large events such as typhoons (Onitsuka *et al.*, 2007).

In addition to environmental cues for juvenile recruitment, warmer sea temperatures could also be used as a cue for sub-adult (~30 mm) tuatua downshore migration. Doing so would result in a benefit from increased food sources in the water column to maximise growth. Such cued movement is beneficial because space is made available for spat to recruit. Without such cueing, juvenile survival could be compromised. Hamner (1978) found that the distance to the nearest neighbour was a key factor in determining the success of a recruit in the boring clam, *Tridacna crocea,* in Great Barrier Reef, Townsville, Australia. Individuals within 4 cm of the nearest neighbour were found to result in death. The current densities in Pegasus Bay are low so space is not a large issue; however, as space becomes limited in high densities this cue would become more important.

Juvenile bivalves exhibit rapid growth until reaching sexual maturity (McLachlan *et al.*, 1996). In the present study individuals had similar growth patterns to a study by Cranfield *et al.* (1996) using surfclams, including tuatua, from Cloudy Bay, Marlborough. In that study, Cranfield *et al.* (1996) found growth of tuatua (*P. donacina*) 25 mm in shell length increased by *ca.* 19 mm yr^{-1}. In the present study, the shell length increase of tuatua 11 mm in shell length was 17.1 mm yr^{-1}. The shell length increase in current study was slightly lower but with smaller shellfish; however, the rates are comparable. The increase in length of *P. donacina* is comparable to similar surfclams from similar latitudes on the eastern coast of their relative continents (*Donax serra,* Southern Africa; *D. Deltoides,* Australia) (Table 4.2).

Table 4.2: Species distribution, size and growth parameters of similar bivalve species found on eastern coasts of the southern hemisphere (information sourced from McLachlan *et al.*, 1996, unless stated otherwise). (N.K.= not known)

Species	**Geographic area**	**Intertidal distribution**	**Size at maturity (mm)**	**Lifespan (years)**	**Timing of reproduction**	**Standard growth index (ϕ')**	**Size at one year (mm)**
Donax serra	Southern Africa	East and South: entirely intertidal. West: adults- subtidal	44	3.5	Late summer and winter	3.5	32-35
Donax deltoides	Australia	Juvenile: intertidal Adults: Low shore to subtidal	36	> 5	All year	3.7	33
Paphies ventricosa	New Zealand	Small (<75 mm): upper shore Larger: lower shore	40	> 10	September to February	3.83	45-59 (Akroyd *et al,* 2012)
Paphies subtriangulata	New Zealand	Juvenile: intertidal Adult: low shore to subtidal	N.K.	> 5	October to December	3.3	N.K.
Paphies donacina	New Zealand	Juvenile: intertidal Adult: subtidal	N.K.	17	November to February (my study)	3.47	25 (Cranfield *et al.*, 1996)

Comparing growth data is difficult because of the range of factors influencing growth of shellfish. For example, warmer sea temperatures correlate with increased food sources and correspond with higher growth rates. The surfclam *Spisula solidissima* has had its growth rates studied extensively (Weinberg & Helser, 1996; Davis *et al.*, 1997; Walker *et al.*, 1998; Weissberger & Grassle, 2003). Weissberger & Grassle (2003) found growth rates to vary between years and temperature. Cranfield *et al.* (1996) used tagging methods to record the shell length increase in the same individuals, whereas in the present study, the shell length increase was calculated from the mean of the samples. This would have had different individuals recorded due to the dynamic nature of shellfish populations. As a result, length increases reported in the present study would have some discrepancies in estimation due to this. Marsden (2002 found newly recruited individuals to increased by 1 mm per month (12 mm yr^{-1}), a value far less than the present and Cranfield *et al.*'s (1996) study. As Cranfield *et al.* (1996) and Marsden's (2002) study took place in different time period and location; it is plausible that the present studies estimation is correct and discrepancies have occurred due to environmental variables.

It has been suggested that shellfish move to lower tidal levels as they get larger (Cranfield *et al.*, 2002); however, the present study found no movement of the juvenile shellfish band despite individuals getting larger as time progressed (Figure 4.5). This population may move downshore suddenly and could be triggered by environmental cues. Through personal observations during other studies, it was noticed on one occasion during the summer months (December - February) a large amount of approximately 30 mm sized individuals were in the low tide swash zone (Figure 4.15). After this migration event, tuatua on the beach were small (5 - 10 mm) and no large ones were found. These observations, paired with data showing reductions in densities and shell length, indicate that, not only can movement be sudden and cued using environmental variables, but recruitment was likely to be environmentally cued and variable.

By following the size distributions over time, the results show that tuatua spawning and recruitment were highly variable between years. For example, Figure 4.6 showed a large change in the abundance of shellfish between the two rounds of sampling whilst shell lengths did not change drastically. This indicates that recruitment took place in both years, but reproductive outputs of the population were significantly reduced in the second year.

Figure 4.15: Tuatua (*Paphies donacina*) in the swash zone migrating to subtidal regions during December, 2010. Shell length = approximately 30 mm.

Burial depth

Many surf clams are known to be buried in the top layers of sediment. Smaller tuatua were found here throughout the period of the study and the results showed that individuals of this size were most shallowly buried which makes them vulnerable to environmental variables. For example, James (1999) found smaller *Donax deltoides* in the surface sediment where they are influenced more by water currents than larger individuals. The toheroa (*P. ventricosa*) is another species of the surf clam which bury shallowly on New Zealand beaches (Cassie, 1951); however, burial depth is also known to change in relatively short time periods. Roberts *et al.* (1989) found that in the intertidal clam, *Mercenaria mercenaria,* at Pines Island, North Carolina, U.S.A. burial depth changed with tidal level. During low tide clams were buried at a depth of 25 mm compared with 5 mm at high tide.

The burial depth of an individual is at a trade-off between other factors which influence its success. For example, deep burying can inhibit growth by reducing feeding capacity; this will reduce the fitness of the individual (Goeij & Luttikhuizen, 1998). Zaklan and Ydenberg

(1997) confirmed three key assumptions when shellfish (*Mya arenaria*) bury deeply; (1) survival from predation increased with depth, (2) feeding rate is slowed down in deeply buried individuals, (3) large individuals fed more rapidly than small ones at all depths. These assumptions were found to be correct, but do not take into account the presence of anthropogenic pressures in these ecosystems (e.g. vehicle use). In relation to vehicle and horse traffic, an assumption could be made that burying deeply will increase survival by avoidance of the physical effects of these users.

Other bivalve species exhibit positive correlations between shell length and burial depth. Zwarts *et al.* (1994) found a linear relationship using a different shellfish species, and that each species (*Macoma balthica* and *Scrobicularia plana***)** had different burial depths and shell length-depth relationships. Both species were of similar shell length, but *S. plana* was able to extend its siphon further from its shell. Zwarts *et al.* (1994) also found burial depth and shellfish size increased with siphon size which in turn allowed deeper burial (weight and length). In the present study, burial depth of tuatua was a positively linear relationship with shell length of the individual (Burial depth= (0.3781 x Shell length) + 4.8426). Roberts *et al.* (1989) found no correlation between clam size and burial depth in *M. mercenaria* and possible reasons included sediment characteristics, wave currents and location being stronger influences on burial depth.

In surfclams as in other bivalves, the burial depth of an individual is influenced by its siphon length (Hull *et al*., 1998). The present research also found shell length to be an indicator of burial depth. Smaller individuals have shorter siphons and bury closer to the surface than larger individuals. Larger individuals were most likely to be buried deeply because a larger siphon permits them to still be able to feed whilst maximizing protection. In addition, being buried deeply may increase the survival fitness of the individual as they are more protected from outside forces. Goej and Honkoop (2002) found that an individual’s burial depth could be correlated with immersion time; however, their results show that small individuals were present high on the shore (low immersion) and large individuals were low on the shore (high immersion). It is more likely this finding is due to the size of the individuals rather than a function of immersion. This suggestion is evidenced in the two previously mentioned studies as well as the present study. Overall, as burial depth increases with shell length, it would be expected that, despite the zone of shore shellfish are in, they will bury as deep as their siphons allow.

Shell strength

As with other similar studies, the results of the present study confirmed that the force required to cause a fatal break increased with shell length of individuals (Grefsrud & Strand, 2006; Nagaragan *et al.*, 2006; Coffen-Smout, 1998). Small tuatua buried shallowly in the sediment which also puts them in closer proximity to predators and other physical forces. Boulding (1984) stated that the absence of other anti-predator structures may also indicate the refuge provided by the sediment, so shell strength becomes very important to reduce the impact of predation and other forces on individuals. Compression testing provided an indication of the forces needed to break a tuatua; however, other environmental factors are likely to be important in determining this also. For example, Zuschin and Stanton Jr. (2001) found that 32% of *Mulinia lateralis* shells broke when arranged in a shell bed touching each other whereas none broke when individually tested.

When assessing shell strength, sediment properties should also be taken into consideration because this can influence the shell orientation due to burial angles changing with sediment compaction (Sassa *et al.,* 2011). Schlacher *et al.* (2008b) found sediment compactness was important when assessing the impacts of vehicles on *Donax deltoides.* Softer sediment resulted in more shellfish mortality because the vehicle effects penetrated deeper into the sediment resulting in higher mortalities in the form of shell breakage. Sediment properties differ spatially, and localised sedimentary characteristics and environmental dynamics could influence the results of beach user impact assessments.

In the present study, compression testing the strength of the shell on the horizontal axis of tuatua had a log relationship whereas the vertical axis was linear and had two distinct break profiles (Figure 4.12). Reasons for the two types of break profiles could be due to weakness in the shell caused by a range of processes. Smith & Jennings (2000) found that more growth went into the edge of the valve when a predator cue was present; this resulted in that region of shell being thicker and stronger. Predation may have some influence on the overall shell strength of the population as it has been shown that bird species can actively select for weaker shells (Nagarajan *et al.,* 2006) which would leave the stronger shells present. Such growth would occur on the vertical axis rather than horizontal (i.e. valves edges are thicker rather than the entire shell). This could explain why vertical orientated individuals withstood higher forces. In addition, the vertical axis had two distinct break types which suggested perhaps that some shells were weaker than others. Weaker shelled individuals may not have developed a thick edge. Without a thick edge, pressure exerted on the shell is not able to build up causing gradual smaller breakages. This break type would be likely to occur until the shell becomes thick enough to allow force to build up before breaking.

In the present study, larger vertically orientated tuatua withstood higher forces than horizontal individuals, but this difference was not found in smaller individuals (< 30 mm) (Figure 4.13). Coffen-Smoult (1998) also observed that the orientation that a shell lands on when dropped can influence the amount of damage in the scallop *Pecten maximus*. Differences in shell strength with orientation could be due to morphological factors of the individual.

Vulnerability

The findings of the present research suggest that intertidal shellfish are vulnerable to a wide range of physical impacts. Many species of shellfish are known to inhabit the intertidal zone worldwide (McLachlan *et al.,* 1996), so the vulnerability of shellfish to heavy beach activities, such as vehicle and horse users, is a key issue in conserving these species. The present study suggested that small tuatua (< 30 mm) in the intertidal zone would be highly vulnerable to damage from vehicle and horse users. Individuals of this size had weak shells and were buried shallowly in the sediment. Furthermore, studies have evaluated these individuals as being more vulnerable to predation (Boulding, 1984).

Intertidal tuatua were buried between 5 and 40 mm deep, so if vehicle and/or horse tracks penetrate to these depths, damage would be expected. In our previous studies conducted on Pegasus Bay beaches, vehicle tracks were found to penetrate as deep as 64 mm after 80 vehicle passes (Marsden & Taylor, 2010). Usually there will not be as many passes as 80 in one area, but as few as five vehicle passes created tracks approximately 10 mm deep. Horse hooves have also been measured to have an imprint 35 mm deep (Chapter 6), so any animal buried shallower than this could be impacted. If vehicle traffic is low, only the shallow smaller individuals would be affected and Marsden and Taylor (2010) found it only took 50 passes to penetrate 35 mm deep. Generally the maximum shell length of individuals in the intertidal zone is 30 mm, and these are buried approximately 16 mm deep, so intertidal shellfish would appear to be highly vulnerable to both types of users.

Shell strength testing showed as little as 8 N was needed to break a tuatua shell; however, the application of these findings is only relevant under situations that involve the individual being removed from the sediment. An off-road vehicle typically has a stationary down force of 14,700 N and a horse of 5880 N; however, using the results to determine if such activities are likely to break an individual's shell must also take into account sediment properties, such as compaction. The mechanics of movement of a horse or vehicle also needs to be accounted for as this could increase the point force of the user. For example, as the horse hoof impacts on the ground the force could exceed the stationary force of the horse itself, whereas a vehicle's forces will be similar to its vertical down force. This is because a vehicle has relatively no vertical component to its movement so additional force is not added.

Tuatua are a species which burrow to maintain position in the sediment, so substrate properties become important in influencing the depth and angle of burial. Sassa *et al.,* (2011) found shellfish lowered their burial angle and burrow shallowly when sediment was more compact. This not only puts shellfish in a position where they have higher potential to be impacted through being closer to the sediment surface, but also changes the shell orientation. The outcome of which was found to result in weaker force resistance. Therefore the angle and depth an individual is buried in the sediment as well as sediment compactness must be considered before applying the results of laboratory experiments to the field.

4.6 Conclusion

The size distribution and recruitment patterns of tuatua in the intertidal zone of Pegasus Bay beaches makes them vulnerable to mortality. Recruitment occurred during the warmer months and juveniles remained in the intertidal zone for approximately one year before moving towards subtidal areas. Intertidal tuatua were small, shallowly buried and had weaker shells, which provide very little protection from predators and heavy beach users such as vehicle and horses. The depths at which intertidal tuatua were buried was not deep enough to protect the majority of individuals from crushing by vehicles, horses and other heavy traffic which penetrate the sediment surface. Shell strength was positively correlated with length of *P. donacina* and the orientation of the shell also influenced the force resisted before breaking. Larger (> 30 mm) vertically orientated individuals were able to resist the most force. Additional protection from the cushioning effect of sandy sediment and shell strength of individuals may aid in protection from these forces. Despite larger tuatua burying more deeply, this was often not deep enough to avoid vehicle and horse users. Further *in situ* evaluation of these users is needed to understand the impact of such activities.

Chapter 5 The effects of vehicles on juvenile tuatua (*Paphies donacina*) on an intertidal surf beach in Canterbury, New Zealand.

5.1 Introduction

As with many locations worldwide, vehicles are permitted to be driven on most sand beaches throughout New Zealand. How does this affect the biota in these ecosystems? Studies in Australia suggest that vehicles cause reductions in species diversity (Schlacher *et al.*, 2008a), alter animal behaviour (Schlacher & Lucrezi, 2010) and result in shellfish mortalities (Schlacher *et al.*, 2008b). These studies have highlighted the need to control vehicles and have led some authorities to implement complete bans, as seen in South Africa (Department of Environmental Affairs and Tourism, 2004), or stipulate where vehicles are permitted (e.g. Northern Pegasus Bay Bylaw, 2010). In New Zealand, vehicles are driven on sand beaches to access fishing areas, for organised events and tourism.

The intertidal zone is often the focal point for activities, such as vehicle driving and horse riding, and the species present in this area are most vulnerable. New Zealand's sand beaches contain a wide range of biota including shellfish, shore birds, polychaetes, amphipods, and other crustaceans. Shellfish have an important ecological role in nutrient cycling, increasing faunal diversity, and reducing water turbidity (Dame, 1993; Marsden, 1999b; Vaughn & Hakenkamp, 2001; Gosling, 2003). Shellfish are a food source for many predatory organisms in the ecosystem (Williams, 1969) as well as for humans. In New Zealand they are a valued source of *mahinga kai*.

Aims

The overall aim of this study was to quantify the relationship between vehicle traffic and shellfish mortality, and to evaluate the sub-lethal effects from these activities. This study extended the study undertaken by Marsden and Taylor (2010) by using experimental manipulation to quantify the relationship between intensity of vehicle traffic and shellfish mortality. Reburial success following runover was also investigated. Experiments were seasonally repeated to identify whether shellfish may be more vulnerable at certain times of the year. Seasonal vulnerability could be due to factors such as differences in shellfish burial depths or sediment texture.

A positive relationship between the number of vehicle passes and shellfish mortality and predicted a seasonal difference in mortality was expected. If increased vehicle passes resulted in more stress on surviving individuals, the burial success might be reduced. Reburial activity may be more successful in the summer due to individuals being more active and in better health and condition (Marsden, 1999b).

5.2 Methods

The method used was designed to minimise disturbance to the shellfish and sediment prior to testing. Other studies have transplanted shellfish into an area of the beach to be runover (Moller *et al.*, 2009). Results from such experiments are unlikely to be indicative of undisturbed populations. Transplanted individuals may not rebury to their original depths and when burying the shellfish the sediment properties may be altered. Finally, the size of individuals used in experiments may not be representative of the natural assemblages for the area. To keep results indicative of natural population impacts, testing was undertaken where shellfish densities were high. Individuals and sediment were not disturbed prior to conducting the experiments.

5.2.1 Site selection

Pines Beach, Canterbury, was selected as the study site for both the winter (14th - 17th June 2010) and summer (6th - 9th December 2010) experiments. Pines Beach is located approximately 4.3 km east of Kaiapoi and is a popular area for vehicle use as it is in close proximity of the Waimakariri River mouth (Figure 5.1). The beach in this area is up to 140 m wide with a 90 m wide intertidal zone. The sediment properties at this beach are similar to the other sand beaches in Pegasus Bay (see Chapter 3). All experiments were conducted on the ebbing tide on days when the Lyttelton tidal predictions ranged from 0.3 to 0.4 m in the winter and 0.4 to 0.5 m in the summer. A population survey confirmed there were more than ten tuatua individuals per 25 x 25 cm quadrat at this location.

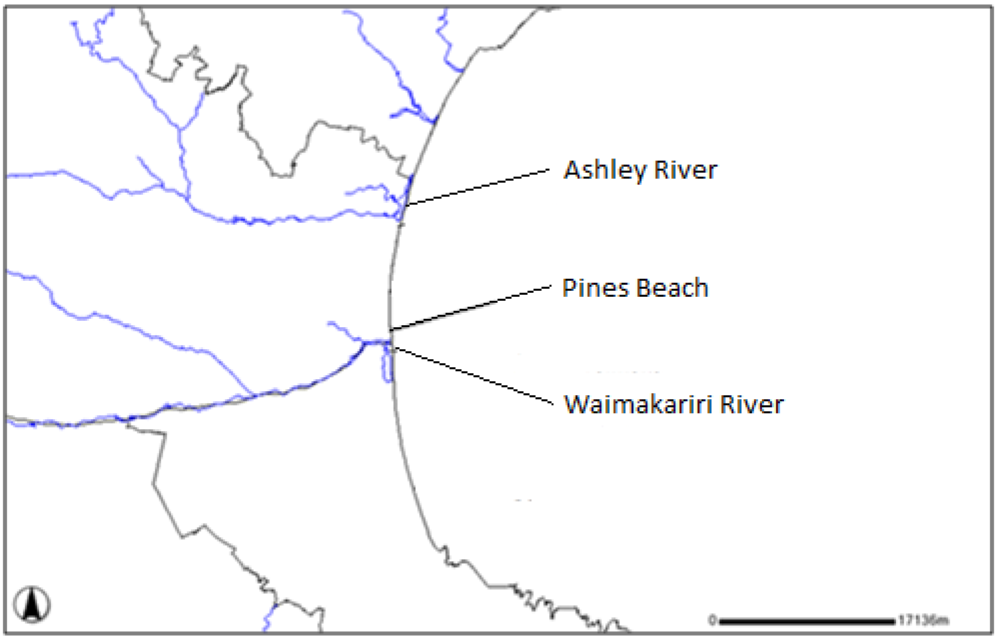


Figure 5.1: Outline map showing the location of Pines Beach; where vehicle impact experiments took place.

5.2.2 Experimental procedures

Vehicle disturbance

A 2008 Mitsubishi Triton fitted with semi-off-road tyres was used for the experiments (Figure 5.2). It weighed 1955 kg with a full fuel tank and was driven by a driver weighing 85 kg. The pressure exerted by the vehicle was 21,230 kgm^{-2} was calculated using the following equation:

$$P = \frac{F}{A}$$

P is pressure exerted by car tyre (kgm^{-2})

F is weight of vehicle (kg)

A is area of tyre tread (m^2)

The exact location on the beach was determined by finding where densities of shellfish were highest. This was done by scraping the sediment surface seaward of the most recent high tide mark. The driving line was marked out where most shellfish were found. The vehicle track was marked by measuring out a 20 m line parallel to and approximately 20 m to 30 m below the last high tide mark. The driver's side tyre was aligned with this line, and was on the landward side in each experiment. The vehicle was driven at speeds between 10 and 30 kmph north to south until the desired level of passes was reached. Each pass took approximately 30 seconds to complete. To ensure accuracy, a person was used to guide the driver through the same tracks. The same number of designated passes was completed for each day in both seasons with a control each day of zero passes. This was taken in the undisturbed experimental area before vehicle driving was started.

After the designated number of passes, tyre treads, shellfish population and sediment pore water levels were measured. Sediment cores were taken as quickly as possible so that water could not re-enter the sample.

Figure 5.2: The Mitsubishi Triton used for shellfish runover experiments.

Table 5.1: Designated number of vehicle passes on each day of testing.

Day	**Number of vehicle passes**
1	0, 1, 10, 25, 40, 50
2	0, 5, 10, 25, 30, 50
3	0, 1, 20, 30, 40, 50
4	0, 5, 15, 20, 35, 50

Sampling of the disturbed population

A quadrat 625 cm² (25 cm x 25 cm) was laid down so that it was in the middle of the tyre track. Sediment within the quadrat was removed carefully to a depth of 15 cm to minimise damage to the tuatua. The sediment was sieved through a 5 mm screen with the number of tuatua retained on the screen counted. Quadrats in the driver's side tyre track were sampled before those on the passenger's side track. The shell length of each individual was measured and any damage recorded until at least 15 non-fatally damaged individuals were found.

Sediment samples

Sediment samples were collected from the middle of the driver's (landward) side tyre tracks using a 50 mm diameter corer. This was taken within ten seconds of the vehicle finishing its passes to ensure that water displaced would not refill the sediment. The sediment sample was bagged, sealed and returned to the lab where it was refrigerated at 4°C before processing. Pore water sample processing entailed breaking the core into three pieces to get an average, measuring the wet weight of the sample, then drying it in a 60°C oven for three days. After three days, samples were removed from the oven and reweighed (dry weight). The difference between the dry and wet weight of the sediment gives the weight of pore water. The overall pore water content was calculated as a percentage of the wet weight and recorded.

Tyre tracks

Tyre tracks were measured for each level of vehicle passes to give an indirect measurement sediment compaction. The width and depth of tyre treads on each side of the vehicle were measured in the same area of the tracks at each time. Tyre track width was measured from the widest part of the tread. Tyre track depth was measured by placing a ruler over the tyre tracks which was assumed to be the original ground level then a ruler was used to measure from the middle of the base of the tyre track up to the flat object. These measurements were then recorded for each tyre track (landward and seaward) (Figure 5.3).

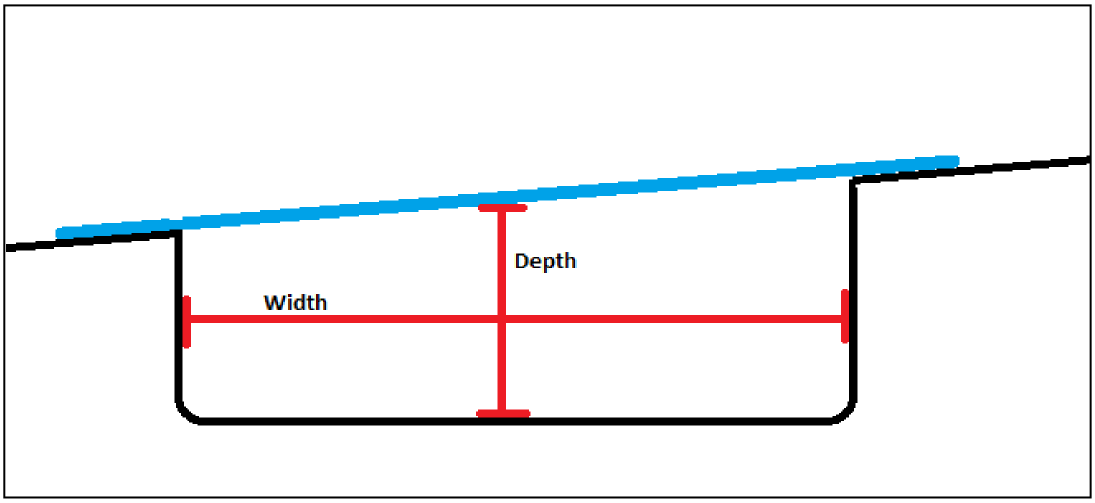


Figure 5.3: Measuring tyre track depth (in mm) and width (in mm).

Reburial testing

The 15 individuals picked for the reburial test were those that appeared undamaged (i.e. there were no cracked or slipped shells). They were placed in a plastic container that contained 5 cm depth sediment, taken from the area that individuals were collected, and seawater added to a depth of 5 cm. Individuals were placed on the sediment surface so that they were lying on their side (horizontal axis). Timing for reburial success started when all individuals were on top of the sediment surface. At the end of each minute for 15 minutes, the numbers of individuals remaining on the surface were counted and recorded. An individual was considered to be buried when it was completely in the sediment, or only the siphons could be seen protruding.

The bivalves were then kept in a laboratory refrigerator in containers of sediment and fresh seawater at 15°C and were retested for burial 24 hours after they were run over. The method described above was used for this testing.

5.2.3 Data and Statistical Analyses

All data were recorded in Microsoft Excel spreadsheets. Mean and standard error were calculated for each of the replicate samples. Generalised Linear Models (GLM) and Regression analyses were used to investigate relationships between vehicle passes and shellfish mortality, reburial success and tyre track characteristics. Statistical testing was carried out using ‘Statistica 7’. Analysis of Covariance (ANCOVA) and tests for homogeneity were used to determine if there were seasonal differences in relationships. The slope of the lines were tested first, if these were the same elevation was tested. If slopes of the lines were different, no further testing was needed because the relationships were different. T-tests were used to determine if there were differences in reburial success after 24 hours.

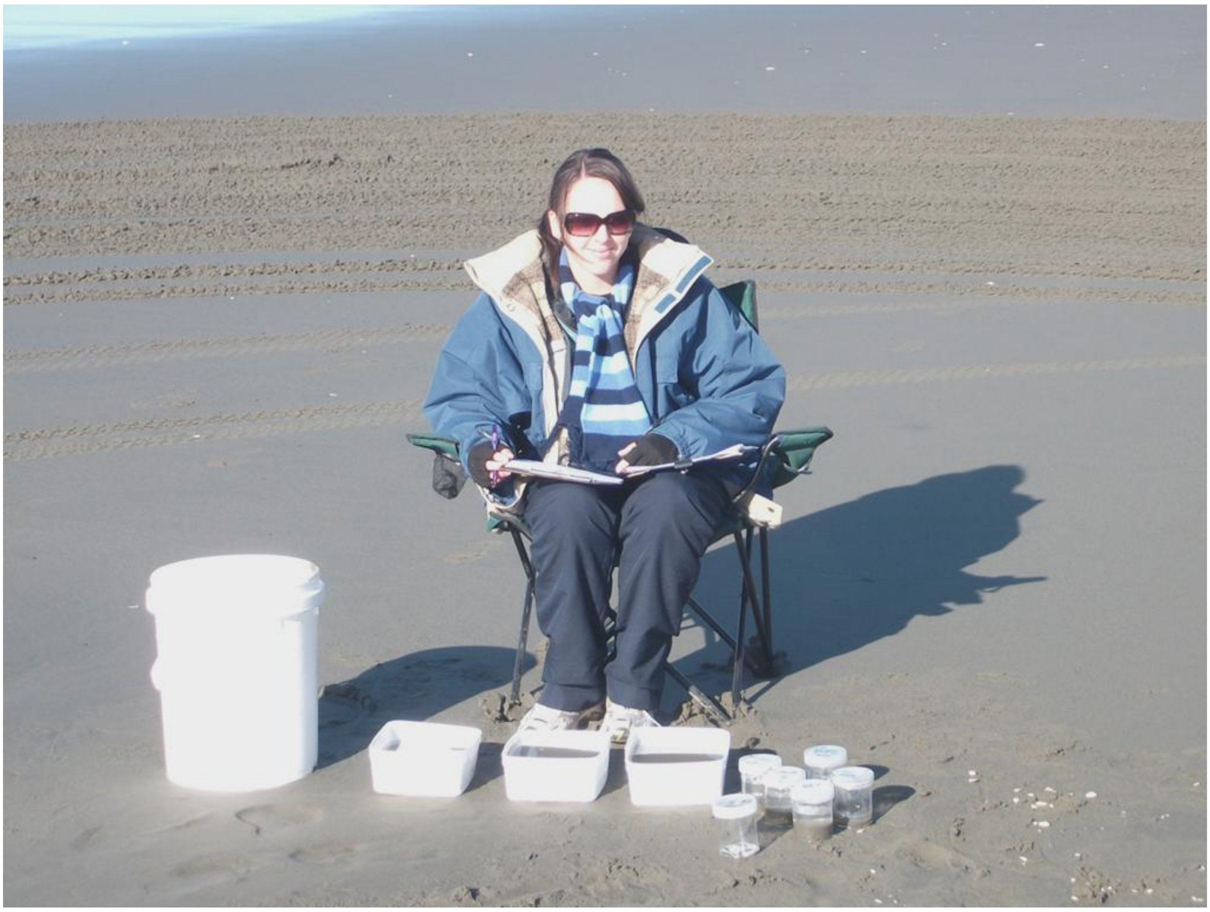


Figure 5.4: Field assistant timing and counting tuatua reburying into the sediment.

5.3 Results

Tuatua densities and mortality

The tuatua collected on the 5 mm mesh in winter ranged in length from 5- 28 mm with a mean of 15 mm (June, 2010), and in summer ranged in length from 5- 32 mm with a mean of 21 mm (December, 2010). Densities of 17 and 107 individuals per quadrat (272-1712 m^{-2}) occurred in the summer, and 15-87 per quadrat (240-1392 m^{-2}) occurred in the winter.

The most common damage caused by vehicles was a slipped shell for the larger individuals, and the smaller individuals had broken shells (Figure 5.5).

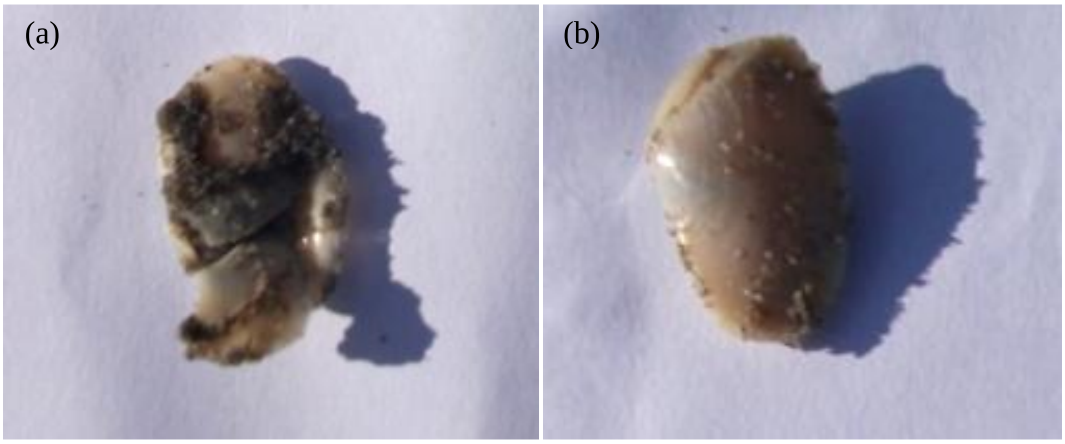


Figure 5.5: Photos of the two common fatal damages caused by vehicles, (a) broken shell (b) slipped shell.

Effects of vehicle passes on shellfish mortality

The percent mortality after 50 passes ranged from 2.3% to 20% in the summer and 13.5% to 29.8% in the winter (Figure 5.6). Tuatua mortalities were variable in both seasons, but individuals of all lengths were affected except from those of shell length 5 to 7 mm. Mortality rates were the same in both summer and winter ANCOVA, F- slope (1,45)= 0.313, $p<0.579$; F-level (1, 45) =3.008, $p<0.09$). The overall rate of increase in shellfish mortality was 0.27% per vehicle pass (line equation: $y=0.27x + 4.79$, R= 0.58, $p<0.001$).

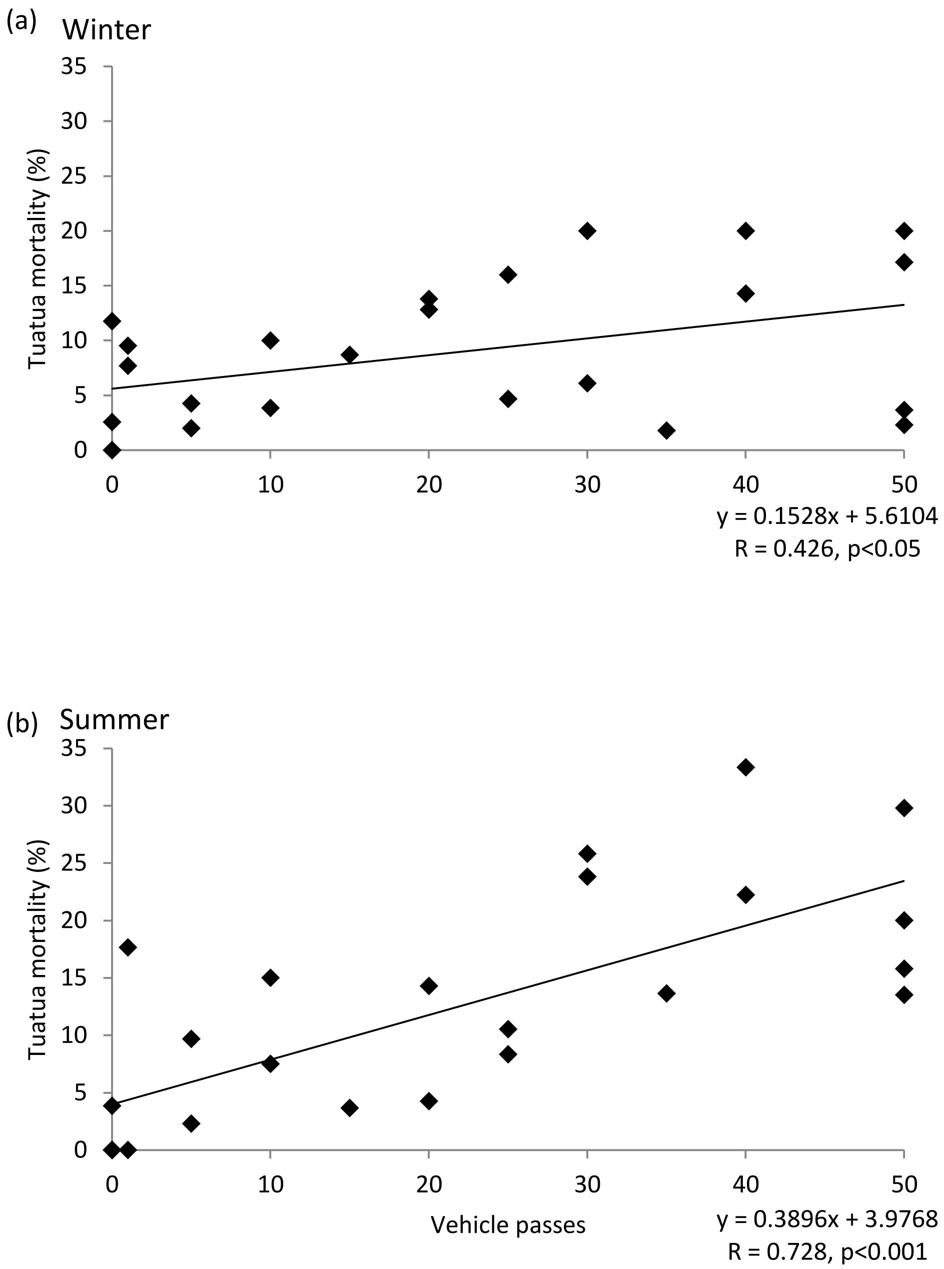


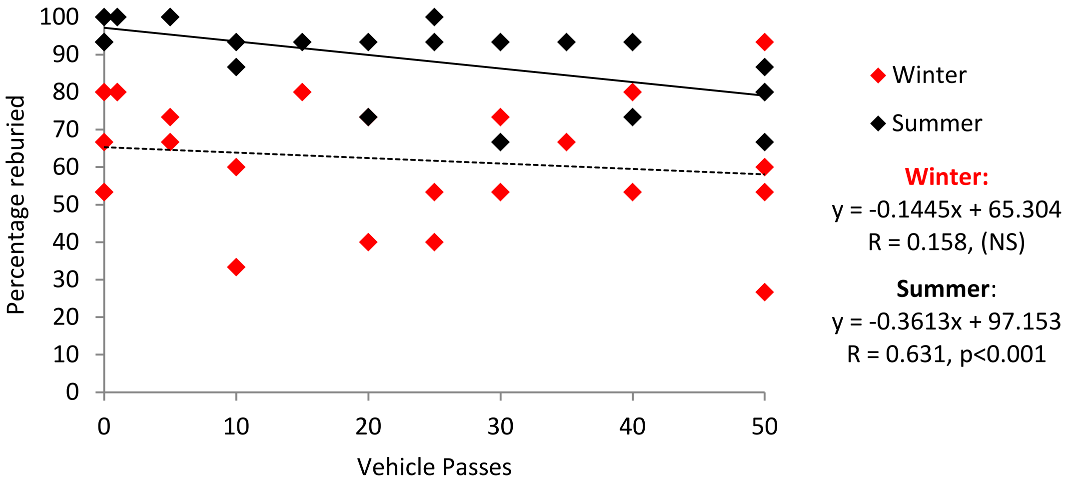
Figure 5.6: The relationship between vehicle passes and individual tuatua mortalities in (a) winter (June, 2010), and (b) summer (December, 2010). Also included are the regression equation, correlation coefficient R and probability p.

Reburial

The results from this study were variable with 26.7% to 93.3% of individuals re-burying successfully after exposure to 50 vehicle passes. In summer there was a statistically significant negative relationship between number of vehicle passes and percentage reburial immediately after the vehicles passes ($p<0.001$). This could be due to individuals being more active and so exhibit faster reactions (i.e. reburying faster). There was no relationship in winter (Figure 5.7). There was a seasonal difference in reburial (ANCOVA, F-Rate (1, 45) = 2.987, $p<0.001$).

Reburial success after 24 hours had a negative relationship with increased vehicle passes for the summer ($p<0.05$), but not in the winter (Figure 5.7). This relationship was significantly different between the winter and summer (F-Rate (1, 45) = 6.5176, $p<0.014$). There was no significant difference between winter and summer average reburial success after 24 hours (Figure 5.8). Reburial success after 24 hours higher than immediately tested individuals in the winter (t test: $t(23) =-3.823$, $p<0.001$), but not significantly different in the summer (t test: $t(23) =1.531$, $p<0.139$).

(a) Immediate response



(b) 24 hour response

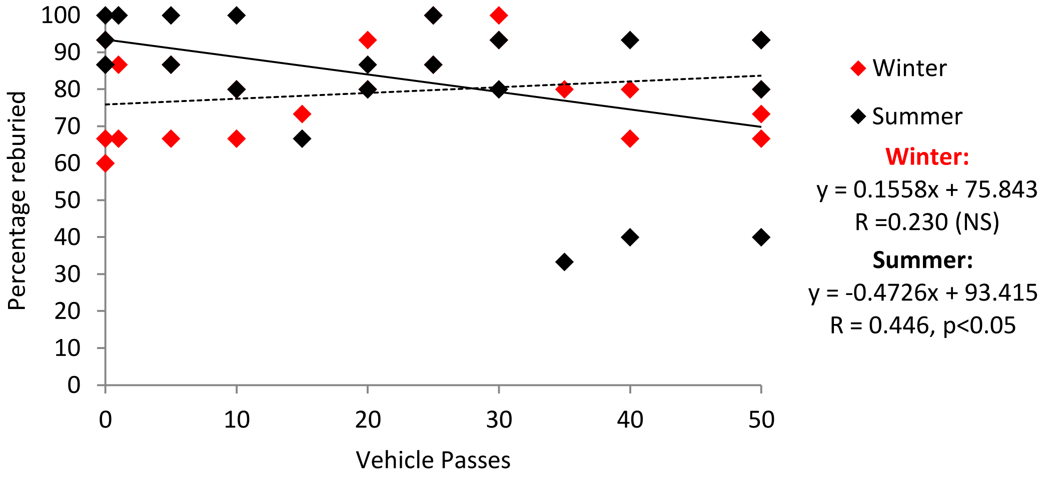


Figure 5.7: The relationship between percentage of tuatua reburied immediately (a) and 24 hours (b) after each number of vehicle passes in the winter (June) and summer (December) of 2010. Also included are the regression equation, correlation coefficient R and probability p. NS= null relationship.

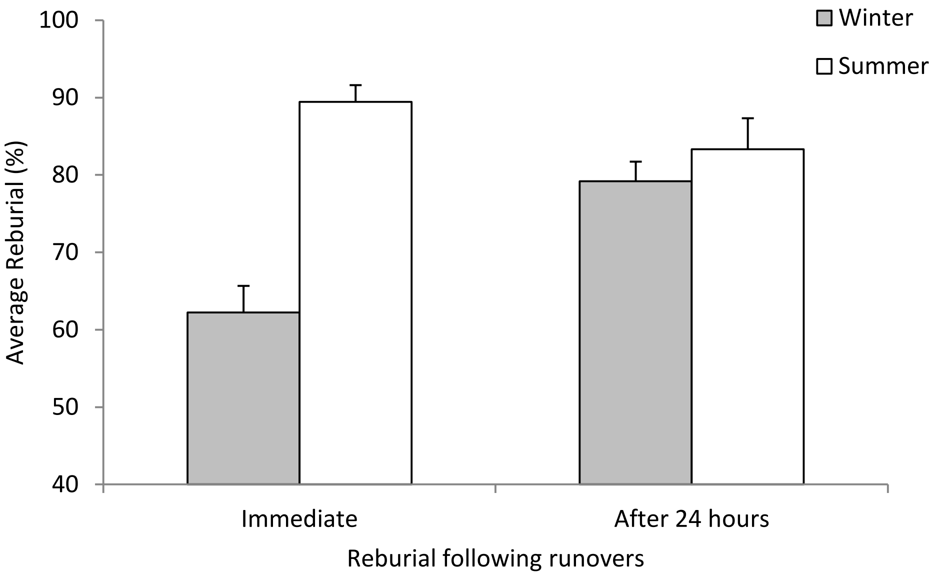


Figure 5.8: The average reburial percentage immediately and 24 hours after being runover in winter and summer of 2010.

Tyre tracks

Sediment displacement caused by vehicle tyres followed a log pattern (Figure 5.9). This showed that as passes increased, sediment became more compacted. This was up to 30 passes then the rate decreased. There was no significant difference to the pattern between seasons (ANCOVA: F-slope (1, 45) = 0.860, p=0.360; F-elevation (1,45)= 3.008, p<0.090).

A positive correlation was found between sediment displacement and tuatua mortality (p<0.001) (Figure 5.10). There was no significant difference in sediment displacement between winter and summer experiments (ANCOVA, F-slope (1,36) = 0.033, p<0.857; F-elevation(1,36)= 0.020, p<0.887).

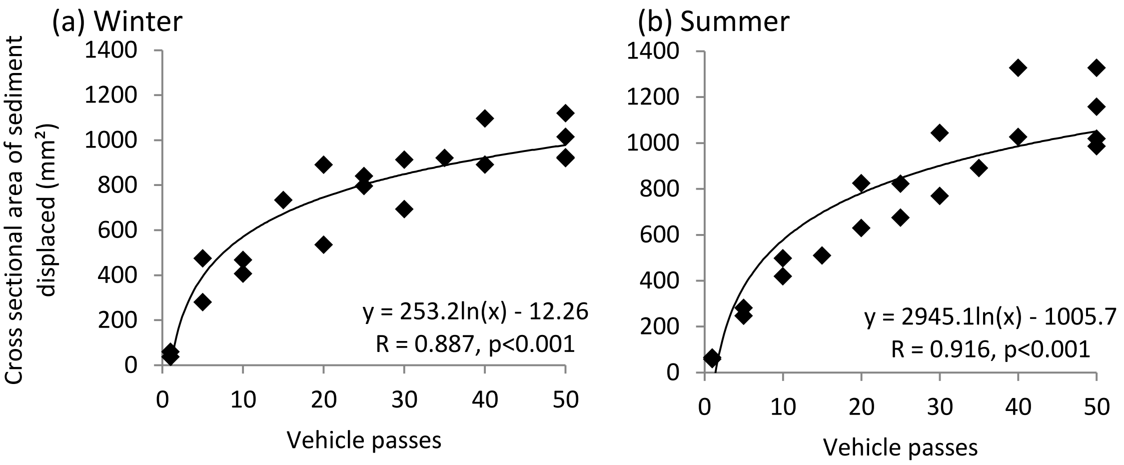


Figure 5.9: The relationship between the number of vehicle passes and cross sectional area of sediment displaced in winter (a) and summer (b). Also included are the regression equation, the correlation coefficient R and probability p.

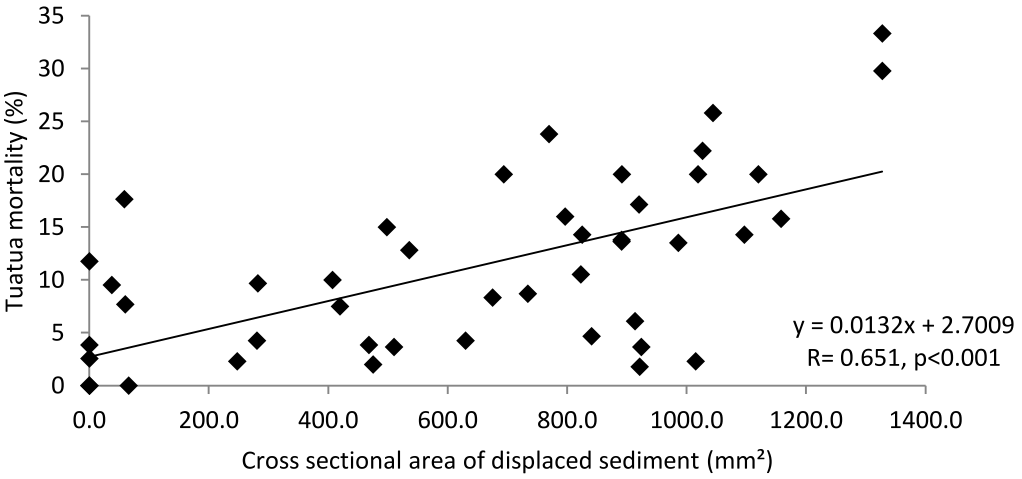
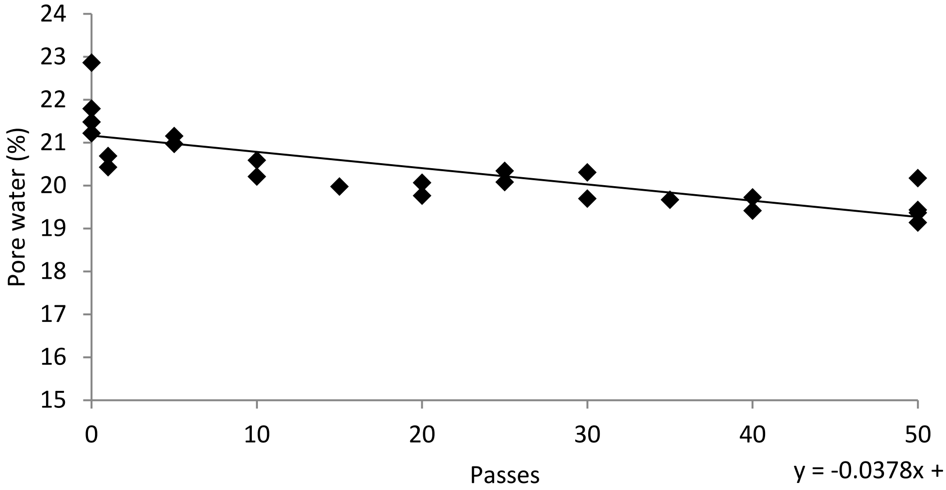


Figure 5.10: The relationship between sediment displacement and tuatua mortality. Also included are the regression equation, correlation coefficient R and probability p.

Pore water

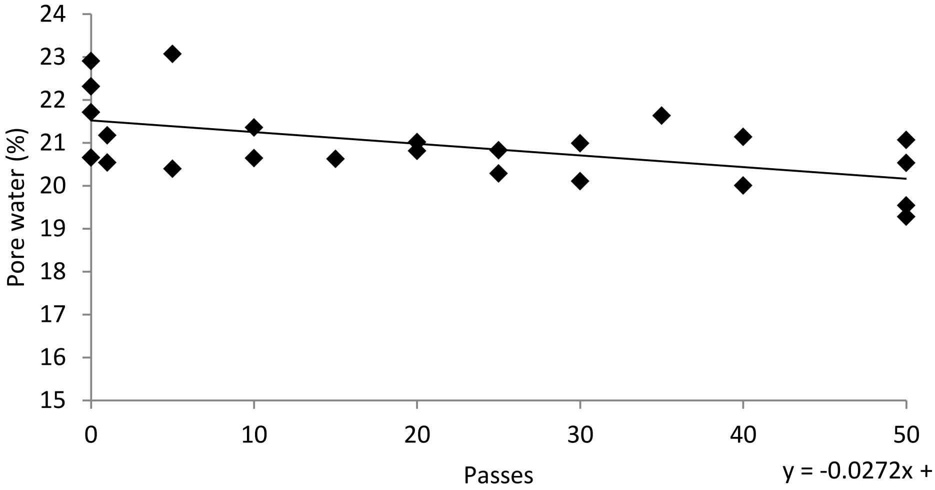
As the number of vehicle passes increased, pore water percentage decreased in both the summer and winter. The percentage pore water between winter and summer experiments were significantly different, with more pore water in the summer than the winter (ANCOVA, F-slope (1,44)= 1.44, $p<0.237$; F-elevation (1,44)=36.39, $p<0.001$).

(a) Winter



y = -0.0378x + 21.162
R^2 = 0.794, p<0.001

(b) Summer



y = -0.0272x + 21.524
R^2 = 0.548, p<0.001

Figure 5.11: The relationship between pore water percentage and vehicle passes during winter (a), and summer (b) of 2010. Also included are the regression equation, correlation coefficient R and probability p.

5.4 Discussion

Juvenile tuatua (*Paphies donacina*) in the intertidal of a Pegasus bay surf beach where vehicles are driven were detrimentally affected. Schlacher *et al.* (2008b) also had similar findings in North Stradbroke Island, Australia, using *Donax deltoides*. The percent mortalities of *P. donacina* in the present study were similar to Schlacher *et al.* (2008b), although the damage rate for *P. donacina* was slightly higher (0.27) than the reported 0.16 for *D. Deltoides* found by Schlacher *et al.* (2008b). The levels of mortality reported in the present study were variable. This variation is likely to be due to factors including sediment properties, burial depth and the size and condition of shellfish. Burial depth could vary on a day-to-day basis because shellfish migrate up and down the beach with the tide.

Mortality effects

In the present study damage rates were similar to those reported by Marsden and Taylor (2010), and the same relationship was found between sediment displacement and tuatua mortality. Other studies on different species of shellfish have also found a similar relationship. Moller *et al.* (2009) conducted a study on Oreti Beach in Southland on toheroa (*P. ventricosa*) which evaluated the effects of different types of vehicles. That study only used five passes, but found that even with this low rate SUV vehicles resulted in 3% damage to toheroa individuals of similar length to the tuatua in the present study. With an average rate of 4.56% damage for five passes (SE=1.78), the damage in the present study is comparable to that of other New Zealand-based studies.

Moller *et al.*'s (2009) methodology involved moving individuals to areas they where they were usually not found and this may have influenced the results. For example, the shellfish used in their study may have been in poor condition, may not be the size naturally found, and may have not buried to their normal depths below the sediment surface. If the individual was not buried as deep it would normally it might not be protected from vehicle exposure.

In the present study, tuatua mortality increased linearly as the number of vehicle passes increased, indicating that higher frequencies of vehicles driving along the beach will exacerbate these effects. Thus, if vehicle numbers stay high over an extended time period, shellfish populations would sustain long-term damage. This could include altering species assemblages and reductions in population size (Schlacher *et al.*, 2007; Schlacher *et al.*, 2008a).

Reburial

Being able to bury in the sediment when disturbed is an important adaptation for bivalves that inhabit sand beaches, it protects them from stressors such as desiccation and predation. Using reburial success as a measurement of stress is not likely to be a clear indicator especially during times of low activity, such as in the winter months. This is because individuals are not as active so the rate of response would differ. These sublethal effects were not as easily identified using the methods chosen, but vehicle passes negatively affected reburial success in the summer- the period when tuatua are likely to be more active (Marsden, 1999b).

Sheppard *et al*. (2009) found that after five vehicle passes the burial time of *Donax deltoides* doubled. The present study did not find this with burial time averaging 6.64 minutes at zero passes and 6.08 minutes at 50 passes. However, Sheppard *et al.* (2009) used transplanted shellfish which may have affected their results. Nonetheless, this dissimilarity may represent species specific differences or an environmental effect such as warmer temperatures. Reburying faster in warm climates is particularly important because the individual will desiccate more quickly if it remains exposed. During winter, desiccation will not be so important as temperatures are lower. Shellfish remain on the sediment surface are prone to predation by shore birds, this will influence the bivalve population size.

Reburial after 24 hours was more successful with on average 79.2% of individuals reburying during the winter testing compared to 62.2% immediately after vehicle passes. Summer results showed no significant difference. The summer sample showed a slight decrease in reburial after 24 hours (immediate= 89.4%, after 24 hours= 85.3%) which could have been caused by the laboratory temperatures being lower than the outside temperature. This could cause shellfish activity to decrease slightly. This response may be as a consequence of individuals being kept in a laboratory 15˚C fridge for 24 hours. The temperature would have been higher than the natural night time temperature in June, and may have allowed the bivalves to become more active.

Sediment properties

Sediment pore water was similar in the winter and summer, with average pore water being 21.84% (SE=0.36) and 21.89% (SE=0.48) respectively. In the present experiments, changes in pore water are unlikely to influence shellfish survival because the reduction observed was a fraction of a percent and water refills the sediment within minutes of being disturbed. As the sediment became more compacted, the displacement in the tyre tracks changed less, but pore water percentage reduced linearly.

There was a positive relationship between sediment displacement and tuatua mortality (i.e. the volume of sediment a tyre displaces influences mortality rates); therefore, harder sediment would be likely to provide more protection to individuals. This finding was also found by Schlacher *et al*. (2008b), who showed that there were increased mortalities due to vehicle runovers in softer sediment when compared with medium compacted sediment.

In the present study, tyre tread depth increased less after compaction had reached 30 mm in depth, so tuatua buried below this would be less likely to suffer lethal damage. However, if a vehicle had off-road tyres which dug into the sediment, it would be expected that more damage would occur as more sediment would be displaced. Schlacher *et al.'s* (2008b) findings also support this idea because there were higher levels of mortality for shellfish in the vehicles turning circles, where the tyres had loosened the sediment.

Research implications

This study has shown that vehicles driven on sand beaches have immediate detrimental effects on intertidal tuatua in Pegasus Bay, Canterbury. The results may also be applied to other New Zealand sand beaches and species of shellfish, depending on the environmental characteristics of the beach. The other species of shellfish would need to be similar in size, morphology and burial depth to the individuals tested. The North Island tuatua (*Paphies subtriangulata*) has an almost identical morphology and distribution in the intertidal zone of sand beaches as *P. donacina* (Figure 5.12) and hence the results from this study could apply to both species. The toheroa (*P. ventricosa*) should also be considered; however, adults (> 80 mm) are also found in the intertidal zone (Morton & Miller, 1973) and so experiments would need to be undertaken to quantify the effects of vehicles on larger individuals.

The damage rate could also be used to determine the amount of mortality that would occur over a defined time period. Other factors would need to be taken into account for this assessment such as the distribution of the shellfish and frequency of vehicle disturbance. Overall, this could give predictions of the impacts of these users.

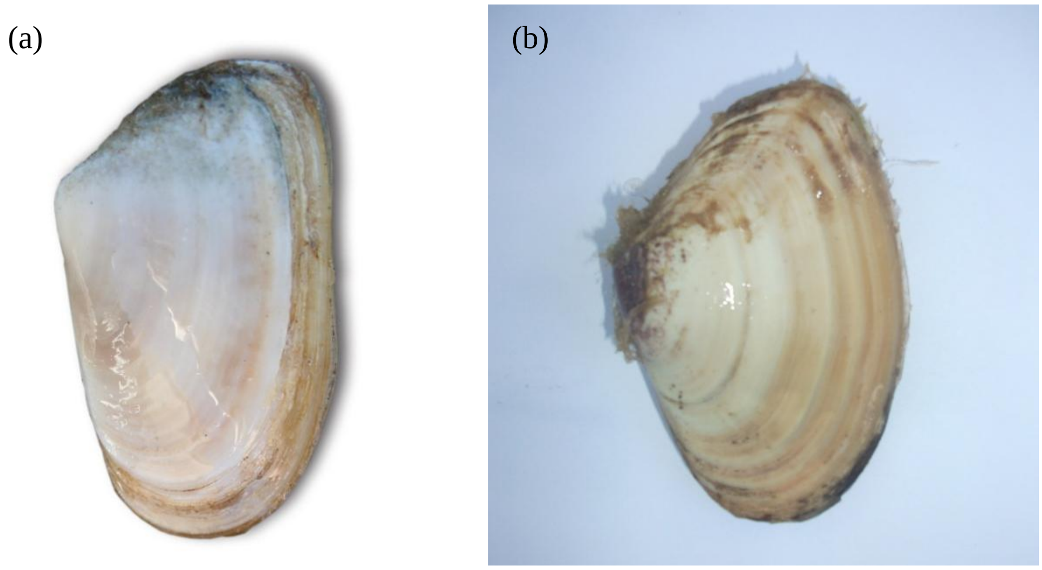


Figure 5.12: Photos of North Island tuatua (*Paphies subtriangulata*) (a), and Southern tuatua (*P. donacina*) (b). (Image a courtesy of NIWA).

Management recommendations

There is no current method of controlling vehicles on beaches in Pegasus Bay except for limiting where they can go. This also involves confinement to the intertidal zone where juvenile shellfish and other intertidal animals are vulnerable. In areas where vehicles are permitted, there is no control except near the Ashley River mouth. If protection of these bivalves is to be ensured, changes to this management method are required. Excluding vehicles from the intertidal zone, and the rest of the beach face, would be the most desirable option. This would allow all communities in the ecosystem to inhabit areas without vehicle disturbance. South Africa is one country where a complete ban of vehicles on beaches has occurred; however, there are exemptions that can be granted where necessary (Full 4x4 Regulations, 2004). Enforcement would be required and many regions of New Zealand may be unable to afford the costs of enforcement over large expanses of coast. However, this could be recouped by reducing the costs associated with construction and maintenance of infrastructure which allow activities to occur.

If driving vehicles is to continue on New Zealand’s beaches, mitigation is needed to reduce the detrimental effects on ecosystems. Management authorities have successfully prevented dune erosion and damage to bird nests by confining vehicles to the intertidal zone; however, there are several improvements than can be made. Reducing the impact of disturbance is required for ecological protection to improve in the presence of vehicles. If management authorities have sufficient funding, the most desirable option would be to confine vehicles to set paths above the Mean High Water Spring level (MHWS). This would reduce the area of impact whilst still allowing access along the beach. Birds would be mostly protected apart from in the paths; however, the high vehicle traffic in this area would deter birds from nesting. This method of management is used in Cape Cod, USA, and only allows vehicles on the intertidal zone if the track is cut off (National Park Service, 2011).

The hard sand of the intertidal zone makes it a highly desirable part of the beach for vehicle drivers, so if this is to continue, mitigation is needed. Options include; driving in the same tracks as other vehicles and/or reducing vehicle numbers. Driving in the same tracks would reduce the area of disturbance and impact a smaller percentage of the population. The present study found a shellfish mortality rate of 0.27% per vehicle pass. If vehicles follow the same track they would be continuing to apply pressure on the surviving individuals, but the overall impact would be less than in a previously undisturbed area. Thus, fewer individual tuatua would be affected than if vehicles were to make new tracks. The linear increase in mortality shows that there is no maximum damage reached within 50 passes. Marsden and Taylor (2010) found this at up to 100 passes, so it would be recommended that the number of vehicles would be limited to reduce the daily impact. This would require a permit, which would incur a cost to the council to carry out administration of these. These costs could be covered by payment systems for permits. For example, Cape Cod, USA, charges $150 for an annual permit or $50 for 7 day permits, which would help to recover costs and deter unnecessary driving.

5.5 Conclusion

This study clearly showed that vehicles cause detrimental damage to tuatua (*P. donacina*). The mortality levels recorded here were comparable to those found in other studies using similar methods and species (Sheppard *et al*., 2009; Moller *et al*., 2010). There was no significant difference in the seasonal rates of mortality. Sediment properties influenced the results of the study with higher mortalities found when more sediment was displaced. Results of this study can be applied to other shellfish species, especially the North Island tuatua (*P. subtriangulata*) whose morphology and distribution is similar to that of *P. donacina*. Management options to mitigate damage include reducing vehicle numbers and driving in the same tracks and directing vehicle use to areas where they are required (e.g. near river mouths for whitebaiting); although, completely banning vehicles from use on sand beaches would be the most ecologically preferable option. However, such methods of control may not be acceptable to the general public who may want to maintain vehicle access to the beach. If these measures were implemented, shellfish populations are likely to be better protected for future generations.

Chapter 6 The effects of horse riding on tuatua (*Paphies donacina*) in Pegasus Bay, Canterbury.

6.1 Introduction

Horse riding is permitted on sand beaches throughout the world, often with little consideration given to potential impacts on the marine environment. This oversight can have serious implications, particularly for biota located in the intertidal zone, where horse use is greatest. One such species is the tuatua (*Paphies donacina)*, a New Zealand shellfish which lives beneath the sand. Juvenile tuatua are buried at depths shallower than five centimetres, giving very little protection from activities occurring on the sediment surface (Chapter 4).

Tuatua are subjected to daily stressors, which include human induced, biotic and abiotic types. Each of these can have effects from individual to ecosystem level. At an individual level, physical disturbance to shellfish can result in reduced activity (Maguire *et al.*, 2002) as well as the suppressing of immune functions (Lacoste *et al.*, 2002). These responses can create vulnerability to predation and disease. Ferns *et al.* (2001) noted in their study that individuals removed from the sediment had increased bird predation. Effects at the ecosystem level are likely to occur as a result of a catastrophic event. These events can deplete the shellfish population, triggering trophic cascades. Ferns *et al*. (2001) showed that harvesting of the cockle (*Cerastoderma edule*) using a tractor also resulted in reduced densities of non-targeted invertebrates. Preventing such disturbances should be a key priority in maintaining ecosystems. Therefore it is important to assess stress caused by recreational users, such as horses, which potentially have similar impacts.

A wide range of horse riding, both recreational and in racing events, occurs on the intertidal zone of sand beaches throughout New Zealand (see Section 2.7). Professional racing trainers use beaches to improve strength and rehabilitate their horses (Crevier-Denoix *et al.,* 2010). Such users are likely to cause significant ecological effects due to a large amount of traffic focused on a small area. This could have flow-on effects for the ecosystem.

Pegasus Bay tuatua are exposed to daily horse use. Professional trainers use the beaches all days of the week apart from Sunday (*pers. coms*. with a Professional Trainer, 26/06/2010). Recreational riders, in contrast, are more sporadic with their use patterns. Higher recreational use is expected in weekends. There is less of an area of focus for recreational use but, generally, it occurs near to access points. Trainers will run horses on the beaches for three hours either side of the high tide and during this time as many horses as possible will be run. One trainer also stated that the beach is only used when the home track is wet. However, this same trainer was observed running horses on the beach during periods of dry weather. The key beach locations used by trainers are Spencer Park, Woodend and Ashworths Beach.

Despite their differences, both commercial and recreational users have a preference for parts of the intertidal zone where the sand is harder and hazardous ground objects such as driftwood are sparse and easily identified. Management authorities also encourage the utilisation of the intertidal zone. This measure is to mitigate dune erosion and prevent damage to bird nests. Such measures have resulted in potentially high amounts of shellfish-damaging traffic in the intertidal zone (Figure 6.1).

Among the plethora of studies evaluating the environmental effects of horses (Cubit, 1990; Liddle, 1991; Ostermann-Kelm *et al.*, 2009; Marion *et al.*, 2010), no research has yet been undertaken evaluating the effects on the coastal environment. These land-based studies have found that trampling by horses reduces biodiversity and biomass of terrestrial floral and faunal communities (Whinam & Comfort, 1996; Whinam & Chilcott, 1999; Torn *et al.*, 2009). A human trampling study by Moffett *et al.* (1998) provides insight into the possible effects of horses on shellfish beds. Moffett *et al.* (1998) found that high human trampling was sufficient enough to cause significant mortality to the infaunal biota including *Donax serra* and *D. sordidus*. It would therefore be expected that horses, being heavier, would be likely to have similarly damaging, if not greater, effects.

Figure 6.1: The horse track covered intertidal zone of Woodend Beach, Canterbury.

Aims

The experimental and observational findings contained in Chapters 3 and 4 indicate that horse use is likely to affect intertidal shellfish. The evidence that leads to this conclusion is that the depth of hoof penetration is such that tuatua burial depths are within range, and the weight of a horse exceeds that needed to break any shell length of tuatua (*Paphies donacina*). The aim of this chapter is to quantify the effects of horses on intertidal shellfish beds in Pegasus Bay, Canterbury. This will be achieved through the use of observational and experimental methods. Mortalities were expected to occur where horses pass over shellfish buried within range of the hoof penetration depth. Different riding styles were tested to see if they result in differing mortality rates. Reburial success was also measured to evaluate sublethal effects on tuatua following disturbance by horses.

6.2 Methodology

This study used *in situ* methods to evaluate the effects of horses on tuatua mortality on beaches where horse use was common. The methods employed aim to provide *in situ* results from unaltered environmental conditions. Observational testing was carried out to evaluate the impacts of actual use by horse riders. Experimental testing was also used to identify any immediate impacts which occurred (e.g. sublethal stress effects). Such testing was necessary because reburial testing is not possible with observational recording. This is because the exact time of shellfish disturbance is unknown. Thus, results may not be indicative because individuals would have had unequal recovery time prior to testing.

Manipulation of environmental conditions may produce results that are non-indicative of real world relationships. For example, transplanting shellfish to new sand plot would loosen the sediment matrix, causing a horse hoof to penetrate deeper, resulting in higher mortality to shellfish. In addition, holes in the sediment would compromise the safety of the horse and rider if the horse was to injure itself. The main weakness of collecting *in situ* data of this type is that it relies on high densities of shellfish which cannot always be ensured.

6.2.1 Observational study procedure

To investigate the impacts of horse riding on intertidal tuatua, observational data were collected between November 2010 and March 2011 to record tuatua mortality occurring in areas currently used for horse riding. Two areas were selected: Woodend Beach (43°20'51.49"S, 172°42'43.09"E) and Spencer Park Beach (43°27'3.37"S, 172°43'6.80"E) (Figure 6.2), see Chapter 3 for descriptions of these areas. A hand-held GPS (Garmin GPSmap 60CSx) was used to mark the route that the horses had taken. This route was then plotted using satellite imagery and the distance of the track was recorded. After the route had been recorded, three points along the track were selected randomly for further sampling and marked using GPS. Firstly, the distance from the last high tide mark to the most landward track was measured and recorded. The track width was taken from the two widest points using a measuring tape. After this, a 10 m area was marked out and three tracks were counted for the number of hoof prints over this distance. This was to provide an indication of the speed the horse had been travelling (i.e. less hoof prints indicate the horse is moving faster). Three hoof prints were randomly selected and the sediment below the track was removed to 15 cm depth. The sediment was put through a 5 mm sieve and tuatua collected from the hoof prints were recorded for shell length and damage.

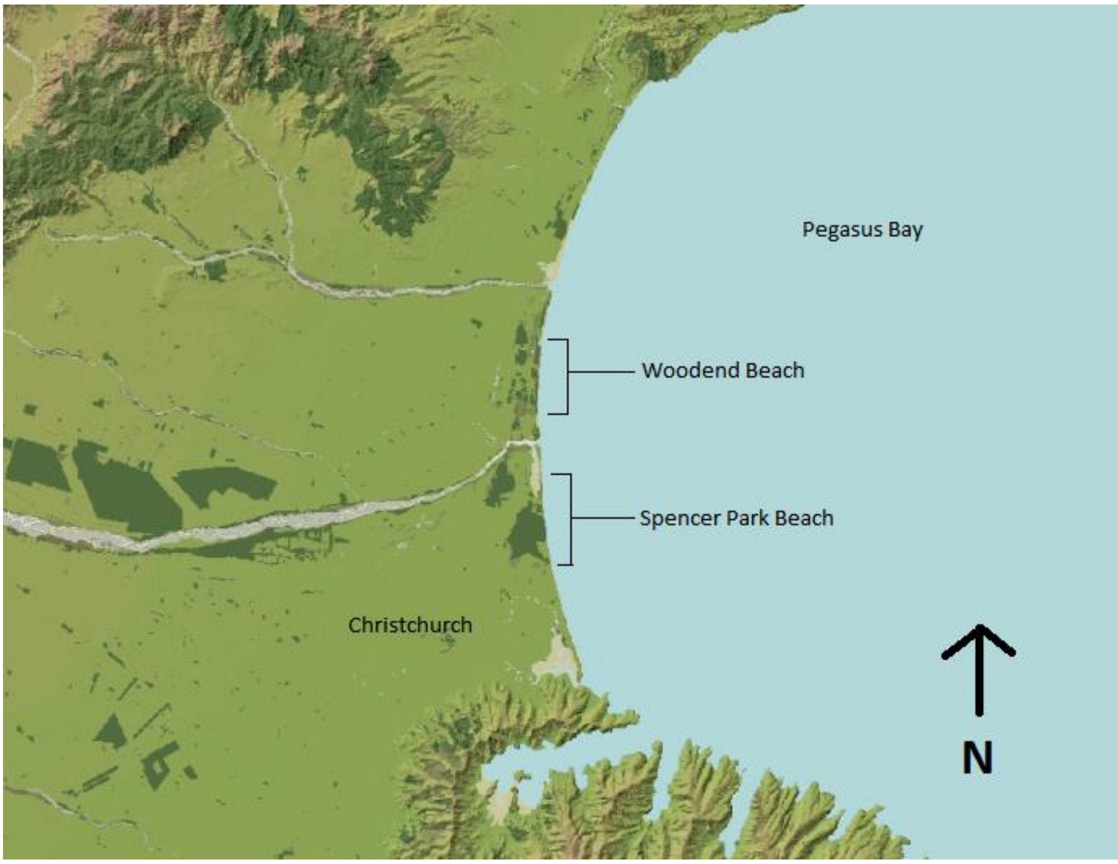


Figure 6.2: Map showing Spencer Park and Woodend Beach in Pegasus Bay, Canterbury.

Figure 6.3: The experimental horse study site at Pines Beach, Pegasus Bay, Canterbury.

6.2.2 Experimental study procedure

Experimental trials were conducted to gather data on the direct impact of horses running over shellfish beds. Testing was conducted on Pines Beach, Canterbury (43°23'0.96"S, 172°42'44.55"E) (Figure 6.3) where shellfish populations were high.

Preliminary experiment

A preliminary trial was conducted on the 25th of August 2010 to test the relationship between shellfish mortality and different horse riding styles. The experimental area had sufficient densities of juvenile tuatua (> 10 per 625 cm^2 quadrat). This trial involved a 600 kg (approximate weight) horse being rode by a 48 kg female rider, over a distance of 20 m, using three different riding styles; walk (approx 5 kmh^{-1}), trot (approx 13 kmh^{-1}), gallop (approx 24 kmh^{-1}). Each riding style was done 2 m above the last track. Sediment cores were taken within 10 seconds of the horse riding over the experimental area, with cores taken from two hoof prints of each style. The cores were 10 cm in diameter, and pushed into the sediment to a depth of 5 cm. Cores were bagged, sealed and refrigerated until they could be processed for pore water. The size of the overall hoof print was measured to provide the area of impact. The number of hoof prints for each riding style was measured over the 20 m area.

A control was taken near to the trot treatment before testing (Figure 6.4). After riding was completed, three hoof prints were selected at random for each riding style. The sediment in these hoof prints was removed to 10 cm depth by hand to avoid further damage to shellfish. The sediment was sieved through a 5 mm mesh and tuatua caught were recorded for shell length (mm) and type of damage. If the damage was considered fatal, individuals were not used for reburial testing.

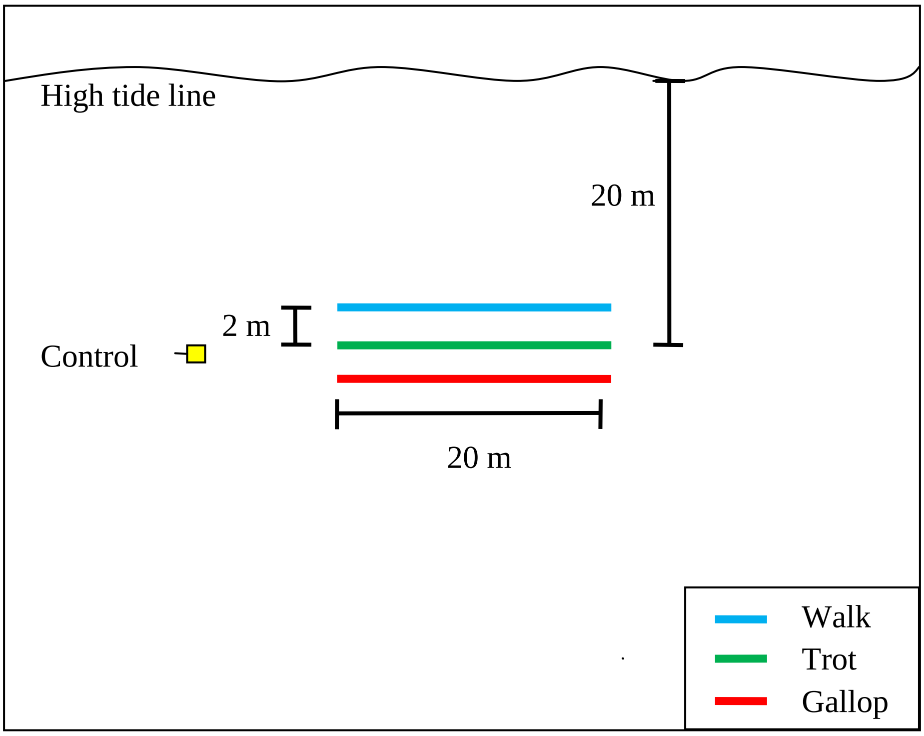


Figure 6.4: Bird's eye view of the layout for preliminary horse impact experiments.

Disturbance intensity experiments

Based on the preliminary trial, methods were refined to test the effects of multiple passes using certain riding styles. Given that commercial harness trainers and recreational riders are the most common users in Pegasus Bay, the two riding styles selected were walking and trotting. These were tested in two treatments; one pass and five passes. Most methods were the same as in the preliminary testing including identification of the 20 m test area, pore water, timing of passes, and reburial testing. A new 626 kg horse, 'Cliff', was used (height of 16.1 hands at the wither) and was ridden by an 80 kg male rider (Figure 6.6). The key difference between the two horses was that 'Cliff' was unshodden (no horse shoes).

The main difference between the preliminary and later trials was that the number of horse tracks was measured by counting the total hooves within a 1 m^2 area, rather than in a straight line. Treatment areas were set at the same vertical position on the shore as in the preliminary experiments but were spread 20 m apart (Figure 6.5). These experiments were conducted in February and April 2012.

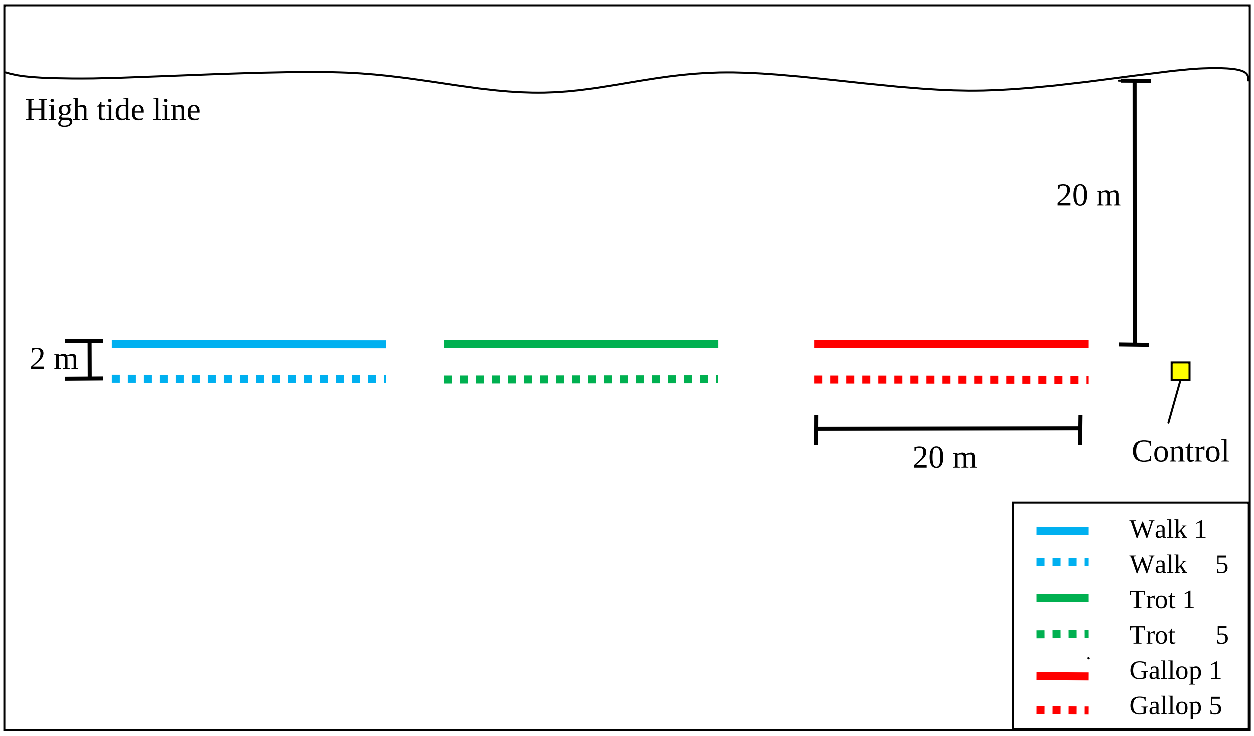


Figure 6.5: Birds eye view of the layout for disturbance intensity horse impact experiments.

Figure 6.6: The horse, “Cliff”, being ridden at walking pace through the defined test area.

Reburial testing

The 15 individual tuatua selected for the reburial test were those that appeared undamaged, that is with no cracked or slipped shells. Individuals were placed in a plastic container which included sediment from the collection area as well as fresh seawater. Sediment within this container had a depth of 5 cm and the seawater a depth of 5 cm above the sediment. Individuals were placed on the sediment surface so that they were lying on their side (horizontal axis). Timing for reburial success started when all individuals has been placed on top of the sediment surface. At the end of each minute for 15 minutes, the numbers of individuals remaining on the surface were counted and recorded. An individual was considered to be buried when it was completely submerged under the sediment, or only the siphons could be seen protruding.

The sample tuatua were then kept in a 15°C laboratory refrigerator in containers of sediment and fresh seawater and were retested for burial 24 hours after disturbance using the methods described above.

Pore water

The sediment sample was bagged, sealed and returned to the lab where it was refrigerated at 4°C before processing. Processing of the pore water samples involved breaking the core into three pieces to get an average, measuring the wet weight of the sample, and then drying it in a 60°C oven for three days. After three days, samples were removed from the oven and reweighed (dry weight). The difference between the dry and wet weight of the sediment gives the weight of pore water. The overall pore water content was calculated as a percentage of the wet weight and recorded.

6.2.3 Data and Statistical Analyses

All data were recorded in Microsoft Excel spreadsheets. Mean and standard error were calculated for each of the replicate samples. Generalised Linear Models (GLM) and regression analyses were used to investigate relationships between horse traffic and shellfish mortality and track characteristics. Statistical testing was carried out using ‘Statistica 7’. Analysis of Covariance (ANCOVA) and tests for homogeneity were used to determine if there were spatial differences in relationships. The slopes of the lines were tested first, and, if these were the same, elevation was tested. If the slopes of the lines were different, no further testing was required because the relationships were different. T-tests were used to determine if there were differences in reburial success after 24 hours.

6.3 Results

6.3.1 Observational results

Horse track characteristics

Observations showed that horse use was generally limited to beach areas near the access points. On Woodend Beach, the most frequently used section of beach was from approximately 3.3 km south of the access way to 1.4 km north of the access way. The longest track to the south ran 4.4 km from the access point while that in the north ran 3.43 km (Figure 6.7). On Spencer Park Beach, the most used section of beach was 2.1 km south and 0.25 km north of the Heyders Road entrance point (Figure 6.7). The horse track farthest north ran 5.2 km before terminating at the Waimakariri River mouth. The farthest south track to the south ran 2.8 km, stopping at a storm drain protruding in the intertidal zone.

The horse tracks at both Spencer Park and Woodend beaches had the same position on the shore in relation to the high tide line, number of hoof prints over 10 m, and overall distance of the tracks along the beach (Table 6.1). Compared to Spencer Park Beach, Woodend Beach was used by larger numbers of horses, with traffic spread over a wider portion of the beach (Table 6.1). Track width positively increased with the number of horse tracks on both beaches (Figure 6.8); however, the relationship was found to be significantly different, with Spencer Park Beach having a faster increase in width (ANCOVA, F-slope (1, 26) = 39.928, p<0.001).

Figure 6.7: Horse tracks on Woodend Beach (a) and Spencer Park Beach (b), Pegasus Bay. The yellow line denotes the highest use during the period of the study. Inset showing location within Pegasus Bay (red star).

Table 6.1: Table showing the characteristics of tracks made by horse riders on Woodend and Spencer Park Beaches.

Variable	**Woodend Beach Mean (SE)**	**Spencer Park Beach Mean (SE)**	**Significance using a T-test. (*t* value(df), probability)**
Number of horse tracks	23.73 (3.25)	6.93 (1.28)	Significant (*t*(28)= 4.937, *p*<0.001)
Distance from the high tide line (m)	30.83 (1.95)	30.32 (1.89)	Not significant (*t*(28)= 0.211, *p*=0.835)
Width of tracks (m)	25.91 (2.56)	11.52 (2.60)	Significant (*t*(28)= 4.110, *p*<0.001)
Hoof prints per 10 m	13.29 (0.92)	14.37 (1.02)	Not significant (*t*(28)=0.693, *p*=0.494)
Distance of tracks (km)	5.38 (0.56)	5.62 (0.67)	Not significant (*t*(8)=0.313, *p*=0.762)

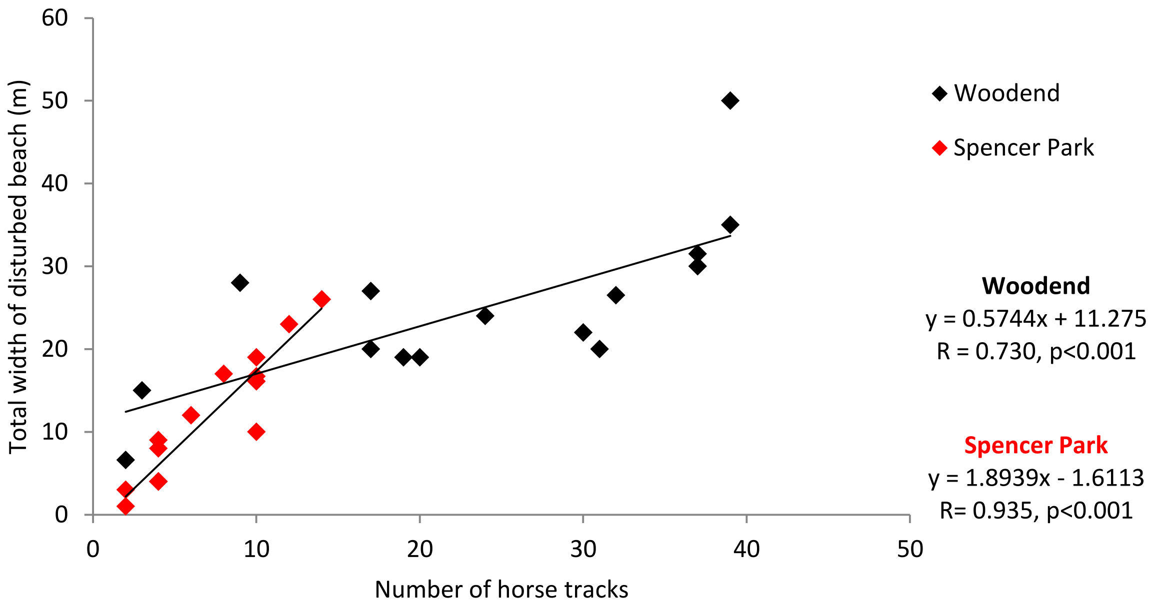


Figure 6.8: The relationship between the number of horse tracks and total width of disturbed beach on Woodend and Spencer Park Beaches, Pegasus Bay.

Tuatua density and size

Woodend Beach densities averaged 137 individual tuatua per m^2 (2.42 per hoof, SE= 0.98), and Spencer Park had 16 individuals per m^2 (0.29 per hoof, SE=0.23). Densities of shellfish during the period of the study were significantly higher at Woodend Beach (t-test, $t(28)=2.148$, $p=0.041$). The average shell length of individuals was significantly different between sites (t-test, $t(122)= 4.817$, $p<0.001$). Woodend Beach had larger tuatua, with an average shell length of 26 mm (SE=0.47), whilst individuals at Spencer Park had an average shell length of 19 mm (SE=1.92).

Tuatua mortality

There was a large variance in tuatua mortality ranging from 0% to 100%. No mortalities were recorded at Spencer Park Beach. Woodend Beach had a mean mortality rate of 36.9% (SE= 14.1). Fatal damage sustained during this study was usually lethal in the form of broken and slipped shells - the same as that found in the vehicle experiments (Chapter 5).

6.3.2 Experimental studies

Preliminary experiments

The horse included in the preliminary trial walked at a speed of 4.9 kmh^{-1}, trotted at 12.8 kmh^{-1} and galloped at 24.1 kmh^{-1}. The number of hoof prints over the 20 m long area was 48, 24 and 20 respectively. The densities of tuatua found during preliminary testing were relatively high at 895 individuals per m^2 (15.8 per hoof, SD=8.651). The average shell length was 14.32 mm (SD= 4.44). The typical break types were similar to those found in observational studies of broken and slipped shells. Walking resulted in 8.33% (SE= 4.81) mortality, trotting was 31.53% (SE= 7.96), and galloping 41.45% (SE= 9.98) (Figure 6.9). Riding style influenced the mortality (ANOVA: $F(3,8)= 5.598$, $p=0.023$). Galloping and trotting resulted in significant mortality compared to the control using a post-hoc Tukey's test. Reburial success was not significantly different between the control and treatments (ANOVA: $F(3,4)= 0.244$, $p=0.862$), nor after 24 hours (t-test, $t(6)= 1.806$, $p=0.121$).

Figure 6.9: Percentage mortality within hoof prints caused by different horse riding styles when ridden over tuatua beds in Pegasus Bay. Error lines denote standard error.

Disturbance intensity experiments

Horse hoof prints were measured to give an average depth of the sediment disturbed. Walking hoof prints were found to be 35.8 mm deep (SE= 2.5), 154.2 mm long (SE= 3.8), and 162.5 mm wide (SE= 3.1). Trotting hoof prints were found to be 36.7 mm deep (SE= 4.4), 155 mm long (SE= 5), and 165 mm wide (SE= 2.9).

The horse included in this second trial walked at a speed of 3.8 kmh^{-1} and trotted at 13.1 kmh^{-1}. The number of hoof prints per m^2 was 2 for one pass of walking and trotting, 6 for five passes of walking, and 9 for five passes of trotting (Figure 6.10). During these experiments, densities of tuatua were very low, most quadrats contained no individuals. The highest number was three individuals, equivalent to 42 per m^2. The average shell length of tuatua was 19.60 mm (SD= 5.69). No damage or mortalities were found in any treatments (0%). Reburial was unaffected by any treatment immediately and 24 hours after being disturbed (ANOVA: F-immediate (4,10)= 0.344, p=0.843; F-24 hours(4,10)= 0.895, p=0.367). Reburial success was not significantly different after 24 hours (T-test: t(18)= 0.861, p=0.400).

Figure 6.10: Hoof prints for experimental treatments - Walking 1 pass (a) and 5 passes, and trotting (b), 1 pass (c), and 5 passes (d). Note photos were taken at different scales.

6.4 Discussion

Horses caused a large amount of disturbance to the sand beach sediment surface and this could result in significant mortality of tuatua. On average, 11 km of beach was used by horse riders on a given day within the study area. Horse tracks widened in intensively used locations, creating a large area of disturbance. High tuatua mortality occurred in areas with high shellfish densities. Preliminary trials indicated that riding style influences tuatua mortality; however, final trials failed to substantiate this. This may be due to low tuatua densities in all of Pegasus Bay's beaches. Results from field observations are likely to be useful for further extrapolation, allowing outcomes from management recommendations to be evaluated as well as comparisons with other user groups, such as vehicle drivers.

Woodend Beach was used in higher numbers than Spencer Park Beach. This preference is likely to be due to trainers being based in close proximity to the Woodend Beach access way. The combination of suitable land for horse stables and high accessibility to the beach has resulted in heavy use of the area. The spread of disturbance was found to increase with higher numbers of horse users, particularly near to the entrance (Figure 6.11). Both locations sampled had a significant relationship between horse numbers and track width. This finding is likely to be due to rider preference for flat smooth areas of beach. This preference may exacerbate the effects of horses due to an increased proportion of intertidal biota being contained in these areas. The overall impacts of horses could easily be reduced by requiring users to stay within set boundaries; however, safety issues may ensue due to unpredictability of the animals when in close proximity to one another.

Tuatua mortality ranged from 0 to 100% representing a large amount of variability both in experimental and observational data sets. The methods used in preliminary and final experiments were unchanged, yet no damage was found in the finalised experiments. It is predicted that some, if not all, of this could be explained by the density and distribution of tuatua in relation to horse users. Shellfish density is likely to be a key factor influencing this result as it reduced in the time period between preliminary and finalised trials. For example, tuatua densities reduced from 576 individual tuatua m^{-2} in preliminary experiments, to a maximum of 48 individual tuatua m^{-2} in finalised experiments. Ferns *et al.* (2002) evaluated the impacts of cockle (*Cerastoderma edule*) dredging using a tractor in Burry Inlet, South Wales, and found that when organisms are in high densities the impacts were far greater. Therefore, with less tuatua present, the impacts of horses are likely to be reduced.

Furthermore, no mortality was found during observational studies on Spencer Park Beach which contained low densities (< 16 individual tuatua m^{-2}) and shellfish were found on only three occasions. However, higher mortality levels (36.9% per hoof) occurred at Woodend Beach where high densities (139 individual tuatua m^{-2}) of tuatua were found. Such findings indicate that horses are likely to have a large effect on tuatua and other intertidal biota when in high densities.

Figure 6.11: Horse tracks near to the horse entrance at Woodend Beach, Pegasus Bay.

More horse traffic is likely to result in greater disturbance and increased shellfish mortality. Field results produced a mean mortality rate of 36.9% on Woodend Beach where shellfish densities were higher (137 individual tuatua m^{-2}) when compared to that of Spencer Park Beach (16 individual tuatua m^{-2}). This is a high level of mortality; however, it is based on the effect of an individual hoof print. Therefore more hoof prints will cause higher numbers of shellfish mortality, so consideration of the number of horses that use the beach is important.

Over a long time period, horses could apply a significant selection pressure for shellfish (Figure 6.12). More importantly, tuatua subjected to this pressure are the future adult population that will move subtidally and breed to replenish shellfish stocks on the beaches. Reduction in the number of these important members of the population could result in decreased reproductive outputs over the long-term (Dame, 2012). If this has occurred in the past and continues, a decline in tuatua abundance in the area would be the most likely outcome. It is difficult to establish if this has already occurred due to a lack of studies providing descriptive data on tuatua populations or horse use and the variability of reproductive outputs between years (Marsden, 2002). However, personal observations on two North Island beaches (Takau Bay in 2011 and Mt Maunganui Beach in 2012), with absence of heavy recreational users, were observed to contain high densities of shellfish in the intertidal zone compared to that found in Pegasus Bay. Chapter 3 showed that areas with different users had no influence on abundance; however, attributing this to horse users is not possible due to longshore processes being responsible for moving shellfish. A high degree of mixing between assemblages may occur, so shellfish abundance in Pegasus Bay must take a holistic view of impacts occurring.

Horse riding occurs on sand beaches around the world, especially in affluent countries including U.S.A., Great Britain, and Australia, and is likely to have similar effects on infauna in the intertidal zone. In addition, popular tourist destinations, such as Spain, also promote riding on beaches as an activity available to visitors (Fantasia Adventure Holidays, 2012). Biota in a similar niche to that found in Pegasus Bay are also present on these beaches and are likely to suffer impacts from beach users. For example, *Donax deltoides* is widely present in the intertidal zone of Australia (Murray-Jones & Ayre, 1997) and Schlacher *et al.* (2008b) found vehicles to cause high levels of mortality to these clams buried in the top 10 cm of sediment. Tuatua are buried to a similar depth (Chapter 4), so it can be assumed that the effects of horses are relatable to other intertidal shellfish species. All beaches differ in physical and biological factors, often as a result of the interaction between each. Species shell morphologies may result in differing impacts and so too would the sediment characteristics through buffering the forces of horses. Further research on other nation's beaches would be needed to understand the finite impact of horses at these locations.

Pegasus Bay contains a wide range of infaunal biota, many species of which are soft-bodied (e.g. polychaete worms). Other nation's beaches also contain high levels of soft-bodied invertebrate fauna. In relation to vehicles, such species have been evaluated as being highly vulnerable (Wolcott & Wolcott, 1984), so it is likely these will also be impacted by horses. As these individuals contain no form of protection, such as a shell, the level of force needed to injure an individual would be far less. In addition, many species are buried to low depths within the sediment. For example, polychaetes generally occur in the top 5-10 cm of sediment (Hutchings, 1998). This shallow burial allows little cushioning from the sediment when forces are applied at the surface and may result in increased damage compared to that of shellfish.

Research limitations

This study has limitations caused by uncontrollable factors, such as low densities of tuatua during the study. In addition, other variables including the weight and speed of horses in the first, observational study are unknown. A large amount of variation in mortalities also occurred between days for the observational experiments. This indicates that there are a range of day-to-day factors which could influence the results. Such factors include dispersal of tuatua, sediment properties and hoof characteristics of horses ridden over the area. Identification and evaluation of these variables would help to narrow down the key factors that influence mortality of shellfish from horse users.

Firstly, the dispersal of the shellfish in relation to horse tracks is a major factor in determining damage for an area of beach. If the shellfish are above or below the tracks then there will be no damage. However, if the band of shellfish (Chapter 3) was within the track, and densities are high, increased levels of mortally would be found (Ferns *et al.*, 2002). This is because the probability of the horse hooves striking shellfish would increase. The position of shellfish within the horse's hoof may also cause variation. The horse hooves were found to penetrate deepest at the front with angle shallower at the back. Therefore, it would be more likely for shellfish to be damaged if they are under the front of the hoof. This damage may be further exaggerated when horses are shod because the front of the hoof may penetrate further into the sediment.

A second factor that varied between experiments was the change of horses between trials with the initial rider no longer available for the final experiments. The weights of the horses were relatively similar (626 kg as compared to 600 kg) with the latter horse slightly heavier and therefore equally likely to cause mortalities. There were other minor differences between horses, with the second horse being unshodden. This lack of horseshoe may have meant that the hoof may not have penetrated as deep in the sediment. The gait of the second horse was also observed to be smoother than that of the first horse; hence the force impact may not have been as high. However, sediment disturbance by the hooves of the two horses was relatively similar. Therefore, the most probable reason for nil damage in finalised experiments is likely to be due to low densities of tuatua.

Unfortunately, tuatua densities decreased during the period of this research, and never returned in time for experiments to be carried out successfully. Reasons for this decrease in tuatua abundance are discussed in Chapter 3. Shellfish densities would need to be high for these experiments to be repeated. If tuatua densities never become high again in Pegasus Bay, use of alternative locations and species of shellfish may be required for future research. An ideal location for such experiments has been identified in Takau Bay, Northland, where high densities of North Island tuatua (*Paphies subtriangulata*) were observed (approx. 1000 individuals m^{-2}) in April 2011 (author observations). A key issue with this location is transporting equipment to the site because it is accessed via a steep narrow gravel road. The beach is also in a Māori owned settlement, so permission from the local iwi would be needed.

Horses moving at higher speeds may impact the ground more; however, different riding styles can change in ground force. Rubin & Lanyon (1982) found horse strain load of tibia and radius to increase by 59% between a walk and a trot and a reduction of 42% between a trot and a canter. This also resulted in similar changes in ground force. Knowing the weight and speed of the horse which created the tracks sample in the earlier observational study is also important if effects are to be clearly determined. Observational results were taken after horses had been ridden through an area; the weight and speed of these horses therefore remained unknown. The preliminary results showed that lower numbers of horse hooves per length of beach indicated higher speeds. The number of hooves averaged 13.3 prints per 10 m, so it could be assumed the styles ridden were likely to be faster types, such as trotting, cantering, or galloping. Overall mortality may have varied due to not knowing which of these styles was used.

Management recommendations

Currently, the Northern Pegasus Bay Bylaw 2010 permits horse use across all beaches. The results of this study suggest however, that the permitted area needs to be reduced if Pegasus Bay ecosystems are to recover. One option would be to identify and designate a particular area in which horse riders are permitted. Identification of this area would need to balance safety, erosion prevention and ecological implications. Woodend Beach, near the existing horse user entrance, would be a suitable area for this option. This area is already in high horse use and no signs of significant erosion have been observed (Chapter 3). Ecological damage from horses would have already occurred in the area. Low pedestrian traffic and vehicles not being permitted here make this a suitable option. An absence of vehicle users reduces conflict and mitigates risk associated with horse riding in public areas.

This study showed that horses can have detrimental effects on intertidal shellfish and mitigation is needed. The mortality rate was found to be 36.9% on Woodend Beach which has the potential to severely impact the population. Furthermore, if there was high horse traffic on a daily basis impacts could be similar to that indicated in Figure 6.12 for recreation and ORVs. However, evidence presented in this thesis suggests that both vehicle and horse users are more likely to impact over a much longer time period - this is further discussed in Chapter 7.

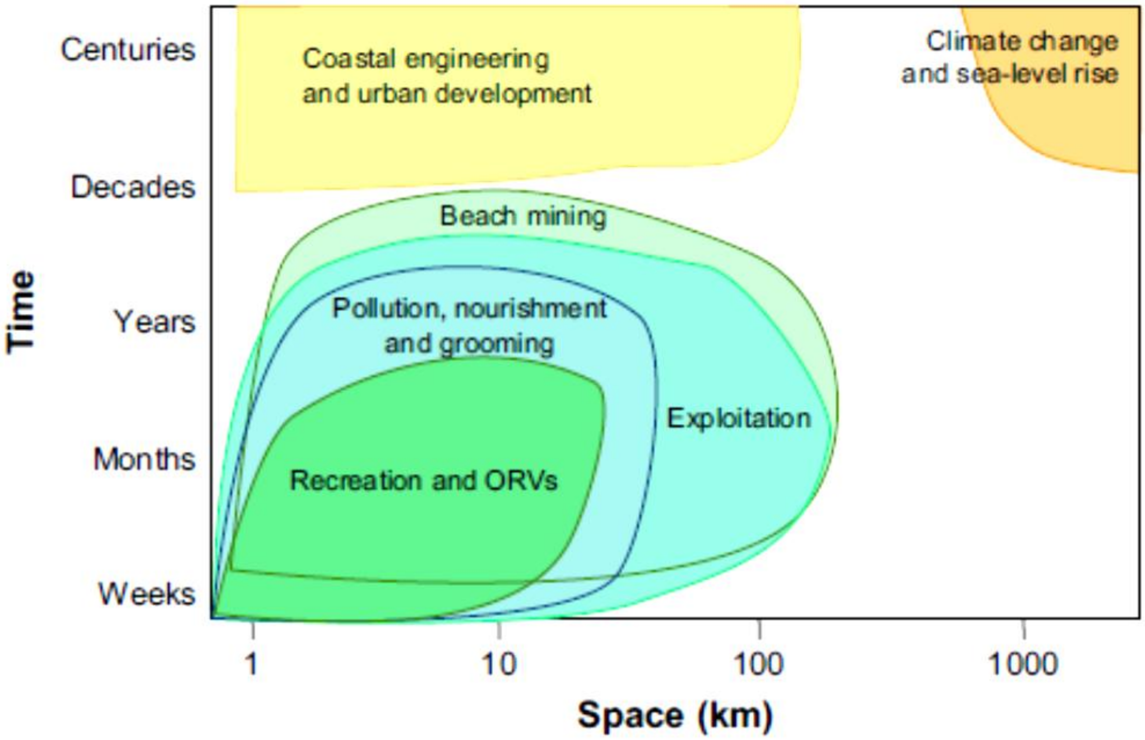


Figure 6.12: Conceptual model and schematic diagram showing the relative spatio-temporal scales in which different impacts reviewed here generally operate on sand beach macrofaunal communities. Envelopes indicate the potential extent of individual impacts in space and time, with the lower curve reflecting the lower limit of impacts in time and space, whereas the upper curve reflects the corresponding maximum (sourced from Defeo *et al*., 2009).

While a complete ban of horses would be most ideal from an ecological perspective, more permissive measures could seek to limit the daily number of horses able to use the beach. This could be enacted through a permit system where riders must seek a license before entering the beach. Enforcement of this permit system would also be manageable in terms of identifying those with or without a permit. The results of such scenarios are presented in Chapter 7 through the use of extrapolation modelling.

Another measure to limit shellfish damage could be to restrict horse access to certain days (e.g. horses only allowed on Wednesdays). Horse use would be high for one day of the week and non-existent the rest, equating to a maximum of 52 times in a year. While damage on this one day may be more significant, it could be coupled with other mitigation measures to create an overall improvement for affected populations. This would most likely need to include limiting horse numbers on these days. If this is not done, more opportunistic trainers may train high numbers of horses on the permitted days. Future research should be conducted to survey beach users and horse communities to investigate the feasibility of such proposed management changes.

6.5 Conclusion

Results from this study reveal that tuatua in Pegasus Bay are affected by horses. Observation studies found an average mortality of 36.9% within a hoof print. The significance of this number becomes especially important where there are large numbers of horses over a large expanse of beach. Flow-on effects are likely to occur which could reduce the success of the population. In addition, soft bodied biota are likely to suffer increased impacts due to a lack of protection. To prevent further damage, management is required that aims to reduce user numbers and the permitted area. A secondary option is to designate a section of beach which is appropriate for horse use. Identification of a permitted area would need to focus on ensuring safety, erosion prevention and ecological protection. If implementation is successful it would be expected for there to be higher levels of intertidal tuatua on the beaches of Pegasus Bay. Overall, this would allow for shellfish to be protected in the rest of Pegasus Bay.

Further research would be advised due to no mortality or damage being found during the disturbance intensity experiments. Low densities of tuatua make *in situ* experiments difficult to be carried out, so it would be recommended for experiments to be repeated at a location with high shellfish densities or when Pegasus Bay populations increase. Local accounts suggest that shellfish densities are in decline, so the former would be most recommended. The effect of horses on other organisms in the intertidal zone also needs to be evaluated. Lastly, observational results could be extrapolated to devise a model which evaluates the overall percentage mortality of shellfish temporally. The overall impact of users could be determined over set time periods and would open the door for new dynamic management options to take place.

Chapter 7 Sand beach management: a synthesis of scientific information for robust outcomes.

7.1 Introduction

Throughout this thesis, an interdisciplinary approach has been utilised to answer two key questions which are critical for successful ecological management on sand beaches: firstly, do vehicles and/or horses on sand beaches impact on intertidal shellfish populations, and, secondly, how can management policies be utilised to mitigate any negative impacts from such activities on intertidal ecosystems? This final chapter provides a synthesis of the information presented regarding the potential effects of vehicle and horse users and makes management recommendations to successfully protect intertidal shellfish. Earlier chapters in this thesis characterised six beaches in Pegasus Bay, described their intertidal shellfish populations and evaluated the vulnerability of intertidal shellfish to human activities. Local and international sand beach management was evaluated to determine the level of protection shellfish currently receive. Vehicle and horse effects on shellfish were quantified to show that significant levels of immediate damage can occur for each of these users.

Sand beaches are dynamic ecosystems which contain unique biota that are vulnerable to human activities. Like others worldwide, the sand beaches of Pegasus Bay are utilised by a wide range of users. Whilst most of these users are likely to have negligible impact on these ecosystems, other activities, such as vehicle driving and horse riding, may be more significant. Beach users are known to accelerate beach erosion, impact user safety and adversely affect wildlife. A key finding of the management review presented in Chapter 2 of this thesis was that biological values are largely underrepresented in sand beach management policies. As a result, management policies often restrict these users to the intertidal zone; an area perceived as being devoid of life. However, this zone is important to the ecosystem and contains diverse intertidal biota which has an important role in ecosystem functioning (Armonies & Reise, 2000). Ignoring biological values in this manner could have adverse impacts on the ecosystem. In order to address this, a holistic approach must be taken by sand beach managers.

Successful sand beach management requires an integrated multidisciplinary approach. Moreover, ecological protection on sand beaches should be an equal priority alongside other facets of coastal management. Protection of species within these areas should utilise information available, and employ a precautionary principle (e.g. NZCPS, 2010) when such information is not available. Use of quality information will not only guide management practitioners, but also allow a synthesis of ideas and lead to the creation of dynamic management plans. Ultimately, it is hoped this approach will result in robust management strategies which protect natural resources for future generations.

Acknowledgement of the limitations of information for decision making should also be made in management considerations. For example, earlier studies by Wolcott & Wolcott (1984) predicted that vehicles would not affect the clam *Donax variablis* because of its hard shell and sediment cushioning providing sufficient protection. This evaluation was based solely on their vehicle impact study using ghost crabs (*Ocypode quadrata*) in Cape Lookout National Seashore, North Carolina, U.S.A, rather than findings from investigations using shellfish. However, subsequent studies have shown negative impacts from vehicles on similar clam species (Schlacher & Thompson, 2007; Schlacher *et al.*, 2008a; Schlacher *et al.*, 2008b; Moller *et al.*, 2009; Sheppard *et al.*, 2009; Marsden & Taylor, 2010).

In this chapter, the importance of considering ecological outcomes in sand beach management and the necessity of detrimental recreational activities is discussed. The Northern Pegasus Bay Bylaw 2010 is evaluated in light of information presented in prior chapters. This information is then used to make key recommendations to beach managers based on extrapolative modelling. Finally limitations of the present research are discussed.

7.2 The impacts of current beach use of intertidal ecosystems

Sand beaches play host to a wide range of activities, each of which is likely to differ in its environmental impacts. Being able to compare the impacts of one activity to that of another is important when making decisions as to which activities are permitted, and where and when they are allowed to take place. The overall impacts of vehicles and horses in sand beaches are difficult to compare. The key difference is that a vehicle continually rolls over the surface, whilst horse hooves lift off the ground as it runs. Horses resulted in an average of 36.9% mortality in the area under the hoof whilst vehicles resulted in 4.8% mortality in the area under the tyre and 0.27% mortality for each subsequent pass within the already impacted area. At first glance, horses appear to result in far higher mortality than vehicles; however, due to the nature of movement of each user, the impacts become similar when extrapolated over time and area of beach impacted.

Comparing mortality due to vehicle and horse users with the results presented in Chapters 5 and 6 requires the use of a mortality rate. For vehicles, this rate is a 0.27% increase per vehicle pass; however, data from horse studies were not in this form and extrapolation was required to calculate this rate. At Woodend Beach, it was found that there was an average of 36.9% mortality per hoof. This rate must be extrapolated over a known distance, so that it can be used to compare with vehicles (Equation 2).

Overall, these equations are not to be used as a singular tool for impact evaluation, but simply a comparative indication of the potential impact on tuatua by certain user groups. This allows for different users to be evaluated using the same parameters. Moreover, these equations can be applied to other users and bivalve or target species.

This model has been designed to be universally applied, that is the mortality to infaunal species can be compared between different activities for any beach. For another region to use this model requires a small amount of impact evaluation. This is because every organism and beach could have differing levels of impact. For example, a beach with coarser sediment grain size may have higher levels of mortality from an activity due to less cushioning being provided to the organism. Therefore it is advisable that the following are completed when using the model; activity impact assessments which evaluates the mortality after one pass and the mortality rate for multiple passes (as many as applicable for the region), survey of the distribution of the organism being evaluated, and measurements of the physical parameters of the beach and the activity. Overall, this data gathering could be successfully completed within four days, allowing impact assessments to be replicated.

Equation 1: Track area for a 4x4 vehicle over 1 m longshore beach distance

$$\begin{aligned} T_{area} \text{ for 4x4} &= (Twr + Twl) \times A \\ &= (0.2 + 0.2) \times 1 \\ &= 0.4\ m^2 \end{aligned}$$

T_{area}- area of the tyre tacks (m²)

Twr- width of right tyre (m)

Twl- width of left tyre (m)

A- 1 m longshore beach distance

Equation 2: Track area for a horse of 1 m longshore beach distance

T_{area} for horse= $(\pi r^2 \times Nh)$ x A

$= (\pi \times 0.0775^2) \times 1.3$ x 1

$= 0.0245$ m²

T_{area}- area of the tyre tacks (m²)

r- radius of hoof print (m)

Nh- average number of hoof prints in 1m of beach length longshore

A- 1 m long-shore beach distance

Equation 3: The remaining population after disturbance by one user

$$Remaining\ population\ (\%) = S \times \left(1 - \left(d_1 \times L \times \left(\frac{Ta}{Bw}\right)\right)\right)$$

S- standing population (%)

d_1- damage rate of one user (0.048 for vehicles, 0.36 for horses)

L- likelihood of moving over the shellfish band

Ta- track area (m²)

Bw- width of usable beach (m)

Equation 4: The remaining population after one day of disturbance

Vehicle:

$$Remaining\ population\ (\%) = S \times \left(1 - \left((d_r \times V_s) + d_1\right) \times \left(\frac{L \times V_d \times Ta}{B_w}\right)\right)$$

Horse:

$$Remaining\ population\ (\%) = S \times \left(1 - \left(\frac{d_1 \times L \times H \times Ta}{B_w}\right)\right)$$

d_r - damage rate (0.0027 for vehicles, not available for horses)

d_1- damage after one pass (0.048 for vehicles, 0.36 for horses)

V_s- Vehicles driving on the same tracks

V_d- Vehicles driving in different tracks

H- Number of horses

L- Likelihood of hitting the shellfish band

Ta- tyre track area per m^2

Bw- Beach width (m^2)

Equation 5: The remaining population after more than one day

$$\text{Remaining population (\%)} = Starting\ population\ (\%) \times\ M2^{Nd}$$

$M2$- Equation 4: The remaining population after one day of disturbance.
Nd- Number of days from the start

In order to utilise these equations some key assumptions are made. Firstly, it is assumed that shellfish are distributed uniformly throughout half of the usable beach area, and secondly the damage rate of each user was assumed to be the same each day. These are both realistic assumptions as field observations and experiments demonstrated that tuatua were dispersed over half the beach and damage rates did not significantly change between seasons for vehicles (see Chapter 5).

For the purpose of this evaluation, the beach width (MLWS to MHWS) was fixed at 100 m – the approximate size of the intertidal zone at most beaches in Pegasus Bay - and the likelihood of hitting the shellfish band was standardised at 50%. For multiple vehicle pass scenarios, the number of vehicles following the same/different tracks; it was assumed that at least one vehicle had to make a new track each day and, thus, cause the initial 4.8% damage in the first track.

To compare the effects of these different users over time we must assess them under equal parameters. Using Equation 3, one vehicle results in 0.0096% mortality whilst a single horse results in 0.0045% mortality. This appears to be very low; however, when this is extrapolated for more than one user, and over a longer period of time, these users have very different levels of impact. Using Equation 4, with 50 vehicles and horses per day there is 0.36% or 0.23% mortality respectively. Furthermore, if the same amount of use occurs throughout a year (365 days) there is 49% or 43.8% mortality caused by vehicles or horses respectively (Figure 7.1). These numbers clearly show that despite mortality levels being small for one pass, as passes and days increase, the cumulative impact of these users can become substantial.

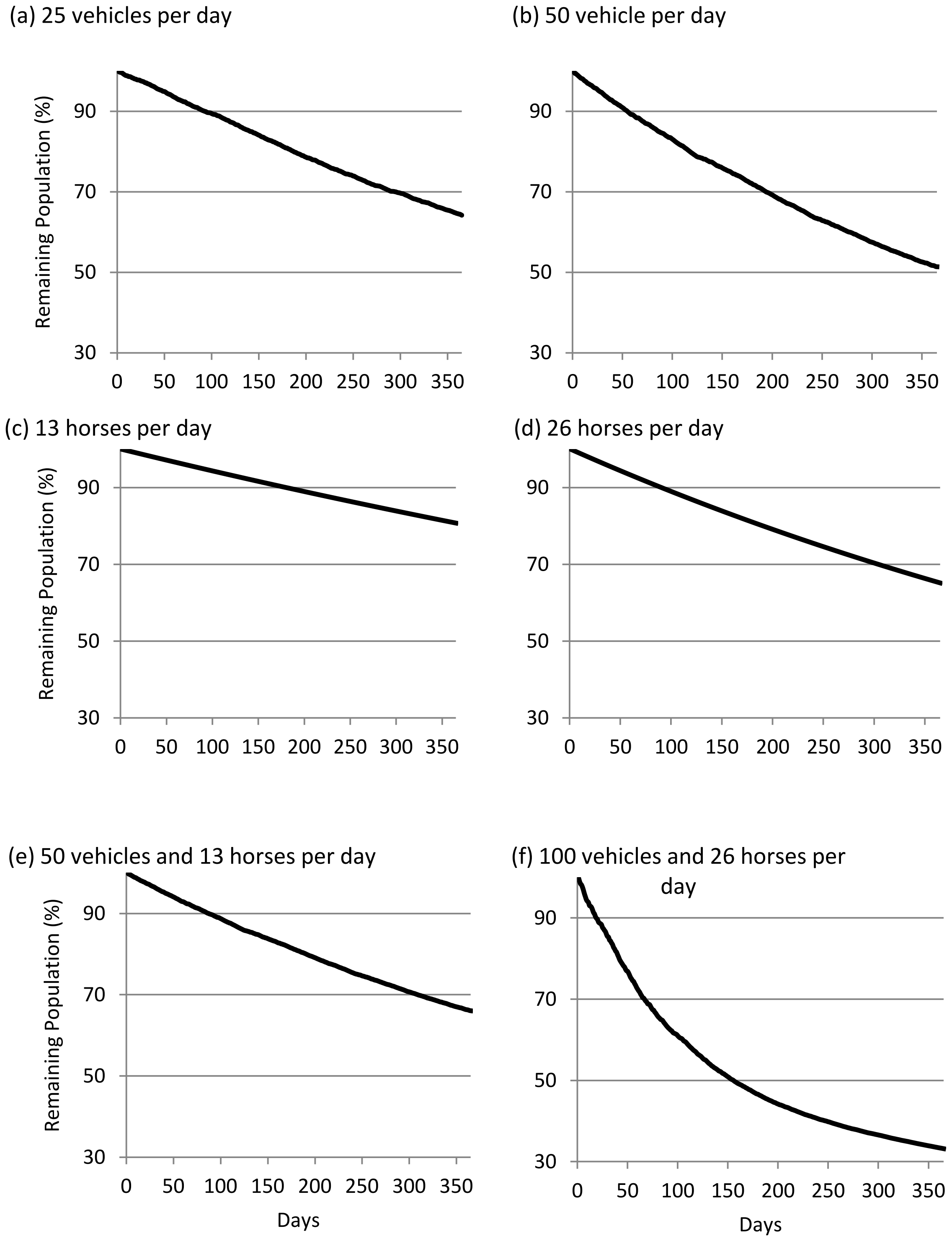


Figure 7.1: The percentage of remaining tuatua after being runover by (a) 25 vehicles, (b) 50 vehicles, (c) 13 horses or (d) 26 horses per day, and combined user impacts in (e) current use and (f) double the current use.

In Pegasus Bay, vehicles are used daily during the whitebait and salmon seasons, which run from 15th August to 30th November and over the summer months to April respectively. This is a total of 258 days when high numbers of vehicles (50+) are driven on the beach in a single tide cycle. Using Equation 5, it was found that after 258 days 37.4% of shellfish on a vehicle impacted beach would have been fatally injured (Figure 7.1).

The second scenario is that on average 13 horses are used daily on Woodend Beach which is consistent with field observations. The equation given above finds that after one year this would result in 19.3% of shellfish mortality (Figure 7.1). This is a significant proportion of the shellfish to be destroyed by a single user group on the beach.

Human populations living within the vicinity of the coastal zone is increasing (Baird, 2009) and so too is coastal tourism and recreation (Hall, 2001). Thus, coastal managers must be prepared for an increased demand for coastal resources. To evaluate the effects that this may have on tuatua in Pegasus Bay, predictions can be made using the equations in Equation 5. No values are available for the increase of beach use in Canterbury, so for the purposes of this analysis, it was assumed that user numbers could double from current user patterns (i.e. 100 vehicles and 26 horses per day). Vehicles could result in 98.8% shellfish mortality, and 26 horses a day resulted in 34.8% shellfish mortality in one year. Furthermore, if horse users were to increase to 100 users per day, 81.8% shellfish mortality would occur after one year, making vehicle users more detrimental to shellfish populations when in high numbers. While these numbers are based on assumptions, they provide an indication of the potential impact of these two user groups. It must be noted that these predictions are to be taken as an indication only and *in situ* results may show other mortality patterns not accounted for.

Table 7.1: Table showing the predicted mortality for tuatua under the different beach user scenarios discussed throughout this chapter (Sections 7.2 – 7.4).

Vehicle users	**No.**	**Scenario**	**Total days**	**Tuatua mortality (%)**
Uncontrolled	1	Free range within the intertidal zone	1	0.0096
	50		1	0.36
	10		365	9.1
	25		365	35.8
	50		365	49
	100		365	98.8
Controlled	25	Using the same tracks	365	8.9
	50	Using the same tracks	365	12.4
	50	Limit to Salmon season	107	17.8
	50	Limit to Salmon + Whitebait	258	37.4
Horse users	**No.**	**Scenario**	**Total days**	**Tuatua mortality (%)**
Uncontrolled	1	Free range within the intertidal zone	1	0.0045
	50		1	0.23
	5		365	7.9
	10		365	15.2
	13		365	19.3
	26		365	34.8
	50		365	43.8
	100		365	81.8
Controlled	13	One day a week	52	3.0
	13	Three days a week	156	8.8
	13	Five days a week	260	14.2
Combined users	**No.**	**Scenario**	**Total days**	**Tuatua mortality (%)**
	13 horses and 50 vehicles	Free range within the intertidal zone	365	33.9
	26 horses and 100 vehicles		365	66.7

7.2.1 Northern Pegasus Bay Bylaw 2010: successes and weaknesses

The Northern Pegasus Bay Bylaw 2010 currently permits vehicles to be driven on the beach from access points near to the river mouths, whilst horses have unrestricted access along the coast. Evidence presented in Chapters 5 and 6 showed these activities were ecologically damaging. In addition, both vehicles and horses have the same environmental requirements and could conflict when they occur together. Compared to many other locations around the world, management authorities in Pegasus Bay have few restrictions on users. For example, authorities at Cannon Beach give permits only for users that have specific reasons to use the beach. In comparison, beach users of Pegasus Bay can freely access beaches for any activity. Vehicle users on beaches of Stradbroke Island, Australia have free access and traffic volumes often reach 500 vehicles a day (Schlacher & Thompson, 2007). However, this high use is not typical for all beaches around the world. New South Wales legislation does not support the use of vehicles on beaches, and South Africa has a complete ban of vehicle use on its beaches (Department of Environmental Affairs and Tourism, 2004), as does France (La Loi Littoral, 1986).

The Northern Pegasus Bay Bylaw 2010 has strengths and weaknesses in relation to the three main areas of coastal management identified in Chapter 2: erosion prevention, ensuring user safety and ecological protection. Beach erosion can be successfully prevented by keeping users away from the sand dunes by permitting vehicles in the intertidal zone as in the Northern Pegasus Bay Bylaw 2010. However, my observations of tyre tracks provide evidence that some vehicle users are still driving above the high tide line and sometimes within the dunes. Further enforcement of the bylaws are needed to prevent this; however, a ban of vehicles would be most effective. Another measure would be similar to that of Cape Cod, U.S.A, where fenced vehicle tracks force users to follow a set path. This could be applied to Pegasus Bay to give users a set track to follow with little possibility of deviation.

Safety around vehicle users has increased as a result of a speed limit of 30 kmh^{-1} and 10 kmh^{-1} within 50 m of people. Vehicles and horses are also not allowed to pass through a surf lifesaving flagged area, ensuring greater safety of swimmers and other such beach users (Section 6.10, Waimakariri Northern Pegasus Bay Bylaw 2010). Overall, these two management steps increase safety of other users; however, horse user speed is not controlled which poses risk to both horse riders and other non-associated beach users.

Figure 7.2: Vehicle being driven near to the sand dunes at Kairaki Beach, Canterbury.

In other parts of the world, horse users are recognised as being a hazard around other users. As such, on Crane Beach, Massachusetts, U.S.A. horse users are only permitted in off-peak times of the year being the 1st October to the 31st March. This mitigates the risk of pedestrian safety being compromised. In Pegasus Bay, horses have comparatively few restrictions placed on them. For example, a horse rider can use the entire stretch of Pegasus Bay beaches and travel as fast as they like. Horses are capable of travelling at speeds in excess of 40 kmh^{-1}. When travelling at high speed, risk is increased to both the horse rider and other users such as pedestrians. Therefore, it may be necessary to impose speed restrictions. This could be technically difficult for riders to follow due to the absence of speedometers on horses, but imposing a control-type rule may be an option. For instance, horses must be walked within 50 m of people. This would allow greater control of the horse and ensure safety of pedestrians. An alternative option would be to only allow certain riding styles to be carried out (i.e. walking).

Figure 7.3: A harness racing horse being trained (trotting) on the intertidal zone.

Ecological protection under the Northern Pegasus Bay Bylaw 2010 is largely focused on preventing disturbance to birds (Policy 6.8, Waimakariri Northern Pegasus Bay Bylaw 2010), including roosting, nesting, resting or feeding. As mentioned in Chapter 2, this is a common theme for wildlife management on sand beaches around the world. For example, beaches where turtles nest have seasonal bans on vehicle use during the nesting period. A second measure to prevent damage to bird nests on the dry beach face is to designate the intertidal zone for recreational use. However, I have observed vehicles and horses on the intertidal zone frequently disturbing shorebirds feeding on polychaetes and shellfish. Horse and vehicle users have potential to cause high levels of disturbance so careful management is needed.

7.2.2 Consequences of beach activities

All anthropogenic activities are likely to affect the surrounding ecosystems where they take place. Defeo *et al.* (2009) produced a figure proposing that recreation and vehicles are likely to have very little effect over space and time (months over hundreds of kilometers) compared to coastal engineering and urban development (decades to centuries over hundreds of kilometers, Figure 6.12). However, the findings of my thesis research suggested that vehicles are more likely to impact beaches over larger time scales than Defeo *et al.* (2009) suggested. Moreover, horse riding fits into the recreation category and, paired with vehicle use, is likely to cause larger impacts over temporal scales.

It is proposed that Defeo *et al.*'s (1999) figure be adjusted to show this potential impact with the ecological outcomes reflected (Figure 7.4). Tuatua in Pegasus Bay recruit over the summer period and move to the adult population after approximately one year (see Chapter 4). During this year, individuals are exposed to vehicle and horse disturbance which could severely reduce the number of individuals which survive to become adults. A reduction in adult tuatua may result in fewer recruits in subsequent years (Peirsma *et al.*, 2001). Overall, this could result in less abundant tuatua populations if use patterns are sustained over multiple years.

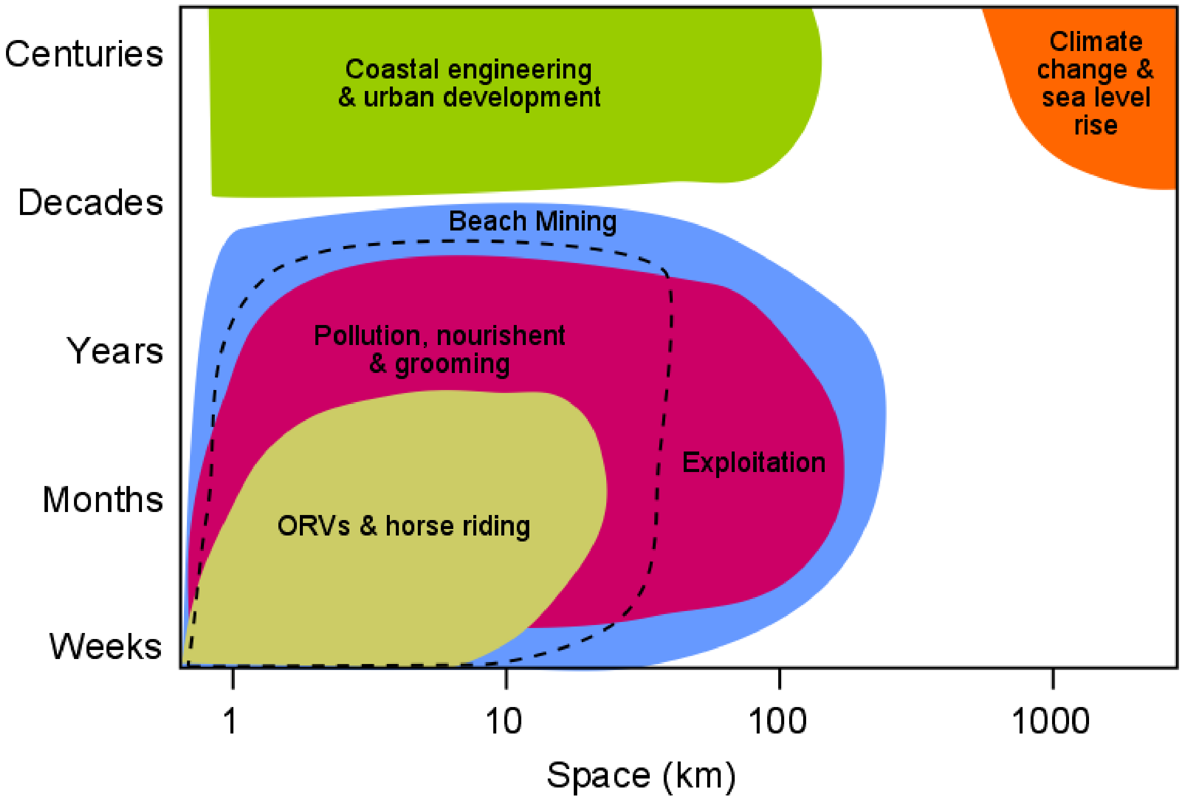


Figure 7.4: Temporal and spatial scale of activities on beaches. Dotted line is the proposed change to Off Road Vehicles (ORVs) and horse impacts compared to that presented by Defeo *et al.* (2009) (see Figure 6.12 for the unmodified diagram).

The ecological cost of permitting vehicle or horse activities on sand beaches

A key question an environmental manager should ask is: what ecological compromise is made when permitting an activity to occur? This compromise must balance a wide range of factors such as ecological impacts, monetary costs, safety and environmental degradation. In the coastal zones of New Zealand, an activity can be prohibited if information indicates that it could cause damage through application of the precautionary principle defined in the NZCS 2010. So for an activity, such as vehicle driving, on sand beaches to be permitted the necessity of the activity must be considered (i.e. is the activity essential?).

A form of objective assessment may be a useful tool for coastal managers to decide whether an activity should be allowed. An Environmental Impact Assessment (EIA) is an example of this, and aims to provide an objective measure of the impacts of an activity on the environment. Generally, similar assessments are carried out by environmental consultants and construction and engineering companies; and the Department of Conservation currently uses an EIA in granting concessions on conservation land. This kind of tool could be applied to recreational activities in the coastal zone. For example, an assessment of vehicle use would provide clear objective information to the coastal manager which would aid in decision making. Decision making using this type of assessment can be difficult when an absence of scientific information on the environmental impacts exists. In such cases the precautionary principle should be employed until research can provide the information needed.

If such a framework was implemented for Pegasus Bay, and vehicles were no longer permitted on the beach, people would be forced to fish and whitebait further up the river (by approximately 750 m) or to carry fishing and whitebaiting gear to the water’s edge. This would not restrict access to less mobile users because at the Waimakariri River mouth there is a car park at the water’s edge before the gate. This parking facility has recently been improved by the Regional Council. Keen fisherman could still carry gear along the beach by foot to be closer to the sea. Currently, the Northern Pegasus Bay Bylaw 2010 has resulted in fanning over the dry beach causing large areas of disturbance (Chapter 2). Therefore restriction of vehicles to the car park would not only protect shellfish, but also the nesting seabirds which the current plans aim to protect.

7.3 Ecological considerations in sand beach management

Currently management plans for vehicle and horse use on sand beaches pay very little regard to intertidal organisms. Previous literature is often a driver in designing management plans.

For example, if literature showed high levels of mortality occurring for ground nesting birds in the presence of vehicles, the key method of mitigation used for such beaches would be to move vehicles away from these species. In addition, birds are iconic species with high public interest whereas other sand beach biota (e.g. polychaetes and shellfish) are not. Historically, this usually resulted in the confinement of heavy recreational users to the intertidal zone, away from nesting birds. However, shorebirds forage in the intertidal zone and are frequently disturbed by vehicles under such management plans.

Considering ecological implications in sand beach management should be of high importance for environmental damage to be prevented. If these important ecosystems are not considered in management plans, the perceived value of the location may be compromised. Often it is the role and function of the organisms present in the ecosystem which provides aesthetically pleasing and healthful qualities for humans. For example, clear water through the reduction of turbidity by filter feeding bivalves makes coastal systems more desirable to human users. Effective management is needed which prevents unwanted environmental outcomes. For example, a reduction in water clarity and quality due to decreased filter feeder abundance as a result of uncontrolled vehicle users.

Recommendations for ecological protection need to take into account all components of an ecosystem. After all, it is the interaction of all these species that forms the ecosystem. An ecosystem approach aims to ‘promote ecological integrity while allowing human use on a sustainable basis’ (Yaffee, 1998). This approach is far more favourable in ecological management as it takes a holistic view of the system and values all aspects of interaction. When a single-species approach is used to prevent environmental damage it does not protect the whole ecosystem; some species may benefit whilst others are negatively affected. For this reason, management practitioners should apply information in a holistic multidisciplinary approach.

Nicholson *et al.* (2009) stated that use of multidisciplinary information would result in a more robust and informative model of environmental change. It is acknowledged by Nicholson *et al.* (2009) that progress may appear slower, but reduces the risk of misleading policy recommendations. This is the reason why recommendations in this chapter are made using a synthesis of information, rather than single-source recommendations in previous chapters.

7.3.1 The importance of mitigating ecological risk

Ecosystem diversity and abundance significantly contribute towards a more resilient ecological community (Tilman *et al.*, 2006) and future management plans need to aim to enhance both of these. A resilient community is able to recover from higher levels of disturbance compared to a less diverse one. Resilience is important when ecosystems are presented with other stressors, as well as horse and vehicle disturbance. During the period of this research these stressors included water contamination, changes in sediment composition from earthquake activity and commercial fishing pressure. All of these can significantly inhibit the function of individuals in the ecosystem which can influence human values of the resource.

Diverse communities are more likely to continue ecosystem function when disturbed (Peterson *et al.*, 1998). This is because other organisms may be able to fulfil the role of the disturbed species. For example, if filter feeding tuatua (*P. donacina*) abundance decreases another bivalve, such as *Dosinia anus*, may fill this role. Therefore, the function of the community is maintained. In the interest of human amenity values, this would ensure that water turbidity did not increase as result of reduced filtering.

Whilst the focus of this thesis was on the impacts of beach users on intertidal organisms, such as tuatua, it is also important to consider other environmental outcomes when making management recommendations. For example, it would be unwise to suggest that vehicles and horses be designated to the same smaller area. Such suggestions would compromise safety of both users through spooking of horses from vehicle traffic, and the possibility of vehicle users being trampled by horses when getting in and out of their vehicles. Therefore it is necessary for these users to be spatially separated. This can be easily achieved in Pegasus Bay. There are approximately 55 km of sand beaches in Pegasus Bay, all of which have sufficient access for vehicle and horse users. However, designation of separate areas results in a wider spread of environmental damage. This creates a conundrum regarding which factor (i.e. safety or ecological protection) takes priority.

If activities, such as vehicle and horse use, are deemed to be environmentally harmful using adapted EIA frame work, or similar, a complete ban may be the most beneficial outcome. As with any type of ban this would not be met with approval from everyone. This would need to be weighed up against the benefits gained. For example, the absence of vehicle and horse users may result in low disturbance to birds, relatively undisturbed intertidal biota and no degradation to sand dunes. Enforcement would be needed, but could be carried out on an on-call basis because public will be able to identify non-permitted users. Schlacher *et al.* (2008a) showed there to be an 87% decline in density of assemblages on the upper shore and 61% in the lower shore of vehicle impacted beaches when compared to non-impacted beaches. If a complete ban was put in place it would be expected that faunal diversity, density and abundance could increase in areas previously affected by vehicle and horse users. This would benefit the ecosystem which could eventually transpire to economic benefits by sustaining local fisheries. However, a complete ban may not be practical and further community consultation would be needed to choose a balanced outcome.

7.3.2 Ecological protection and the role of communities

Chapter 2, comprising of an extensive international review, identified three main focuses of sand beach management in respect to recreational activities: erosion prevention, ensuring user safety, and ecological protection. The weighting of these was unbalanced, with less emphasis placed on the latter. When ecological protection occurs, birds are often the main species being protected. One outcome of such management is that ‘hidden’ species are ignored and often negatively impacted by management plans.

Identifying key species for protection is important if positive environmental outcomes are to be ensured, but indirect effects on other members of the ecosystem need to be understood and acknowledged. For example, trophic cascades could occur when a single species changes in abundance which could cause reduced or increased abundances of an associated species via ecosystem feedback loops and processes (Daskalov, 2002). Such changes in abundance could affect the protected species in the long-term. To avoid this, protection should take place which aims to sustain or increase target species abundances whilst maintaining equilibrium between species (i.e. holistic conservation). Why increase the abundance of one species when its food sources will be depleted as a result?

Single sources of information to guide management decisions are considered to have limited scope for the overall interactions within the environment and often result in unwanted outcomes (Born & Sonzogni, 1995). Coastal margins are dynamic zones with a large range of ecological interactions, so multidisciplinary management strategies are required. The implementation of such strategies may have potential to affect the entire ecosystem. Therefore a range of information is needed to successfully address the conservation requirements of coastal ecosystems.

Five key options employed to control vehicle and horse users of sand beaches were considered; permit systems, seasonal closures, complete banning, and area- and zone-based designation. Each of these options has advantages and disadvantages. To provide the best possible environmental outcome, ecosystems must be protected as a whole. The ecologically best option to do this is to completely exclude all activities which are known (or have potential) to cause damage to the ecosystem. This option would be most likely to have a successful recovery and result in a more resilient ecosystem. In a democratic society, where general public can influence management outcomes, a complete ban is rarely likely to occur due to political backlash from stakeholders. The political climate must be conductive to the use of a ban as a management option to be successfully introduced.

It is acknowledged that public awareness is hard to gauge, but can be a powerful driver in the mitigation of environmental issues (Winkler *et al.*, 2007). Public awareness via education is a key aspect in mitigation of environmental impacts, and significant large scale initiatives have occurred as a result (e.g. the ban on ozone depleting chemicals or the introduction of carbon emissions schemes). Winkler *et al.*, (2007) suggested that awareness can be increased through use of alternative media outlets in addition to purely science-based ones. These could include the use of social networking media such as ‘Facebook’.

Implementing a complete ban on vehicle and horse use on sand beaches in Pegasus Bay would be difficult and requires community-based approach. Community settlements, such as Waikuku and Spencerville, make up a large proportion of beach users in this area, making local engagement particularly important. For example, the horse trainers which frequent Woodend Beach own stables within 2 km of the beach. With community involvement, management authorities may be more successful in achieving conflict-free compliance (Burger, 2000). Engaging the community through education to highlight the importance of shellfish and other such assemblages within an ecosystem would be required. This would improve public perception of the intertidal zone as being an area where important organisms are living, rather than that of a dead zone. With more people aware of the environmental impacts of these activities, it is hoped that unnecessary vehicle and horse use of the beaches would reduce.

7.4 Final management recommendations

Shellfish were found to be adversely affected by vehicle and horse users so the need to control these users is pertinent for shellfish to be sustained. The following recommendations are based on all of the findings of the present research. Overall, the outcomes of these recommendations are difficult to predict due to the dynamic nature of the coastal environment; however, extrapolative modelling was utilised to provide an indication of the benefit for each option wherever possible.

The results and findings of previous chapters can be brought together in the form of three key recommendations for beach managers which aim to protect intertidal shellfish populations by:

1. reducing the permitted area for activities,
2. putting limits on the frequency and types of users permitted, and
3. requiring beach users to follow predefined tracks.

These recommendations will benefit the infaunal biota in any sand beach ecosystem. The success of these recommendations for management practitioners requires assessment to understand what will be achieved. A key goal in implementing these options is to not only prevent further ecological damage, but to enhance the community abundance. As discussed, this will influence function and stability of the ecosystem as a whole. Data extrapolation from results presented in Chapter 5 and 6 and guidance from beach characteristics described in Chapter 3 can be used to derive equations which indicate differences in mortality. Evaluation of the enhancement in community abundance can only take place after these recommendations have been implemented.

1. *Spatially constrain the area permitted for vehicle and horse users*

Previous research found that beaches which allow vehicles contain altered and less diverse assemblages compared to those without such users (Schlacher *et al.,* 2008a). As such, it is necessary for vehicles to have their area constrained on sand beaches to prevent widespread damage to the ecosystem. Because vehicles are not the only users on many beaches, it is important that users requiring similar resources be separated to avoid conflict (Phillips & House, 2009). In light of the evidence presented in Chapters 5 and 6 and the points discussed in this chapter, horses and vehicles are likely to require separate designated areas. These might be spatially separated to allow sufficient space for intertidal shellfish populations to be protected and self sustaining.

Area-based designation will need to take into account the possible environmental effects of doing so. The evidence presented in this thesis shows vehicle and horse users to cause significant mortality to tuatua, so it can be assumed that at least similar damage would occur to other infaunal organisms, specifically soft bodied polychaetes or small crustaceans. Designated areas would be ecologically beneficial (if not directly next to each other) because organisms outside of the permitted area would be undisturbed.

The Waimakariri River mouth is the most popular fishing and whitebaiting location in Pegasus Bay (author observations), so this could be the permitted vehicle area. Woodend and Ashworths beach are the two most popular horse user areas, but it may be more beneficial to allow riding in only one area. This would reduce the disturbance caused by horses over Pegasus Bay. Either location would be suitable; however, if Woodend was chosen, spacing between that and the vehicle area would be needed.

The configuration of permitted areas for vehicle and horse use needs to allow for shellfish protection and connectivity between populations. For example, if the disturbed area is too large, organisms will not be able to disperse past this area and have a lower chance of survival. In shellfish, dispersal of propagules is predicted to be between 20 and 500 km (Kinlan & Gaines, 2003). Therefore recruitment of juveniles is not likely to be affected; however, juvenile tuatua ride the swash and may not be able to disperse as far. This could reduce the connectivity between populations as tuatua become impacted when in the vehicle and horse permitted zones.

Dispersal in shellfish can be influenced by a range of factors including ocean currents and temperature (O'Connor *et al*., 2007). The predominant nearshore currents in Pegasus Bay are southwards, so tuatua could disperse a large distance in that direction. However, geographical barriers such as the Waimakariri River mouth could break these currents and alter the supply of recruits. Evidence of this nearshore current and tuatua movement being broken was observed when large densities of adult tuatua were found built up on the north side of the Waimakariri River mouth but not the south (unpublished data).

Overall, separating recreational vehicle and horse users would not only reduce ecological damage, but also increase safety by mitigating conflict between them. A smaller permissible area would reduce the spread of environmental disturbance and allow for enforcement to be carried out effectively. Designing these areas would need to take into account the population dynamics of intertidal organisms if they are to be sufficiently protected.

Firstly, reducing the permitted area for activities is very important in aiding recovery of intertidal biota. It must be acknowledged that traffic will be heavily concentrated in permitted areas and increased effects on biota will occur, but the beach zones outside of this will benefit. Providing areas free from heavy impacting activities will allow for individuals to be less disturbed and likely to grow faster, and larger with have higher reproductive outputs. The latter of which will allow replenishment of current populations. In addition to this the immediate outcome will be that lower numbers of individuals will be fatally injured in the absence of users.

In an international review of studies, Lester *et al.* (2009) showed biota in marine reserves increased in biomass, size, density and richness. Similar outcomes are expected to occur in the intertidal zone if vehicle and horse users were removed. This would allow organisms to grow and respond to natural processes. Lester *et al.* (2009) also found temperate areas had an increased response rates compared to tropical areas, so it might be expected for these changes to be successful in Pegasus Bay. The expected timing for population’s recovery cannot be predicted as easily due to the processes of this recovery relying on a range of environmental cues.

2. *Limit the frequency and types of users*

It is recommended that control be put in place to limit the frequency of activities occurring on sand beaches. For example, setting limits for the numbers of users permitted in a day and/or the number of days a year in which the beach can be used. This would not be a new form of user management. For example, in the U.S.A. Crane Beach limits the number of horse users to 50 a day, and in Donegal County, Ireland, horse users need permits to be on the beach during certain periods of the day and year (see Chapter 2). Evidence presented in Chapters 5 and 6 indicated that vehicles and horses are likely to significantly impact shellfish. Further extrapolation in this chapter has shown there is the potential for large amounts of mortality to occur over extended time periods. If all these measures are implemented intertidal populations will have a chance to recover and increase in abundance.

Firstly, types of activities need to be controlled. If large heavy vehicles are used on the beach they are far more likely to cause damage to infaunal biota. This would be especially likely if the vehicle penetrates deeply into the sediment. Currently vehicles are the most predominant recreational user in Pegasus Bay; however, there is potential for new events to be held as more people live near the beaches. For example, the increased development of Pegasus Town could result in novelty beach events similar to the Onetangi Beach Races, Waiheke Island, Auckland. In this event, tractors and bulldozers race on the beach which is likely to cause large impacts to the infauna. In Pegasus Bay, it is advised that a weight restriction be put on vehicles driven on the beach, unless special permission is granted. The weight limit could be set to include standard off-road vehicles, such as the Toyota Hilux or Mitsubishi Pajero. Granting permission should consider the necessity of using the vehicle (see Section 7.2.2).

Secondly, vehicle and horse users could be limited in numbers of users per day. This would reduce the frequency of disturbance resulting in less damage per day and a lower level of damage would benefit tuatua populations. This would be likely to result in increased reproductive outputs for the population. Dawson (1954) predicted that for every tuatua 35,000 spat would be produced. Therefore, every individual saved will result in increased levels of spat and recruits in future generations.

Thirdly, the number of days for vehicle and horse use could be limited. The most common use of vehicles is for fishing and whitebaiting. Whitebait season runs from 15th August to 30th of November. Salmon fishing runs over the summer months to April. The entire ecosystem will benefit if vehicles are prohibited from the beach outside of these times. Horse users could be limited in the number of days a week that the beach could be used. This would reduce the impact of these users in the long-term and allow for periods with no disturbance to intertidal biota. The results in Chapter 4 indicated that stress levels are reduced within 24 hours, so it would be recommended for there to be a 48 hour period between permitted use days. This would allow recovery and undisturbed function of shellfish during such periods.

The recommendation of limiting the frequency of activities on the beach is the most difficult option to implement, but is very important if ecological protection is to be ensured. There are options for management that could be effective for reducing the impacts of these users whilst still allowing some use. One option is to allow vehicles only on the beach during the whitebait season as the gear associated with whitebaiting is often large and heavy to carry. Salmon fishing gear is relatively light and can be carried in a backpack so there is really no need for a vehicle to be used. This management option would reduce the number of days vehicles are driven on the beach down to 107 days and would result in 17.8% mortality - approximately one third of predicted current rates (49%).

If horse users are limited to using the beach only on a certain number of days, there could be significant benefits to the shellfish population over the year. If the average of 13 horses were only allowed on the beach three days a week, it is predicted that there would be 16.8% mortality over the year (Table 7.1). Better still, if the same numbers of horses are allowed only one day a week (52 days a year) there would be 5.9% mortality. If horses are allowed only on weekdays (five days a week), there would be 26.4% mortality. The first two predictions are far lower than the prediction for the *status quo* (34.8%) and should achieve more positive outcomes than for five days of use. In addition, a weekday limit for horse users would avoid conflict from increased pedestrian users during weekends.

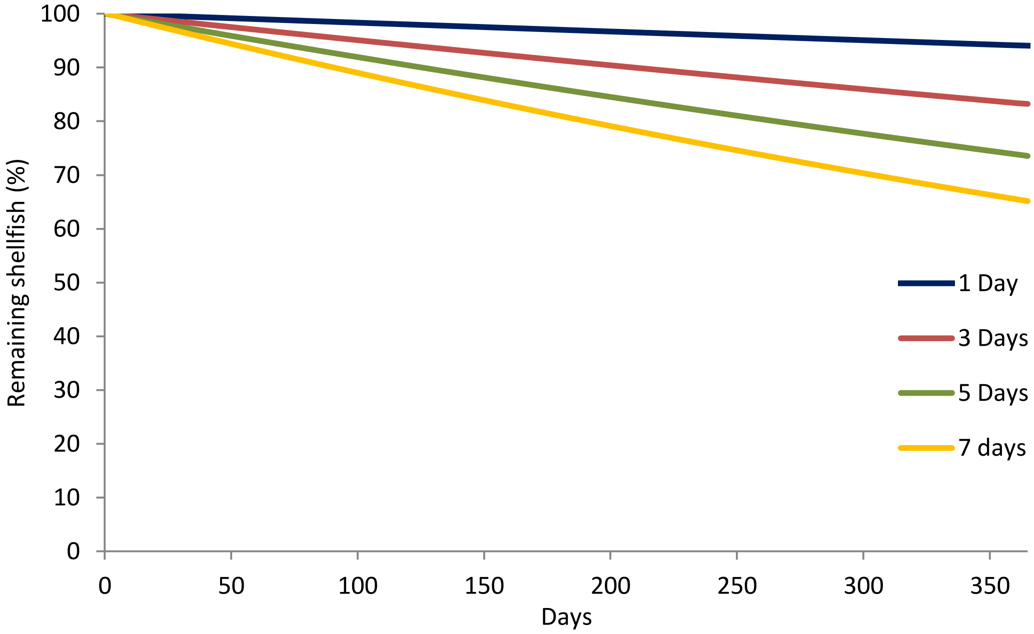


Figure 7.5: The mortality rates of shellfish subjected to 13 horses a day with different numbers of days in a week.

Reducing the number of users on the beach could also prove successful to protect shellfish populations. If user numbers are reduced to 10 vehicles and 10 horses a day, over a year there would be 9.1% and 15.2% mortality caused respectively. This impact for vehicles would be relatively low, but horse impacts are still high. Even five horses a day could result in 7.9%

mortality. Therefore, it is likely to be more beneficial to intertidal biota for horses to be limited in number of days of use in a week.

3. Define vehicle tracks to be followed

Many sand beaches in which permit vehicle use focus on confining vehicles to the intertidal zone. Once in this zone, vehicles usually have free-range and can drive anywhere they wish. Reducing the spread of disturbance is a key measure to mitigate the overall impact of vehicles on intertidal fauna. Shore birds nest and roost around river mouths and this spread of disturbance has the potential to be detrimental. Buick and Paton (1988) have shown vehicle traffic alone resulted in destruction to 81% of nests during the incumbent season. With studies showing less diverse and altered intertidal assemblages on beaches used by vehicles (Foster-Smith *et al.*, 2007; Lucrezi & Schlacher, 2010; Schlacher *et al.*, 2008), it is believed that vehicle impacts on intertidal shellfish could be similar. Therefore defining the route a vehicle must follow can reduce this spread of disturbance.

Currently the defined route under the Northern Pegasus Bay Bylaw 2010 is that vehicles and horses must enter at set access points and move directly to below the last high tide line. However, the most direct route to the high tide line is left up to the user’s interpretation. This has resulted in fanning of tracks. Kairaki Beach has the largest amount of fanning from access ways (Figure 7.6). Fanning is likely to be as much of an issue for tuatua mortality due to the additive effect of creating new tracks on the beach face. Therefore stipulating how vehicles move in the intertidal zone, and limiting the area of disturbance, is advised to effectively reduce additional stress and mortality. The use of signage in the intertidal zone is difficult due to wave forces at high tide. Therefore, two management options would need to be incorporated to achieve a positive outcome for shore birds and intertidal biota.

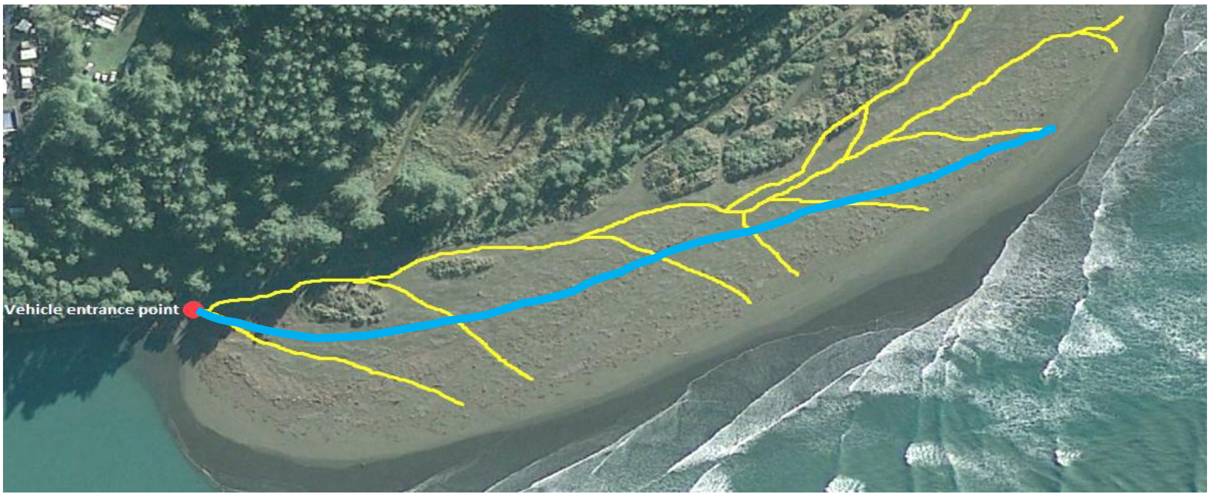


Figure 7.6: Proposed vehicle track from the entrance point to the high tide line (Blue) at Kairaki Beach. Yellow lines denote current vehicle tracks.

Firstly, it is advisable for tracks from the access way to the high water line to be defined and clearly marked (Figure 7.6). These could be marked in a similar way to dune system fences (e.g. rope and wood posts) on either side of the track to prevent any possibility of deviation from the track. The exit of this track should also be at one end of the permitted area to avoid fanning from the point (i.e. vehicles can only turn in one direction from this point). This recommendation would achieve two outcomes: the spread of disturbance from users would be reduced, and confusion over the most suitable track to use would be eliminated.

Secondly, when below the high tide line, vehicles could be required to follow pre-existing tracks. This reduces the area of disturbance and also ensures vehicles do not get stuck in non-driven areas of beach. These two options, when used in combination, should reduce the spread of disturbance to the entire beach environment. Whilst Schlacher & Thompson (2007) noted that vehicle use above the high tide line can cause deep rutting, this would not be the case in the intertidal zone. This is because wave processes during high tide would break down the tracks. The sediment is also far more compacted in the intertidal zone. Enforcement would be needed to ensure these rules are being obeyed. Utilisation of a user pays enforcement system, similar to that on Hatteras Island, North Carolina, U.S.A., could help to recoup the costs of this extra enforcement.

The recommendation for users to follow predefined tracks is going to have benefits for intertidal organisms and shore birds. This is because the upper shore will be less disturbed by vehicles, resulting in a larger area for birds to roost, nest, rest and feed without disturbance. An outcome of this may be more birds on the beaches. It would also be expected that ground nesting species would return to the area and maintain abundance. As a further measure, nests may need to be closed from pedestrians to prevent damage.

In terms of benefits for the shellfish populations, reducing fanning will decrease the spread of disturbance to the area. Every new track results in 4.8% mortality within the track, with an increase of 0.27% for every subsequent pass within the same track after that. As creation of new tracks is an additive effect, vehicles following preexisting tracks would cause far less damage overall. This will benefit infaunal species as they will be disturbed less frequently. Those individuals that were disturbed the previous day will also be likely to recover between tides.

To provide an indication of how beneficial the above discussed option could be, 25 vehicles going through the same tracks each day, over the course of one year is predicted to cause 8.9% mortality. This is a large reduction from 35.8% mortality if they were to create their own tracks. High numbers of vehicle use still demonstrate an improvement with 50 vehicles using the same tracks resulting in 12.4% mortality over a year; a large reduction from 49% if given free reign (Figure 7.7).

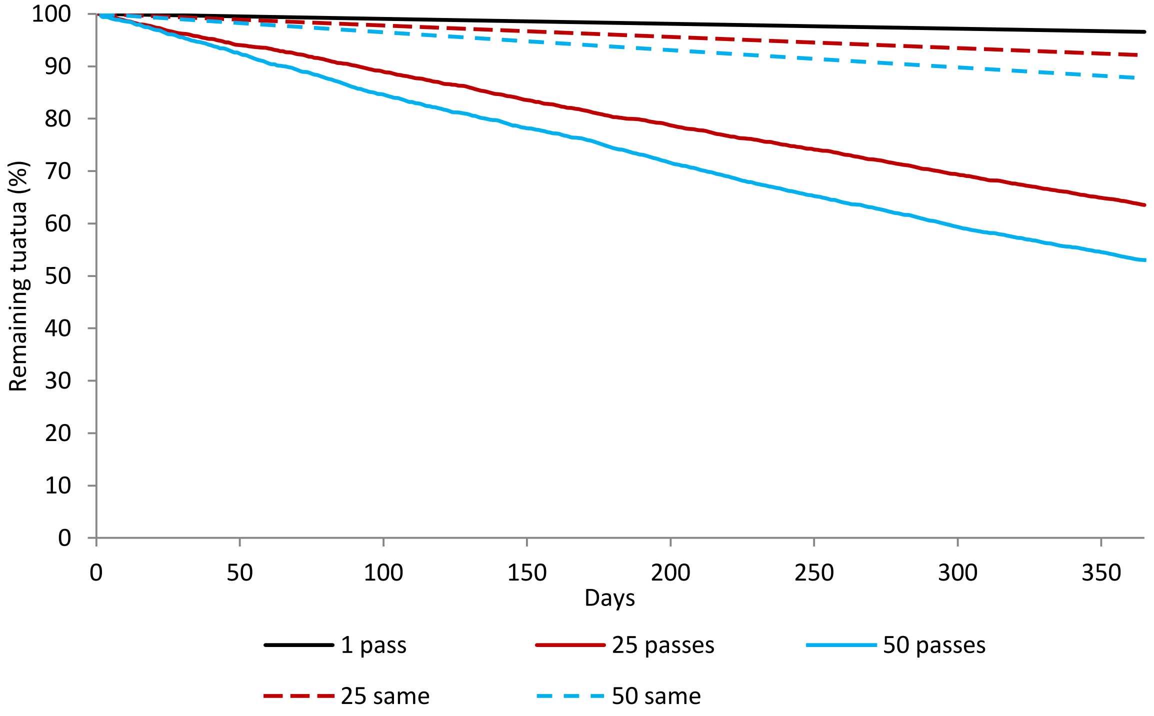


Figure 7.7: Comparative number of tuatua remaining after vehicle use when using the same tracks or allowed to make new tracks.

7.5 Research limitations

7.5.1 Methodology

Overall, the methodologies used in this thesis were successful in that qualitative and quantitative data were found to satisfy the objectives. A key objective within this research, setting it apart from prior studies in New Zealand (Moller *et al*., 2009), was for all results to be truly indicative of natural conditions. This meant all testing had to be done *in situ.* For use in future studies, some methods may need to allow for changing environmental conditions. For example, methods used to test the effects of horses may need to be devised so experiments can be carried out successfully with low densities of shellfish.

Management review

Reviewing the current management of vehicle and horse users on sand beaches was successful in that a range of policies were found from various regions of the world. However, identifying specific drivers of these is difficult. This is because these policies would have been developed for a multitude of reasons. The only way to do this would be to interview a representative of the authority that developed the policy. This would be time consuming and difficult due to the possibility of the relevant employee no longer working for that authority. Therefore, drivers had to be inferred from previous literature indicating environmental effects of certain types of use in beach environments.

Many local authorities rely on information which is focused on their region and scientific studies may be commissioned for this purpose. Often these studies are in technical reports and other grey literature which is not always freely available. It can be assumed that in addition to the peer-reviewed literature indicating possible drivers for management plans, a large amount of unpublished of grey literature has been also produced.

Some countries/regions do not have policies or specific plans for these users electronically available. This makes identification of trends hard to assess. Generally, less affluent nations had lower levels of management. This is expected due to prioritisation in other areas of resource management. Technology may also have an influence on this because some policies may exist but are not available online.

Habitat evaluation and shellfish distribution

Research describing spatial and temporal changes in distribution must seek to sample in absence of bias. Kingett Mitchell Ltd. (2003) focused more sampling in the higher shore levels and this may have some bias when describing distribution of these species. The present study used systematic sampling to describe the dispersal of tuatua over a set time period. This methodology is ideal for a spatially variable population, such as tuatua, because it keeps the sampling design consistent and comparable temporally.

Because shellfish distributions are variable, results may not accurately describe the population. The use of set position transect lines may miss shellfish which move along the shore. If further monitoring is to take place and sufficient resources are available, it would be advisable to reduce the spacing between quadrats and to use gridded sampling methods. This would reduce the likelihood of missing the shellfish in the 20-30 m band below last high tide range and should also take into account movement along the shore.

The results from beach profiling and seasonal population sampling showed that shellfish were variable in dispersal and abundance whilst the profiles of beaches they inhabit are relatively stable. It was hoped that pairing shellfish abundance with erosion and accretion events would provide a useful tool for population prediction but no relationship was shown in the data (Chapter 3). In order to determine if beach face events of this type could influence populations, an intensive sampling effort would need to be focused on one location over a long period of time. This would still use the same methods as those in the study presented in Chapter 3.

It is likely that the benchmarks used in this thesis would have moved slightly. Movement at individual benchmarks was not able to be assessed because these were not established with the NZVD09 until the end of the study. Originally, when benchmark locations were established no earthquakes had occurred, so it was assumed the position would not have changed during the study. As each major earthquake occurred, Environment Canterbury were required to reassess their own nearby benchmarks, which meant those that I used could not be established until this occurred. Final reassessment was completed in April 2012. Because of this the benchmarks and profiles in this study may not be completely true to the changes observed but were deemed adequate to show major beach face changes and trends.

Horse impact experiments

The experimental studies on vehicles were successfully conducted when there were sufficient densities of shellfish, but some of the horse impact experiments did not. This was scheduled to take place in the first year of sampling when tuatua densities were high; however, the horse rider was not available due to being busy as a result of the earthquake activity in the Canterbury region. The preliminary trial took place when shellfish were in high densities, during which significant mortalities were found. However, finalised experiments took place the following year, when shellfish densities were low and no mortalities were found. If densities were high it would be expected that high levels of mortality would be found. This is evidenced by the burial range of tuatua and penetration depth of horse hooves presented in Chapter 3. It would be recommended that horse experiments are repeated when shellfish densities are high.

It was observed that the horse hooves penetrate at an angle with the deepest part at the front. For future evaluations it may also be useful to understand the area of the hoof where most damage takes place. A vehicle's force is comparatively easier to evaluate due to there being no vertical component of the movement; however, the stamping motion of a horse makes it difficult to evaluate. Doing this would involve getting a force profile of the hoof when the horse is moving, which was not able to be done in these experiments due to resources available. This would allow researchers to understand the forces being exerted on organisms below the activity.

All research methods were designed with the assumption that there would be a location in Pegasus Bay with sufficient densities of shellfish. Other studies, such as Moller *et al.* (2009) and Sheppard *et al.* (2009), transplanted shellfish into the experimental area. However, this was one environmental factor that would not be compromised because transplanting shellfish may alter other environmental conditions, such as sediment compactness. Transplanting shellfish would be likely to result in shellfish that are not representative of those found naturally. For example, artificially placing shellfish would result in loosened sediment and unnatural burial depths. In addition, stress is placed on the animals through handling prior to the experimental procedure.

To mimic natural shellfish assemblages and environmental conditions, transplanting of individuals would need to take place a couple of tide cycles prior to conducting experiments. A key issue with this is that shellfish may migrate out of the area in this time, so ensuring the transplanted individuals stay in the area is relatively difficult. As beaches where tuatua are abundant are sand beaches with large wave dynamics, construction of apparatus to retain shellfish is also difficult.

Vehicle impact research

The vehicle experiments were very successful due to shellfish densities being sufficient and methods being simple and effective to give a clear damage rate. Having a clear damage rate is a useful tool in management as it allows for data to be extrapolated temporally in relation to the number of users on the beach.

The vehicle experiments specifically examined the effects of increased vehicle passes when driven through the same tracks. Further studies would be needed that examine the effects of different driving patterns to understand how vehicle use could affect the beach. This is because most vehicle users in Pegasus Bay do not follow pre-existing vehicle tracks. Methods to evaluate this may involve examining turning vehicles and vehicles criss-crossing over other tracks. Differences in positioning of traffic may also be needed because the penetrability of the sediment may differ between shore levels (Heathershaw *et al.,* 1981). Moller *et al.* (2009) found penetrability to be highest at high tidal levels due to sand being less compacted.

Certain aspects of a vehicle may cause increased mortality. If these were identified managers could prevent further ecological damage. Moller *et al.* (2009) showed vehicles with narrower tyres with wider spaces between lugs were most detrimental when driven over toheroa beds. Use of different vehicle types should also be evaluated for tuatua.

7.5.2 External variables

On September 4th 2010, a 7.1 magnitude earthquake shook the Canterbury region. This resulted in significant disruption to the activities which commonly take place on the beaches of Pegasus Bay. This and two other large earthquakes on 22nd February and 13th June 2011 liquefied the sediment producing silt in the Christchurch area. Silt was deposited both on the land surface and in waterways.

Introduction of silty sediment to the ecosystem may have resulted in negative impacts for abundance and distribution of shellfish in Pegasus Bay. It was observed that sediment in the 3.5 phi category increased during the study and appeared to be introduced after the September earthquakes. This sediment introduction may have resulted in smothering of shellfish populations; however, shellfish are also found to migrate constantly (Norkko *et al.,* 2001). Morton and Miller (1973) suggest that tuatua strictly avoid silt, so redistribution of the population may also have occurred. In addition to silt, habitat area for tuatua may also have been lost due to ground movement. In a post earthquake study on the Chilean coast, Jaramillo *et al.* (2012) found that areas which subsided had reduced abundances of all taxa after the earthquake.

Indirect impacts on shellfish may have occurred due to earthquake activity. For example, the remainder of the whitebait season and other commercial fisheries was closed due to water contamination (see Section 3.5.2, Chapter 3). As a result, the beaches were not used by vehicles in as high a numbers as previous years. This change in activity patterns could result in shellfish population surveys not reflecting the actual user impacts that the areas were selected to represent. This is because disturbance was lower and shellfish may have benefited from not having vehicles passing over them.

7.5.3 Future research

Further research is needed to expand on the findings of this thesis to expand on what is known for New Zealand sand beach user impacts. As human populations grow near to coastal boundaries, increased use of the coastal margins may occur so management practitioners must be proactive to avoid environmental degradation. Therefore, research conducted should provide information that is relevant to the area’s present use and likely uses to occur in the future.

Additional research using findings presented in this thesis includes statistically testing models that extrapolate data to get robust predictions of damage occurring to these users. This will allow coastal managers to be assured that their management options are beneficial to the ecosystems which they aim to protect. The application of such models will provide clear outcomes to increase ecological protection as well as saving time for coastal managers. These models should be made as universal as possible so other species and users can be evaluated and compared with one another.

Further research is needed to test vehicles and other heavy impact activities to prevent further damage to intertidal organisms of New Zealand’s sand beaches. Other species of shellfish need to be tested due to their differing dispersal patterns on the beaches. This would include toheroa which is of most concern because of its small population remaining. Organisms, such as polychaetes and sand hoppers, should be evaluated because they are important to the ecosystem as a significant food source. Management methods need to be devised which aim to prevent further ecological damage occurring, and need be evaluated by ongoing monitoring after implementation.

Another key area of research that needs to take place in New Zealand is quantifying the effects of vehicle and horse users on the entire ecosystem. This would not just include shellfish but other fauna that inhabit the intertidal zone of these beaches. Other activities also need to be quantified. This would need to include machinery, such as diggers, that are used in beach maintenance. In light of sea level rise with climate change, practices such as this may become more common in order to stabilise coastal margins. In addition more information is needed on tuatua dispersal within the sediment. As discussed in Chapter 4, other species of clam have been found to move vertically throughout tide cycles. If this is the case for tuatua, they may be less vulnerable to vehicles and horses during certain periods.

As with all disturbance events, the subsequent recovery of the individual and population exposed is important. This could be examined at using biochemical assessments which will be able to provide a clear indication of the significance of the disturbance to surviving individuals. Particular enzymes could be used to indicate stress; these include metabolic enzyme activity, ribonucleic acid to deoxyribonucleic acid ratio (RNA:DNA), or heat shock proteins (Snyder *et al.*, 2001; Dahlhoff, 2004). This would provide a measure of physiological response as opposed to physical response as used in the present methods (see reburial success methods, Chapter 5) which was not easily identifiable.

Coastal areas are highly dynamic environments and it is expected for ecological communities to be influenced by this. Identifying ecological changes that are influenced by abiotic factors could also prove to be an important tool in coastal management. Studies would need to be designed which take a multidisciplinary approach in order to examine these factors. The study presented in Chapter 3 aimed to link beach profiles and total numbers of shellfish as a starting point; however, no significant relationship was found. If such a relationship does exist, it would be more likely to be identified using an intensive sampling regime at a single location. This methodology would identify causes of variability and allow detection of small changes in environment and shellfish abundance.

7.6 Thesis Conclusions

The objectives of this thesis were:

1. To examine the relationship between physical habitat properties and intertidal shellfish distribution and abundance;
2. To experimentally evaluate the effects on shellfish survival of human use of vehicles and horses on sand beaches;
3. To review and evaluate sand beach management policies to minimise potential effects of vehicle and horse users.

The first objective was achieved by characterising the sand beaches of Pegasus Bay to evaluate their suitability as habitat for tuatua. Intertidal shellfish surveys were also conducted over a two year period which identified the density, species and position of shellfish on the intertidal zone of the beach. The beaches of Pegasus Bay were relatively stable and suitable habitat for tuatua. Fine sediment increased as result of earthquake activity; however, the long-term effects of this sediment on tuatua are likely to be negligible. Tuatua exhibited a distinct banding pattern 30 m below the last high tide line and size of individuals changed with seasons. Tuatua densities were variable and changed between the years of sampling. Recruitment occurred over the warmer months and those individuals remain for the year until moving subtidally in the following summer. Overall, tuatua show a high degree of variability in distribution despite the beaches of Pegasus Bay being relatively stable. This finding is important because it demonstrates that despite the stable dynamics of beaches, the biota within these ecosystems can have high variability due to a range of abiotic and biotic factors.

The second objective was achieved by assessing recreational beach activities that may affect intertidal shellfish and evaluating the characteristics which make individuals vulnerable. Experimental testing was then carried out on vehicles and horses which examined the lethal and sublethal effects of these users on shellfish. Prior to this research, the evaluation of horses in a coastal environment had not been evaluated. In addition, the impact of vehicles on *P. donacina* was unknown. Findings indicated that both users have the potential to significantly impact shellfish populations. Sublethal effects were not clearly identified using the methodology: however, summer testing indicated significant stress levels did occur. Overall, heavy beach users are likely to impact infaunal populations especially when tracks penetrate into the sediment within range of biota. Extrapolative modelling indicated a high levels of impacts from different use regimes by vehicle and horse users. Such modelling can be universally translated to other beaches and species and compare the impacts of beach users on other species within the coastal environment.

The final objective was achieved by carrying out a review of available management legislation that pertained to the use of vehicles and horses on sand beaches. It was important to understand how these beach users are controlled in order to evaluate the management options to protect tuatua of Pegasus Bay. Management legislation and literature was analysed and evaluated to provide an indication of the effects of management plans on intertidal ecosystems. Findings highlighted that management authorities have often overlooked intertidal biota when controlling activities and the effects of these may result in less diverse and altered assemblages. Management practitioners are urged to consider all biota and take an ecosystem-based approach to achieve positive ecological outcomes. Furthermore, disregard for biological values of these unique ecosystems will compromise these unique areas for future generations, so management practitioners must design policies which address such issues using a holistic approach.

To conclude, consideration of ecology in sand beach management is often lower in priority compared to hazard reduction and increasing user safety; however, if such considerations are not made we will lose the fauna which make the beaches such a valuable amenity. This thesis has shown that tuatua populations are highly variable and can be influenced by a range of processes, yet this is not unique to this species. Other surfclam species around the world are likely to be influenced by similar processes. These similar species are also vulnerable to heavy recreational users. Three mitigation methods for managing vehicle and horse users in Pegasus Bay could be; reduce the permitted area for heavy recreational activities, put limits on the frequency and types of users permitted, and require users to follow predefined tracks. If such methods were implemented on sand beaches worldwide, intertidal shellfish populations and associated fauna at these locations would benefit.

References

Akroyd, J-A, M., Walshe, K.A.R., & Millar, R.B. (2002) Abundance, distribution, and size structure of toheroa (*Paphies ventricosa*) at Ripiro Beach, Dargaville, Northland, New Zealand. *New Zealand Journal of Marine and Freshwater Research, 36*(*3)*: 547-553.

Allan, J.C., Kirk, R.M., Hemmingsen, M., & Hart, D.E. (1999). Coastal processes in southern Pegasus Bay: A review. Land and Water Studies (International) Ltd. 88 pp. A Report produced for Canterbury regional Council by Land and Water Studies Ltd.

Anders, F.J., & Leatherman, S.P. (1987). Effects of off-road vehicles on coastal foredunes at Fire Island, New York, USA. *Environmental Management, 11(1)*: 45-52.

Ansell, A.D. (1983). The biology of the genus *Donax.* In, *Sandy beaches as ecosystems,* edited by A. McLachlan & T. Erasmus, Junk Publ., The Hague: 607-636.

Armonies, W., & Reise, K. (2000). Faunal diversity across a sandy shore. *Marine Ecology Progress Series, 196*: 49-57.

Armstrong, J.W., Thom, R.M., & Chew, K.K. (1980-81). Impact of a combined sewer overflow on the abundance, distribution and community structure of subtidal benthos. *Marine Environmental Research, 4*: 3-23.

Bailey, R.G. (2005). Identifying ecoregion boundaries. *Environmental Management, 34(1)*: 14–26.

Baird, R.C. (2009). Coastal urbanization: The challenge of management lag. *Management of Environmental Quality, 20(4)*: 371-382.

Beentjes, M.P., Carbines, G.D., & Willsman, A.P. (2006). Effects of beach erosion on abundance and distribution of toheroa (*Paphies ventricosa*) at Bluecliffs Beach, Southland, New Zealand. *New Zealand Journal of Marine and Freshwater Research, 40(3)*: 439-453.

Blake, G.J. (1968).The rivers and the foreshore sediment of Pegasus Bay, South Island, New Zealand. *New Zealand Journal of Geology and Geophysics, 11(1)*: 225-235.

Boening, D.W. (1999).An evaluation of bivalves as biomonitors of heavy metals pollution in marine waters. *Environmental Monitoring and Assessment, 55*: 45-470.

Born, S.M., & Sonzogni, W.C. (1995) Integrated environmental management: strengthening the conceptualization. *Environmental Management, 19(2)*: 167-181.

Boulding, E. G. (1984). Crab-resistant features of shells of burrowing bivalves: decreasing vulnerability by increasing handling time. *Journal of Experimental Marine Biology and Ecology, 76*(3): 201-223.

Bradshaw, M., & Soons, J. (2008). The lie of the land. In Winterbourn, M., Knox, G.A., Burrows, C., & Marsden, I.D. (Eds.), *The Natural History of Canterbury* (3rd ed., pp. 13-36). Christchurch: Canterbury University Press.

Brodhead, J.M., & Godfrey, P.J. (1977). Off road vehicle impact in Cape Cod National Seashore: Disruption and recovery of dune vegetation. *International Journal of Biometeorology*: *21(3)*: 299-306.

Brown, L. J., Wilson, D. D., Moar, N. T., & Mildenhall, D. C. (1988). Stratigraphy of the late Quaternary deposits of the northern Canterbury Plains, New Zealand. *New Zealand Journal of Geology and Geophysics, 31(3)*: 305-335.

Bryan, K.R., Kench, P.S., & Hart, D.E. (2008). Multi-decadal coastal change in New Zealand: Evidence, mechanisms and implications. *New Zealand Geographer, 64*: 117-128.

Buick, A.M. & Paton, D.C. (1989). Impact of off-road vehicles on the nesting success of Hooded Plovers *Charadrius rubricollis* in the Coorong region of South Australia. *Emu,* 89: 159-172.

Bulleri, F. (2005). Comment: The introduction of artificial structures on marine soft- and hard-bottoms: ecological implications of epibiota. *Environmental Conservation, 32 (2)*: 101-102.

Buonaccorsi, J.P., Elkinton, J., Koenig, W., Duncan, R.P., Kelly, D., & Sork, V. (2003). Measuring mast seeding behaviour: relationships among population variation, individual variation and synchrony. *Journal of Theoretical Biology, 224:* 107-114.

Burger, J. (2000) Consumption advisories and compliance: the fishing public and deamplification of risk. *Journal of Environmental Planning and Management, 43(4)*: 471-488.

Burton, I., Kates, R.W., & White, G.F. (1978). *The Environment as Hazard.* Oxford University Press. New York, U.S.A.

Carter, R.W.G. (1988). *Coastal Environments*. Academic Press Ltd., London, England.

Cassie, R. M. (1951). A molluscan population with an unusual size frequency-distribution. *Nature, 167*(*42*): 284-285.

Christchurch City Council (2010) Brooklands Lagoon Master Plan. 146 pp.

Christchurch City Council (2011) retrieved 01/05/2012 from: http://resources.ccc.govt.nz/files/FactsheetBrooklands-popularparks.pdf

Christchurch City Council (2012) retrieved 28/07/2012 from: http://resources.ccc.govt.nz/files/FactsheetTheCoast-christchurchbeaches.pdf

Christchurch City Council (n.d.) retrieved 24/01/2010 from http://www.ccc.govt.nz/cityleisure/projectstoimprovechristchurch/wastewater/oceanoutfall/abouttheproject/index.aspx

Clynick, B.G. (2008). Characteristics of an urban fish assemblage: distribution of fish associated with coastal marinas. *Marine Environmental Research, 65*: 18-33.

Coffen-Smout, S.S. (1998) Shell strength in the cockle *Cerastoderma edule* L. under simulated fishing impacts. *Fisheries Research, 38*: 187-191.

Cole, R.G., Hull, P.J., & Healy, T.R. (2000). Assemblage structure, spatial patterns, recruitment, and post-settlement mortality of subtidal bivalve molluscs in a large harbor in north-eastern New Zealand. *New Zealand Journal of Marine and Freshwater Research, 34*(*2*): 317-329.

Compton, T.J., Troost, T.A., Drent, J., Kraan, C., Bocher, P., Leyrer, J., Dekinga, A., & Piersma, T. (2009). Repeatable sediment associations of burrowing bivalves across six European tidal flat systems. *Marine Ecology Progress Series, 382*: 87-98.

Compton, T.J., Troost, T.A., van der Meer, J., Kraan, C., Honkoop, P.J.C., Rogers, D.I., Pearson, G.B., de Goeij, P., Bocher, P., Lavaleye, M.S.S., Leyrer, J., Yates, M.G., Dekinga, & Piersma, T. (2008). Distributional overlap rather than habitat differentiation characterizes co-occurrence of bivalves in intertidal soft sediment systems. *Marine Ecology Progress Series, 373:* 25-35.

Connell, S.D. (2001). Urban structures as marine habitats: an experimental comparison of the composition and abundance of subtidal epibiota among pilings, pontoons and rocky reefs. *Marine Environmental Research, 52*: 115-125.

Costil, K., Royer, J., Ropert, M., Soletchnik, P., & Mathieu, M. (2005). Spatio-temporal variations in biological performances and summer mortality of the pacific oyster *Crassostrea gigas* in Normandy (France). *Helgoland Marine Research, 59(4)*: 286-300.

Cranfield, H.J., Michael, K.P., & Dunn, A. (2002). The distribution, abundance, and size of tuatua (*Paphies donacina*) on New Brighton Beach, Christchurch, in 2001. *New Zealand Fisheries Assessment Report 2002/5,* 24 pp.

Cranfield, H.J., Michael, K.P., & Stotter, D.R. (1993). Estimates of growth, mortality, and yield per recruit for New Zealand surf clams. *New Zeal*and *Fisheries Research Assessment Document 1993(20)*. 26 pp.

Cranfield, H.J., Michael, K.P., & Francis, R.I.C.C. (1996). Growth rates of five species of subtidal clam on a beach in the South Island, New Zealand**.** *Marine and Freshwater Research, 47(6)*: 773-784.

Crevier-Denoix, N., Robin, D., Pourcelot, P., Falala, S., Holden, L., Estoup, P., Desquilbet, L., Denoix, J.M., & Chateu, H. (2010). Ground reaction force and kinematic analysis of limb loading on two different beach sand tracks in harness trotters. *Equine Veterinary Journal, 42(38)*: 544-551.

Cubit, S. (1990). Horse riding in national parks: some critical issues. *Australian Parks and Recreation, 26(1)*: 24-25.

Dahlhoff, E.P. (2004) Biochemical indicators of stress and metabolism: applications for marine and ecological studies. *Annual Review of Physiology, 66*: 183-207.

Dame, R.F. (1993). *Bivalve filter feeders in estuarine* and *coastal ecosystem processes*. NATO ASI series, Vol. G 33. Springer-Verlag. Berlin Heidelberg, Germany.

Dame, R.F. (2012). *Ecology of marine bivalves*: *an ecosystem approach* (2nd Ed.). CRC Press: Taylor and Francis Group: Florida, U.S.A. 272 pp.

Daskalov, G. M. (2002). Overfishing drives atrophic cascade in the black sea. *Marine Ecology Progress Series, 225*, 53-63.

Davenport, J., & Macalister, H. (1996). Environmental conditions and physiological tolerances of intertidal fauna in relation to shore zonation at Husvik, South Georgia. *Journal of the Marine Biological Association of the United Kingdom*, *76*: 985-1002.

Davis, C.V., Scully, K.C., & Shumway, S.E. (1997). Juvenile and yearling growth of Atlantic surfclams *Spisula solidissima* (Dillwyn, 1817) in Maine. *Journal of Shellfish Research, 16(1)*: 161-168.

Dawson, E.W. (1954). Studies in the biology of *Amphidesma* in an inter-tidal mollusc of the sea shore, with particular reference to certain aspects of population distribution fluctuation and taxonomy. M.Sc. thesis, University of Canterbury, Christrchurch. 222 pp.

de Goeij, P., & Honkoop, P.J.C. (2002). The effect of immersion time on burying depth of the bivalve *Macoma balthica* (Tellinidae). *Journal of Sea Research, 47*: 109-119.

de la Ossa Carrtero, J.A., del Pilar Ruso, Y., Giménez Casalduero, F., & Sánchez Lizaso, J.L. (2008). Effect of sewage discharge on *Spisula subtruncata* (da Costa 1778) populations. *Arch Environ Contam Toxicol, 54*: 226-235.

Defeo, O., McLachlan, A., Schoeman, D.S., Schlacher, T.A., Dugan, J., Jones, A., Lastra, M., & Scapini, F. (2009). Threats to sandy beach ecosystems: A review. *Estuarine, Coastal and Shelf Science, 81*: 1-2.

Department of Conservation (2011): Viewed 21/10/2011 http://www.doc.govt.nz/conservation/native-animals/birds/sea-and-shore-birds/nz-fairy-tern-tara-iti/facts/

Department of Environmental Affairs and Tourism. (2004). Guidelines on the implementation of regulations pertaining to the control of vehicles in the coastal zone. *Government Gazette, No. 27066*; 23 pp.

Dernie, K.M., Kaiser, M.J., & Warwick, R.M. (2003). Recovery of benthic communities following physical disturbance. *Journal of Animal Ecology, 72*: 1043-1056.

Dexter, D.M. (1992). Sandy beach community structure: The role of exposure and latitude. *Journal of Biogeography, 19(1)*: 59-66.

Dolbeth, M., Ferreira, O., Teixeira, H., Marques, J.C., Dias, J.A., & Pardal, M.A. (2007). Beach morphodynamic impact on a macrobenthic community along a subtidal depth gradient. *Marine Ecology Progress Series, 352*: 11-124.

Donn, T.E. (1990). Zonation patterns of *Donax serra* Röding (Bivalvia: Donacidae) in Southern Africa. *Journal of Coastal Research, 6(4)*: 903-911.

Dugan, J.E., Hubbard, D.M., & Lastra, M. (2000). Burrowing abilities and swash behaviour of three crabs, *Emerita analoga* Stimpson, *Blepharipoda occidentalis* Randall, and *Lepidopa californica* Efford (Anomura Hippoidea), of exposed sandy beaches. *Journal of Experimental Marine Biology* and *Ecology, 255*: 229-245.

Duns, R.A. (1995). Sediment budget analysis of Pegasus Bay. M. A. thesis. University of Canterbury, Christchurch. 165 pp.

Environment Canterbury (n.d.). Retrieved January 26, 2013, from http://ecan.govt.nz/services/online-services/monitoring/Pages/water-contamination-christchurch-post-22-feb-2011-earthquake.aspx

Environment Canterbury (n.d.). Retrieved March 21, 2012, from http://ecan.govt.nz/publications/General/water-monitoring-results-post-eq.pdf

Ellers, O. (1995). Behavioral control of swash-riding in the clam *Donax variabilis*. *Biological Bulletin, 189* (*2):* 120-127.

Fantasia Adventure Holidays (2012), retrieved 5/11/2012 from: http://www.fantasiaadventureholidays.com/riding.htm

FAO (2007). FAO Yearbook. Fisheries and Aquaculture statistics.

Ferns, P.N., Rostron, D.M., & Siman, H.Y. (2000). Effects of mechanical cockle harvesting on intertidal communities. *Journal of Applied Ecology, 37*: 464-474.

Floerl, O., Inglis, G.J., Dey, K., & Smith, A. (2009). The importance of transport hubs in stepping-stone invasions. *Journal of Applied Ecology¸ 46*: 37-45.

Forsyth, P.J., Barrell, D.J.A., & Jongens, R. (compilers). (2008). Geology of the Christchurch area. Institute of Geological & Nuclear Sciences 1:250 000 geological map 16, Lower Hutt, New Zealand. *GNS Science*. 67 pp.

Foster-Smith, J., Birchenough, A.C., Evans, S.M., & Prince, J. (2007). Human impacts on Cable Beach, Broome (Western Australia). *Coastal Management, 35 (2-3)*: 181-194.

Freites, L., Cordova, C., Arrieche, D., Montero, L., García, N., & Himmelman, J.H. (2010). Reproductive cycle of the penshell A*trina seminuda* (mollusca: Bivalvia) in northern waters of Venezuela. *Bulletin of Marine Science, 86(4)*: 785-801.

Fylde Borough Council (2011)- Viewed 21/06/2011 www.ribblecoastandwetlands.com/horseriding

Gabites, B. (2006). A summary of monitoring and investigations on the Pegasus Bay coastline, 1998-2005. ECan U06/43, 100 pp.

Garden, G.M. (1998). Instrumentation for mussel (Perna canaliculus) shell strength measurements. *Computers and Electronics in Agriculture, 19*: 311-315.

Geonet (2012). Retrieved April 5, 2012 from: http://www.geonet.org.nz/canterbury-quakes/significant.html

Goff, J.R., Nichol, S.L., & Rousse, H.L. (2003).*The New Zeal*and *coast*: *Te Tai O Aotearoa*. Dunmore Press and Whitireia Publishing with Daphne Brasell Associates Ltd: Palmerston North, New Zealand.

Gosling, E. (2003). *Bivalve molluscs: biology, ecology and culture*. Fishing New Books, Blackwell Publishing, Oxford, England.

Gosselin, L.A., & Qian, P.Y. (1997). Juvenile mortality in benthic marine invertebrates. *Marine Ecology Progress Series, 146*: 265-282.

Grant, C.M., & Creese, R.G. (1995). The reproductive cycle of the tuatua- *Paphies subtriangulata* (Wood, 1828), in New Zealand. *Journal of Shellfish Research, 14*: 287-292.

Grefsrud, E.S., & Strand, O. (2006). Comparison of shell strength in wild and cultured scallops (*Pectin maximus*). *Aquaculture, 251*: 306-313.

Gregory, D. (2008). “There is a tide”: An examination of the evolution of New Zealand coastal policy statements. *New Zealand Geographer, 64*: 144-153.

Griffiths, G.A., & Glasby, G.P. (1985). Input of river derived sediment to the New Zealand continental shelf. I. Mass. *Estuarine, Coastal and Shelf Sciences, 21*: 773–87.

Haag, W. R., & Staton, J. L. (2003). Variation in fecundity and other reproductive traits in freshwater mussels. *Freshwater Biology, 48*(*12*): 2118-2130.

Hall, C.M. (2001) Trends in ocean and coastal tourism: the end of the last frontier? *Ocean & Coastal Management, 44*: 601-618.

Halpern, B.S., & Warner, R.R. (2003). Matching marine reserve design to reserve objectives. *Proceedings of the Royal Society B, 270*: 1871-1878.

Hammond, A. (1992). *World Resources 1992–1993*: *Towards Sustainable Development*. Oxford University Press, Oxford.

Hamner, W.M. (1978). Intraspecific competition in *Tridacna crocea*, a burrowing bivalve. *Oecologia, 34*: 267-281.

Hart, D.E., Marsden, I.D.M., & Francis, M. (2008). Coastal Systems. In Winterbourne M, Knox G.A., Burrows C, & Marsden I.D., eds, *The Natural History of Canterbury* (3rd ed., Pp. 653-684), Canterbury University Press, Christchurch.

Hayward, B.W., Stephenson, A.B, Morley, M., Riley, J.L., & Grenfell, H.R. (1997). Faunal changes in Waitemata Harbour sediments, 1930s-1990s. *Journal of the Royal Society of New Zealand, 27(1)*: 1-20.

Heathershaw, A.D., Carr, A.P., Blackley, M.W. L., & Wooldridge, C.F. (1981) Tidal variations in the compaction of beach sediments. *Marine Geology, 41(3-4)*: 223-238.

Hentrich, S., & Salomon, M. (2006). Flexible management of fishing rights and a sustainable fisheries industry in Europe. *Marine Policy, 30*: 712-720.

Hesp, P.A., Shepherd, M.J., & Parnell, K. (1999). Coastal geomorphology in New Zealand, 1989-99. *Progress in Physical Geography, 23(4)*: 501-524.

Holmstrup, M., Bindesbol, A., Oostingh, G.J., Duschl, A., Scheil, V., Köhler, H., Loureiro, S., Soares, A.M.V.M., Ferreira, A.L.G., Bayley, M., Svendsen, C., & Spurgeon, D.J. (2010). Interactions between effects of environmental chemicals and natural stressors: a review. *Science of the Total Environment, 408*: 3746-3762.

Hosier, P.E., & Eaton, T.E. (1980). The impact of vehicles on dune and grassland vegetation on a south-eastern North Carolina barrier beach. *Journal of Applied Ecology, 17*: 173-182.

Hosier, P.E., Kochhar, M., & Thayer, V. (1981). Off-road vehicle and pedestrian track effects on the sea-approach of hatchling loggerhead turtles. *Environmental Conservation, 8(1*): 158-161.

Hughes, R.N. (1980). Optimal foraging theory in the marine context. *Oceanography and Marine Biology: an Annual Review, 18*: 323-481.

Hull, P.J., Cole, R.G., Creese, R.G., & Healy, T.R. (1998). An experimental investigation of the burrowing behaviour of *Paphies australis* (bivalvia: Mesodesmatidae). *Marine* and *Freshwater Behaviour and Physiology, 31(3)*: 167-183.

Hutchings, P. (1998). Biodiversity and functioning of polychaetes in benthic sediments. *Biodiversity and Conservation, 7(9)*: 1133-1145.

Ipswich Coucil, 2011: Viewed 05/07/2011 http://www.town.ipswich.ma.us/index.php?option=com_contentandview=articleandid=250:policies-for-horses-on-crane-beachandcatid=63:collectortreasureranditemid=93

James, R.J. (1999). Cusps and pipis on a sandy ocean beach in New South Wales. *Australian Journal of Ecology, 24*: 587-592.

James, R.J. (2000). From beaches to beach environments: Linking the ecology, human-use and management of beaches in Australia. *Ocean and Coastal Management, 43*: 495-514.

James, R.J., & Fairweather, P.G. (1996). Spatial variation of intertidal macrofauna on a sandy ocean beach in Australia. *Estuarine, Coastal and Shelf Science, 43*: 81-107.

Jaramillo, E., Dugan, J.E., Hubbard, D.M., Melnick, D., Manzano, M., Duate, C., Campos, C., & Sanchez, R. (2012). Ecological implications of extreme events: footprints of the 2010 earthquake along the Chilean coast. *PLoS ONE, 7(5)*: e35348, doi: 10.1371/journal.pone.0035348.

Kingett Mitchell Limited. (2003). Fisheries resources of inshore Pegasus Bay. Report for URS. 28 pp.

Kingett Mitchell Limited. (2003). Water quality in inshore Pegasus Bay, Pg 1.

Kinlan, B.P., & Gaines, S.D. (2003) Propagule dispersal in marine and terrestrial environments: a community perspective. *Ecology, 84(8)*: 2007-2020.

Knox, G.A. (2001). *The Ecology of Seashores*. CRC Press LLC. Washington DC, U.S.A.

Komar, P.D. (1997). *Beach Processes and Sedimentation*, 2nd Ed. Prentice Hall.

Lacoste, A., Malham, S.K., Gélébart, F., Cueff, A., & Poulet, S.A. (2002). Stress-induced immune changes in the oyster *Crassostrea gigas*. *Developmental and Comparative Immunology, 26*: 1-9.

Le Hir, M., & Hily, C. (2005). Macrofaunal diversity and habitat structure in intertidal boulder fields. *Biology and Conservation, 14*: 233-250.

Lester, S.E., Halpern, B.S., Gororud-Colvert, K., Lubchenco, J., Ruttenberg, B.I., Gaines, S.D., Airamé, S., & Warner, R.R. (2009) Biological effects within no-take marine reserves: a global synthesis. *Marine Ecology Progress Series, 384*: 33-46.

Liddle, M.J. (1991). Recreation ecology: effects of trampling on plants and corals. *Trends in Ecology and Evolution, 6(1)*: 13-17.

Lohrer, A. M., Hewitt, J. E., & Thrush, S. F. (2006). Assessing far-field effects of terrigenous sediment loading in the coastal marine environment. *Marine Ecology Progress Series, 315*: 13-18.

Lord, A., Waas, J.R., Innes, J., & Whittingham, M.J. (2001). Effects of human approaches to nests of northern New Zealand dotterels. *Biological Conservation, 98*: 233-240.

Loreau, M., Naeem, S., Inchausti, P., Bengtsson, J., Grime, J.P., Hector, A., Hooper, D.U., Huston, M.A., Raffaelli, D., Schmid, B., Tilman, D., & Wardle, D.A. (2001). Biodiversity and ecosystem functioning: Current knowledge and future challenges. *Science, 294*: 804-808.

Luckenbach, R.A., & Bury, R.B. (1983). Effects of off-road vehicles on the biota of the Algodones Dunes, Imperial County, California. *Journal of Applied Ecology, 20(1)*: 265-286.

Lucrezi, S., & Schlacher, T. (2010). Impacts of Off-Road Vehicles (ORVs) on burrow architecture of Ghost Crabs (Genus *Ocypode*) on sandy beaches. *Environmental Management, 45*: 1352-1362.

Lyver, P. O. (2005). Co-managing environmental research: Lessons from two cross-cultural research partnerships in New Zealand. *Environmental Conservation, 32*(*4*): 365-370.

Maguire, J.A., Coleman, A., Jenkins, S., & Burnell, G.M. (2002). Effects of dredging on undersized scallops. *Fisheries Research, 56*: 155-165.

Marion, B., Bonis, A., & Bouzillé, J.-B. (2010). How much does grazing induced heterogeneity impact plant diversity in wet grasslands? *Eroscience, 17(3)*: 229-239.

Marsden, I.D. (1999a). Reproductive cycles of the surf beach clam *Paphies donacina* (Spengler, 1793) from New Zealand. *Journal of Shellfish Research, 18(2)*: 539-546.

Marsden, I.D. (1999b). Respiration and feeding of the surf clam *Paphies donacina* from New Zealand. *Hydrobiologia, 405*: 199-188.

Marsden, I.D. (2002). Recruitment in the swash zone - Temporal variations in juvenile recruitment of an exposed sand beach surf clam. *Hydrobioligia, 477*: 47-57.

Marsden, I.D. (2010). Assessment of intertidal tuatua on Pegasus Bay surf beaches. *University of Canterbury: Estuarine Research Report 39*. University of Canterbury, New Zealand. 36 pp.

Marsden, I.D., & Taylor, G.F. (2010). Impacts of vehicles on juvenile tuatua, *Paphies donacina*, on Pegasus Bay surf beaches. *Estuarine Research Report 38,* University of Canterbury, New Zealand. 28 pp.

Mclachlan, A. (1990). Dissipative beaches and macrofauna communities on exposed intertidal sands. *Journal of Coastal Research, 6*(*1)*: 57-71.

McLachlan, A. (1996). Physical factors in benthic ecology: effects of changing sand particle sine on beach fauna. *Marine Ecology Progress Series, 121*: 205-217.

McLachlan, A., & Dorvlo, A. (2005). Global patterns in sandy beach macrobenthic communities. *Journal of Coastal Research, 21(4)*: 674-687.

McLachlan, A., & Erasmus, T. (1983). Developments in hydrobiology: Sandy beaches as ecosystems (19). Dr W. Junk Publishers. The Hague, Netherlands.

McLachlan, A., Dugan, J.E., Defeo, O., Ansell, A.D., Hubbard, D.M., Jaramillo, E. & Penchaszadeh, P.E. (1996). Beach clam fisheries. *Oceanography and Marine Biology an Annual Review, 34*: 163–232.

McLachlan, A., Jaramillo, E., Defeo, O., Dugan, J., de Ruyck, A, & Coetzee, P. (1995). Adaptations of bivalves to different beach types. *Journal of Experimental Marine Biology and Ecology, 187*: 147-160.

MFE (Ministry for the Environment), 2012; Viewed 13/01/2012 http://www.mfe.govt.nz/publications/rma/everyday/overview/

Micallef, A., & Williams, A.T. (2002). Theoretical strategy considerations for beach management. *Ocean and Coastal Management, 45*: 261-275.

Miller, B. (2011). Numerical modelling and field trials for the Christchurch ocean outfall. *International Symposium on Outfall Systems, May 15-18, Mar del Plata, Argentina.* 9 pp.

Minchin D (1992) Induced spawning of the scallop, *Pecten maximus*, in the sea. *Aquaculture, 1*: 187–190.

Ministry of Fisheries (2011): retrieved 03/10/2011 from: http://www.fish.govt.nz/en-nz/Recreational/Most+Popular+Species/Fish+Identification/S+-+Z/Toheroa.htm?wbc_purpose=Basic&WBCMODE=PresentationUnpublished+++++++&MSHiC=65001&L=10&W=toheroa%20&Pre=%3Cspan%20class%3d'SearchHighlight'%3E&Post=%3C/span%3E

Ministry of Fisheries (2012). Retrieved 27/03/2012 from: http://www.fish.govt.nz/en-nz/Recreational/Most+Popular+Species/Fish+Identification/S+-+Z/Toheroa.htm?wbc_purpose=Basic&WBCMODE=PresentationUnpublished+++++++&MSHiC=65001&L=10&W=toheroa%20&Pre=%3Cspan%20class%3d'SearchHighlight'%3E&Post=%3C/span%3E

Moffett, M.D., McLachlan, A., Winter, P.E.D., & D Ruyck, A.M.C. (1998). Impact of trampling on sandy beach macrofauna. *Journal of Coastal Conservation, 4*: 87-90.

Moller J.S., Moller S.I., Futter J.M., Moller J.A., Harvey J.P., White H.A., Stirling F.F., & Moller H. (2009). Potential impacts of vehicle traffic on recruitment of Toheroa (*Paphies ventricosa*) on Oreti Beach, Southland, New Zealand. *He Kōhinga Rangahau* No. 5. 61 pp.

Morrison, M.A., Lowe, M.L., Parsons, D.M., Usmar, N.R., & McLeod, I.M. (2009). A review of land-based effects on coastal fisheries and supporting biodiversity in New Zealand. *New Zealand Aquatic Environment and Biodiversity Report No. 37.* 100 pp.

Morton, J.E., & Miller, M.C. (1973). *The New Zealand Seashore (2nd Ed.).* Glasgow, Great Britain: William Collins Sons and Co. Ltd. 652 pp.

Moss, D., & Mcphee, D.P. (2006). The impacts of recreational four-wheel driving on the abundance of the ghost crab (*Ocypode cordimanus*) on a subtropical sandy beach in SE Queensland. *Coastal Management, 34*: 133-140.

Mozambique Horse Safari (2011). - retrieved 21/06/2011 from: www.mozambiquehorsesafari.com

Murray-Jones, S.E., & Ayre, D.J. (1997). High levels of gene flow in the surf bivalve *Donax deltoides* (bivalvia: Donacidae) on the east coast of Australia. *Marine Biology, 128 (1)*: 83-89.

Nagarajan, R., Lea, S.E.G., Goss-Custard, J.D. (2006). Seasonal variations in mussel, *Mytilus edulis* L. shell thickness and strength and their ecological implications. *Journal of Experimental Marine Biology and Ecology, 339*: 241-250.

Nakamura, Y., Nakano, T., Yurimoto, T., Maeno, Y., Koizumi, T., & Tamaki, A. (2010). Reproductive cycle of the venerid clam *Meretrix lusoria* in Ariake Sound and Tokyo Bay, Japan. *Fisheries Science, 76*(*6*), 931-941.

National Park Service (2011). retrieved 5/07/2011 from: http://www.nps.gov/caco/cape-cod-national-seashore-oversand-beach-driving.htm

Nel, R., McLachlan, A., & Winter, D.P.E. (2001). The effect of grain size on the burrowing of two *Donax* species. *Journal of Experimental Marine Biology and Ecology, 265*: 219-238.

New Jersey Department of Environmental Protection (2011). - retrieved 21/06/2011 from: www.state.nj.us/dep/parksandforrests/parks/island.html

New Zealand Racing Board (2010). Size and scope of the New Zealand racing industry. 65 pp.

Nicholls, R.J., & Mimura, N. (1998). Regional issues raised by sea-level rise and their policy implications. *Cimate Research, 11*: 5-18.

Nicholson, E., Mace, G.M., Armsworth, P.R., Atkinson, G., Buckle, S., Clements, T., Ewers, R.M., Fa, J.E., Gardner, T.A., Gibbons, J, Grenyer, R., Metcalfe, R., Mourato, S., Muûls, M., Osborn, D., Reuman, D.C., Watson, C., & Milner-Gulland, E.J. (2009). Priority research areas for ecosystem services in a changing world. *Journal of Applied Ecology, 46*: 1139-1144.

NIWA (2011a). Retrieved 21/03/2012, from: http://www.niwa.co.nz/climate/summaries/seasonal/summer-2010-11

NIWA (2012). Retrieved 21/03/2012, from: http://www.niwa.co.nz/summer-2011-12

NIWA, (2011b). *Coastal Explorer*, Viewed 15/09/2011: http://wrenz.niwa.co.nz/webmodel/coastal

Nolan, T.J., Kirk, R.M., & Shulmeister, J. (1999). Beach cusp morphology on sand and mixed sand and gravel beaches, South Island, New Zealand. *Marine Geology, 157*: 185-198.

Norkko, A., Cummings, V.J., Thrush, S.E., Hewitt, J.E., & Hume, T. (2001). Local dispersal of juvenile bivalves: implications for sandflat ecology. *Marine Ecology Progress Series, 212*: 131-144.

Norkko, A., Hewitt, J.E., Thrush, S.F., & Funnell, G.A. (2006). Conditional outcomes of facilitation by a habitat-modifying subtidal bivalve. *Ecology, 87(1)*: 226-234.

Nybakken, J.W., & Bertness, M.D. (2005). Marine biology: an ecological approach (6th Ed). Benjamin Cummings: San Francisco, USA.

O’Connor, M.I., Bruno, J.F., Gaines, S.D., Halpern, B.S., Lester, S.E., Kinlan, B.P., & Weiss, J.M. (2007). Temperature control of larval dispersal and the implications for marine ecology, evolution, and conservation. *Preceedings of the National Academy of Sciences, 104 (4)*: 1266-1271.

Onitsuka, T., Kawamura, T., Horii, T., Takiguchi, N., Takami, H., & Watanabe, Y. (2007). Synchronized spawning of abalone *Haliotis diversicolor* triggered by typhoon events in Sagami Bay, Japan. *Marine Ecology Progress Series, 351*: 129-138.

Ostermann-Kelm, S.D., Atwill, E.A., Rubin, E.S., Hendrickson, L.E., & Boyce, W.M. (2009). Impacts of feral horses on a desert environment. *BMC Ecology, 9(22)*: 1-10.

Peterson, C.H., Bishop, M.J., Johnson, G.A., D'Anna, L.M., & Manning, L.M. (2006). Exploiting beach filling as an unaffordable experiment: Benthic intertidal impacts propagating upwards to shorebirds. *Journal of Experimental Biology and Ecology,* 338: 205-221.

Peterson, G., Allen, C.R., & Holling, C.S. (1998) Ecological resilience, biodiversity, and scale. *Ecosystems, 1*: 6-18.

Pethick. (1984). *An introduction to coastal geomorphology*. Edward Arnold; London, England.

Pfister, C.A. (2007). Intertidal invertebrates locally enhance primary production. *Ecology, 88(7)*: 1637-1653.

Phillips, M.R., & House, C. (2009). An evaluation of priorities for beach tourism: Case studies from South Wales, Uk. *Tourism Management*: *30*: *176-183.*

Piersma, T., Koolhas, A., Dekinga, A., Beukema, J.J., Dekker, R., & Essink. K. (2001) Long-term indirect effects of mechanical cockle-dredging on intertidal bivalve stocks in the wadden sea. *Journal of Applied Ecology, 38(5)*: 976-990.

Pikering, C.M., Hill, W., Newsome, D., & Leung, Y. (2010). Comparing hiking, mountain biking and horse riding impacts on vegetation and soils in Australia and the United States of America. *Journal of Environmental Management, 91*: 551-562.

Porirua City Council (2011), retrieved 8/09/2011 from: http://www.pcc.govt.nz/Publications/Bylaws

Priskin, J. (2003). Physical impacts of four-wheel drive related tourism and recreation in a semi-arid, natural coastal environment. *Ocean and Coastal Management, 46*: 127-155.

Priskin, J. (2003). Tourist perceptions of degradation caused by coastal nature-based recreation. *Environmental Management, 32*: 189-204.

Rees, G., Pond, K., Kay, D., Bartram, J., & Santo Domingo, J. (2010). *World Health Organization*: *Safe management of shellfish and harvest waters*. IWA Publishing. London, United Kingdom.

Reopanichkul, P., Schlacher, T.A., Carter, R.W., & Worachananant, S. (2009). Sewage impacts coral reefs at multiple levels of ecological organization. *Marine Pollution Bulletin, 58(9)*: 1356-1362.

Reynolds-Fleming, J.V. & Fleming, J.G.(2005). Coastal circulation within the Banks Peninsula region, New Zealand. *New Zealand Journal of Marine and Freshwater Research, 39(1)*: 217-225.

Richardson, J.R., Aldridge, A.E., & Smith, P.J. (1982). Analyses of tuatua populations- *Paphies subtriangulata* and *P. donacina*. *New Zealand Journal of Zoology, 9*(*2)*: 231-237.

Roberts, D., Rittschof, D., Gerhart, D.J., Schmidt, A.R., & Hill, L.G. (1989). Vertical migration of the clam *Mercenaria mercenaria* (L.) (Mollusca: Bivalvia): environmental correlates and ecological significance. *Journal of Experimental Marine Biology and Ecology, (126)*: 271-280.

Rubin, C.T., & Lanyon, L.E. (1982). Limb mechanics as a function of speed and gait: a study of functional strains in the radius and tibia of horse and dog. *Journal of Experiment Biology, 101*: 187-211.

Sassa, S., Watabe, Y., Yang, S., & Kuwae, T. (2011). Burrowing criteria and burrowing mode adjustment in bivalves to varying geoenvironmental conditions in intertidal flats and beaches. *PLoS ONE 6(9)*: e25041. doi:10.1371/journal.pone.0025041

Schlacher, T.A., & Lucrezi, S. (2010). Compression of home ranges in ghost crabs on sandy beaches impacted by vehicle traffic. *Marine Biology, 157*: 2467-2474.

Schlacher, T.A., & Thompson, L.M.C. (2007). Exposure of fauna to off-road vehicle (ORV) traffic on sandy beaches. *Coastal Management, 35(5)*: 567-583.

Schlacher, T.A., Dugan, J., Schoeman, D.S., Lastra, M., Jones, A., Scapini, F., McLachlan, A., Defeo, O. (2007). Sandy beaches at the brink. *Diversity and Distributions, 13*: 556-560.

Schlacher, T.A., Richardson, D., & McLean, I. (2008a). Impacts of off-road vehicles (ORVs) on macrobenthic assemblages on sandy Beaches. *Environmental Management, 41*: 878-892.

Schlacher, T.A., Thompson, L., & Price, S. (2007). Vehicle versus conservation of invertebrates on sandy beaches: mortalities inflicted by off-road vehicles on ghost crabs. *Marine Ecology, 28*: 354-367.

Schlacher, T.A., Thompson, L.M.C., & Walker, S.J. (2008b). Mortalities caused by off-road vehicles (ORVs) to a key member of sandy beach assemblages, the surf clam *Donax deltoids. Hydrobiologia, 610*: 345-350.

Schoeman, D.S., & Richardson, A.J. (2002). Investigating biotic and abiotic factors affecting the recruitment of an intertidal clam on an exposed sandy beach using a generalized additive model. *Journal of Experimental Marine Biology and Ecology, 276*: 67-81.

Seike, K. (2008). Burrowing behaviour inferred from feeding traces of the opheliid polychaete Euzonus sp. as response to beach morphodynamics. *Marine Biology, 153(6)*: 1199-1206.

Sheppard, N., Pitt, K.A., & Schlacher, T.A. (2009). Sub-lethal effects of off-road vehicles (ORVs) on surf clams on sandy beaches. *Journal of Experimental Marine Biology and Ecology, 380*: 113-118.

Shluter, D. (2001). Ecology and the origin of species. *Trends in Ecology and Evolution, 16(7)*: 372-380.

Short, A.D. (1999). Wave dominated beaches, Chp 7; *Handbook of Beach and Shoreface Morphodynamics*. John Wiley and Sons Ltd.

Shulmeister, J. & Kirk, R.M. (1993). Evolution of a mixed sand and gravel barrier system in North Canterbury, New Zealand, during Holocene sea-level rise and still-stand. *Sedimentary Geology, 87*: 215-235.

Shulmeister, J., & Kirk, R.M. (1997). Holocene fluvial- coastal interaction on a mixed sand and sand and gravel beach system, North Canterbury, New Zealand. *Cantena, 30*: 337-355.

Smith, L.D., & Jennings, J.A. (2000). Induced defensive responses by the bivalve *Mytilus edulis* to predators with different attack modes. *Marine Biology, 136*: 461-469.

Smith, S. D. A. (1997). The effects of domestic sewage effluent on marine communities at Coffs Harbour, New South Wales, Australia. *Marine Pollution Bulletin, 33*(*7-12*): 309-316.

Snyder, M.J., Girvetz, E., & Mulder, E.P. (2001) Induction of marine mollusc stress proteins by chemical or physical stress. *Archives of Environmental Contamination and Toxicology, 41*: 22-29.

Soons, J.M. (1994). Changes in geomorphic environments in Canterbury during the Aranuian. *New Zealand Journal of Botany, 32(3)*: 365-372.

Sorensen, J. (1993). The international proliferation of Integrated Coastal Zone Management efforts. *Ocean and Coastal Management, 21*: 45-80.

Speybroeck, J., Bronte, D., Courtens, W., Gheskiere, T., Grootaert, P., Maelfait, J., Mathys, M., Provoost, S., Sabbe, K., Stienen, E.W.M., Van Lancker, V., Vincx, M., & Degraer, S. (2006). Beach nourishment: an ecologically sound coastal defence alternative? A review. *Aquatic Conservation*: *Marine and Freshwater Ecosystems, 16*: 419-435.

Statistics New Zealand (2011), retrieved 05/12/2011 from: http://www.stats.govt.nz/browse_for_stats/population/Migration/internal-migration/are-nzs-living-closer-to-coast.aspx

Steiner, A.J., & Leatherman, S.P. (1981). Recreational impacts on the distribution of Ghost Crabs *Ocypode quadrata* Fab. *Biological Conservation, 20*: 111-122.

Stillman, R.A., & Goss-Custard, J.D. (2002). Seasonal changes in the response of oystercatchers *Haematopus ostralegus* to human disturbance. *Journal of Avian Biology, 33*: 358-365.

Tassariki Ranch (2011). Retrieved 21/06/2011 from: www.tassarikiranch.com.au

Tauranga City Council (2007). Tauranga City Council Beaches Bylaw 2007.

The Northern Pegasus Bay Coastal Management Plan Steering Committee (2008). *Coastal Management Plan*: *Northern Pegasus Bay.* Environment Canterbury. 16 pp.

Thia-Eng, C. (1993). Essential elements of Integrated Coastal Zone Management. *Ocean and Coastal Management, 21*: 81-108.

Thompson, L.M.C., & Schlacher, T.A. (2008). Physical damage to coastal dunes and ecological impacts caused by vehicle tracks associated with beach camping on sandy shores: a case study from Fraser Island, Australia. *Journal of Coastal Conservation, Vol 12*: 67-82.

Thrush, S.F., Hewitt, J.E., Cummings, V.J., Ellis, J.I., Hatton, C., Lohrer, A., & Norkko, A. (2004). Muddy waters: elevating sediment input to coastal and estuarine habitats. *Frontiers in Ecology and the Environment, 2(6)*: 299-306.

Thrush, S.F., Hewitt, J.E., Herman, P.M.J., & Ysebaert, T. (2005). Multi-scale analysis of species-environment relationships. *Marine Ecology Progress Series, 302*: 13-26.

Tilman, D., Reich, P.B., & Knops, J.M.H. (2006) Biodiversity and ecosystem stability in a decade-long grassland experiment. *Nature, 441*: 629-632.

Tintoré, J., Medina, R., Gómez-Pujol, L., Orfila, A., & Vizoso, G. (2009). Integrated and interdisciplinary scientific approach to coastal management. *Ocean and Coastal Management, 52*: 493-505.

Törn, A., Tolvanen, A., Norokorpi, Y., Tervo, R., & Siikamäki, P. (2009). Comparing the impacts of hiking, skiing and horse riding on trail and vegetation in different types of forest. *Journal of Environmental Management, 90*: 1427-1434.

van Polanen Petel, T., & Bunce, A. (2012). Understanding beach users’ behaviour, awareness, and attitudes to shorebird conservation in Central Queensland: tools for effective shorebird conservation. *Coastal Management, 40(5)*: 501-509.

Vaughn, C.C., & Hakenkamp, C.C. (2001). The functional role of burrowing bivalves in freshwater ecosystems. *Freshwater Biology, 46*: 1431-1446.

Waimakariri District Council. (2012). Retrieved 26/01/2013 from: http://www.waimakariri.govt.nz/your_council/media-release-detail.aspx?release=Council%20Approves%20Funding%20for%20Remedial%20Work%20on%20Ocean%20Outfall

Waldbusser, G.G., Marinelli, R.L., Whitlatch, R.B., & Visscher, P.T. (2004). The effects of infaunal biodiversity on biogeochemistry of coastal marine sediments. *Limnology and Oceanography, 49(5)*: 1482-1492.

Walker, R.L., Hurley, D.H., & Kupfer, R. (1998). Growth and survival of Atlantic surfclam, *Spisula solidissima,* larvae and juveniles fed various microalga diets. *Journal of Shellfish Research, 17(1)*: 211-214.

Walker, S.J., & Schlacher, T.A. (2011). Impact of a pulse human disturbance experiment on macrofaunal assemblages on an Australian sandy beach. *Journal of Coastal Research, 27(6a)*: 184-192.

Weinberg, J. R., & Helser, T. E. (1996). Growth of the Atlantic surfclam, *Spisula solidissima*, from Georges Bank to the Delmarva Peninsula, USA. *Marine Biology, 126(4)*: 663-674.

Weissberger, E.J., & Grassle, J.P. (2003). Settlement, first-year growth, and mortality of surfclams, *Spisula solidissima*. *Estuarine, Coastal and Shelf Science, 56(3-4)*: 669-684.

Whinam, J., & Chilcott, N. (1999). Impacts of trampling on alpine environments in central Tasmania. *Journal of Environmental Management, 57*: 205-220.

Whinam, J., & Comfort, M. (1996). The impact of Commercial Horse Riding on Sub-Alpine Environments at Cradle Mountain, Tasmania, Australia. *Journal of Environmental Management, 47*: 61-70.

Williams, A., & Mecallef, A. (2009). *Beach Management*: *Principles and Practice*. Earthscan, London, England.

Williams, B.G. (1969). The rhythmic activity of *Hemigrapsus edwardsi* (Hilgendorf). *Journal of Experimental Marine Biology and Ecology, 3*: 215-223.

Wilson, D.D. (1985). Erosional and depositional trends in rivers of the Canterbury Plains, New Zealand. *Journal of Hydrology, 24(1)*: 32-44.

Wilson, J.G. (1999) Population dynamics and energy budget for a population of *Donax variabilis* (Say) on an exposed South Carolina beach. *Journal of Experimental Marine Biology and Ecology, 239*: 61-83.

Winkler, H., Baumert, K., Blanchard, O., Burch, S., & Robinson, J. (2007) What factors influence mitigative capacity? *Energy Policy, 35*: 692-703.

Wolcott, T.G., & Wolcott, D.L. (1984). Impact of Off-Road Vehicles on Macroinvertebrates of a Mid-Atlantic Beach. *Biological Conservation*, *29*: 217-240.

Woodroffe, C.D. (2002). *Coasts*: *Form, Process and Evolution*. Cambridge University Press. Cambridge, United Kingdom.

World Health Organization (2010). *Safe Management of Shellfish and Harvest Waters.* IWA publishing. London, United Kingdom.

Wright, L.D. & Short, A.S. (1984). Morphodynamic variability of surf zones and beaches: a synthesis. *Marine Geology, 56*: 93-118.

Yaffee, S.L. (1998). Three faces of ecosystem management. *Conservation Biology, 13(4)*: 713-725.

Zajac, R.N., & Whitlatch, R.B. (2003). Community and population-level responses to disturbance in a sandflat community. *Journal of Experimental Marine Biology and Ecology, 294*: 101-125.

Zaklan, S.D., & Ydenberg, R. (1997). The body size-burial depth relationship in the infaunal clam *Mya arenaria*. *Journal of Experimental Marine Biology and Ecology*, *215*: 1-17.

Zeldis, J., Skilton, J., South, P., & Schiel, D. (2011). Effects of the Canterbury earthquakes on Avon-Heathcote Estuary/ Ihutai ecology. Report no. U11/14. 31 pp.

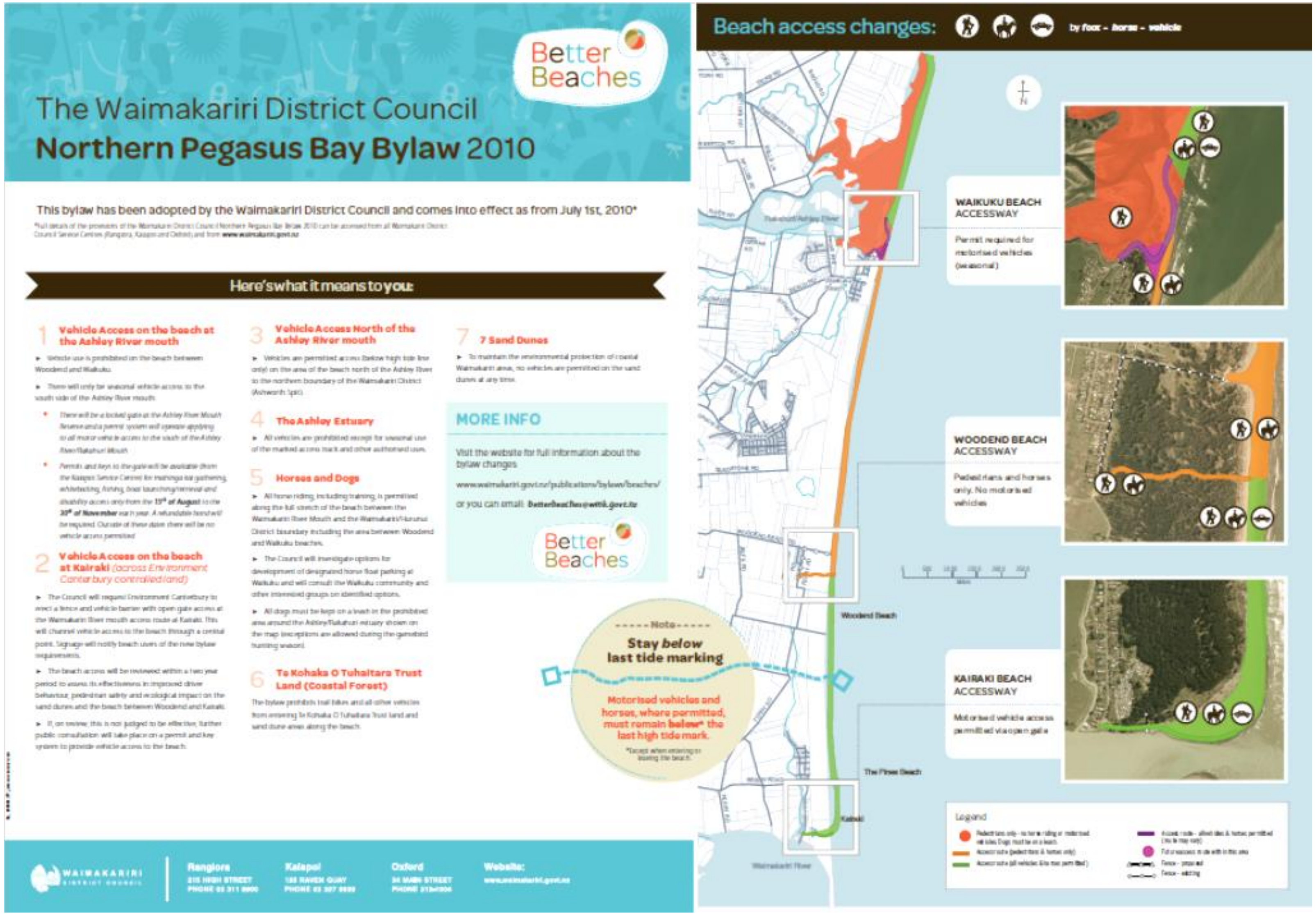
Zuschin, M., & Stanton JR., R.J. (2001). Experimental measurement of shell strength and its taphonomic interpretation. *Palaios, 16*: 161-170.

Zwarts, L., Blomert, A.M., Spaak, P., & de Vries, B. (1994). Feeding radius, burying depth and siphon size of *Macoma balthica* and *Scrobicularia plana*. *Journal of Experimental Marine Biology and Ecology, 183*: 193-212.

Zwarts, L., Wanink, J. (1989). Siphon size and burying depth in deposit- and suspension-feeding benthic bivalves. *Marine Biology*, *100*: 227-240.

Appendices

Appendix 2.1 Waimakariri Northern Pegasus Bay Bylaw, 2010, Advert.



Better Beaches

The Waimakariri District Council
Northern Pegasus Bay Bylaw 2010

This bylaw has been adopted by the Waimakariri District Council and comes into effect as from July 1st, 2010*

*Full details of the provisions of the Waimakariri District Council Northern Pegasus Bay Bylaw 2010 can be accessed from all Waimakariri District Council Service Centres (Rangiora, Kaiapoi and Oxford) and from **www.waimakariri.govt.nz**

Here's what it means to you:

1 **Vehicle Access on the beach at the Ashley River mouth**

- Vehicle use is prohibited on the beach between Woodend and Waikuku.
- There will only be seasonal vehicle access to the south side of the Ashley River mouth.
  - *There will be a locked gate at the Ashley River Mouth Reserve and a permit system will operate applying to all motor vehicle access to the south of the Ashley River/Rakahuri Mouth.*
  - *Permits and keys to the gate will be available from the Kaiapoi Service Centre for mahinga kai gathering, whitebaiting, fishing, boat launching/retrieval and disability access only from the **15th of August** to the **30th of November** each year. A refundable bond will be required. Outside of these dates there will be no vehicle access permitted.*

2 **Vehicle Access on the beach at Kairaki** *(across Environment Canterbury controlled land)*

- The Council will request Environment Canterbury to erect a fence and vehicle barrier with open gate access at the Waimakariri River mouth access route at Kairaki. This will channel vehicle access to the beach through a central point. Signage will notify beach users of the new bylaw requirements.
- The beach access will be reviewed within a two year period to assess its effectiveness in improved driver behaviour, pedestrian safety and ecological impact on the sand dunes and the beach between Woodend and Kairaki.
- If, on review, this is not judged to be effective, further public consultation will take place on a permit and key system to provide vehicle access to the beach.

3 **Vehicle Access North of the Ashley River mouth**

- Vehicles are permitted access (below high tide line only) on the area of the beach north of the Ashley River to the northern boundary of the Waimakariri District (Ashworth Spit).

4 **The Ashley Estuary**

- All vehicles are prohibited except for seasonal use of the marked access track and other authorised uses.

5 **Horses and Dogs**

- All horse riding, including training, is permitted along the full stretch of the beach between the Waimakariri River Mouth and the Waimakariri/Hurunui District boundary including the area between Woodend and Waikuku beaches.
- The Council will investigate options for development of designated horse float parking at Waikuku and will consult the Waikuku community and other interested groups on identified options.
- All dogs must be kept on a leash in the prohibited area around the Ashley/Rakahuri estuary shown on the map (exceptions are allowed during the gamebird hunting season).

6 **Te Kohaka O Tuhaitara Trust Land (Coastal Forest)**

The bylaw prohibits trail bikes and all other vehicles from entering Te Kohaka O Tuhaitara Trust land and sand dune areas along the beach.

7 **7 Sand Dunes**

- To maintain the environmental protection of coastal Waimakariri areas, no vehicles are permitted on the sand dunes at any time.

MORE INFO

Visit the website for full information about the bylaw changes

www.waimakariri.govt.nz/publications/bylaws/beaches/

or you can email: **betterbeaches@wmk.govt.nz**

Better Beaches

----- Note -----

Stay *below* last tide marking

Motorised vehicles and horses, where permitted, must remain below* the last high tide mark.

*Except when entering or leaving the beach.

Beach access changes: by foot - horse - vehicle

WAIKUKU BEACH ACCESSWAY

Permit required for motorised vehicles (seasonal)

WOODEND BEACH ACCESSWAY

Pedestrians and horses only. No motorised vehicles

KAIRAKI BEACH ACCESSWAY

Motorised vehicle access permitted via open gate

Legend
- 🟥 Pedestrians only - no horse riding or motorised vehicles. Dogs must be on a leash.
- Access route (pedestrians & horses only)
- Access route (all vehicles & horses permitted)
- Access route - [illegible] & horses permitted ([illegible])
- ● [illegible]
- Fence - proposed
- Fence - existing

WAIMAKARIRI DISTRICT COUNCIL

Rangiora
215 HIGH STREET
PHONE 03 311 [illegible]

Kaiapoi
[illegible] RAVEN QUAY
PHONE 03 327 [illegible]

Oxford
34 MAIN STREET
PHONE [illegible]

Website:
www.waimakariri.govt.nz

Appendix 2.2 Table of peer-reviewed literature. V=Vehicle, H= Horse.

	Activity literature covers						
Location	**V**	**H**	**Other**	**Study species**	**Purpose**	**Findings**	**Author (s), year published.**
Fire Island, New York, USA.	X			Dune ecosystem	To evaluate effects of ORVs on dune systems	Vegetation severely reduced and erosion higher	Anders & Leatherman, 1987.
Algodunes Dunes, California, USA.	X			Dunes, Plants, mammals, birds	To evaluate effects of ORVs on dune ecosystems	Reduction in biota with low level passes. None in high use	Luckenbuch & Bury, 1983.
Queensland, Australia	X			All beach fauna	Quantify spatial and temporal trends in vehicle traffic	Up to 65% of species are exposed to vehicle traffic	Schlacher & Thompson, 2007.
Queensland, Australia	X			Intertidal Macrobenthos	Quantify ORV effects by comparing between beaches with different use	ORV beaches have reduced, less diverse populations and altered assemblages.	Schlacher, Richardson, & McLean, 2008.
Queensland, Australia	X			*Donax Deltoides,* Bivalve	Quantify the relationship between vehicle traffic and shellfish mortalities	Increase in mortalities at higher levels of passes	Schlacher, Thompson, & Walker, 2008.
Fraser Island, Australia	X			Dune, Fauna and Ghost Crab, *Ocypode* spp	Quantify ORV effects on dunes and link to biota	Accelerated erosion and shoreline retreat. No dune plants in tracks and reduced Ghost crab abundance	Thompson & Schlacher, 2008.

Queensland, Australia	X			*Donax Deltoides*, Bivalve	Evaluate the sub-lethal effects of ORVs	Increased passes impaired burrowing performance	Sheppard, Pitt, & Schlacher, 2009.
North Stradbroke Island, Australia	X			*Ocypode cordimanus* & *O. ceratophthalma* (Ghost Crabs)	Quantify magnitude and mechanism of ORVs on Ghost Crab populations	Crabs with deeper burrows have lower mortality. Lower densities in high traffic area. More mortality at dusk.	Schlacher, Thompson, & Price, 2007.
North Stradbroke Island, Australia	X			Ghost crabs (*Ocypode spp.*)	Observe if movement patterns were affected by vehicle traffic	Traffic halved pop. Densities and changed movement to be more erratic with compressed home ranges.	Schlacher & Lucrezi, 2010.
North Carolina, USA	X			Beach Macrofauna, including *Donax variabilis*	Evaluating the potential and actual impacts of ORVs	Most species predicted to be undamaged. Night driving would have largest effect on ghost crabs.	Wolcott & Wolcott, 1984.
Cape Cod, Massachusetts, USA	X			Dune vegetation	Evaluating impact of vehicles on dune grasses	All above ground is killed, but below ground biomass is enough to recover.	Brodhead, & Godfrey, 1977.
Coorong, South Australia, Australia	X			Hooded Plover, *Chardrius rubricollis*	Evaluate the vulnerability of bird nests	Over the incumbent period 81% of nests would be runover. Rate of 8% per day.	Buick, & Paton, 1988.

Cable Beach, Western Australia, Australia	X			Shore crabs, *Ocypode* spp. And sand bubbler, *Scopimera inflata*	Testing the link between human usage and shore crab abundance	Less dense crab populations in high vehicle use areas.	Foster-Smith *et al.*, 2007.
Algodunes, California, USA	X			Peirson's milk-vetch, *Astragalus magdalenae* var. *peirsonii*	Identify differences of abundance between high/low use areas to decide impact was significant	Reduced survival by 33%, but recovery did occur in closed off areas.	Groom *et al.*, 2007.
Fort Fisher Beach, North Carolina, USA	X		Pedestrians	Loggerhead turtles, *Caretta caretta caretta*	Evaluate the effects of vehicles and pedestrians on behaviour and sea-approach	Tyre tracks caused increased transit time to reach the sea reducing survival chances.	Hosier *et al.*, 1981.
Cape Fear, North Carolina, USA	X			Dune and grassland vegetation	Determine the effects of vehicles on dune and grassland ecosystems	Vegetation cover and species richness decreased in vehicle area. Soil was more compacted in vehicle area.	Hosier & Eaton, 1980.
Sharon National Park, Israel			Pedestrian, Motorbike	Dune vegetation	Testing effects of passes and trampling on vegetation	Trampling had low effect on plants. Motorcycles had large immediate effects, highest in wheel tracks.	Kutiel *et al.*, 2000
Eastern Australia, Australia	X			Ghost crabs, *Ocypode* spp.	To test whether burrow architecture is affected by vehicle traffic	Vehicle beaches: Smaller crabs, deeper burrows, simplified shapes	Lucrezi & Schlacher, 2010.

Massachusetts, USA	X			Piping plover, *Charadrius melodus*	To document mortalities caused by vehicles on beaches	Piping plover were killed by vehicles and recommended closure of area at hatch date of nests.	Melvin *et al.*, 1994.
Alexandria Coastal Dunefield and University of Port Elizabeth, South Africa	X		Pedestrian	Dune vegetation	Investigate the effects of varying traffic intensities on vegetation height and cover for pioneer and climax dune	Vehicle: Curved path more destruction. Pioneer communities recover quickly. Impacts may not be realised for 3months.	Rickard *et al.*, 1994.
Assateague Island, Maryland-Virginia, USA	X		Pedestrian	Ghost crab, *Ocypode quadrata* Fab.	Determine if relative number of crabs was subject to recreational use	Vehicles likely to stop reproduction and crushing crabs. Pedestrians have no effect.	Steiner & Leatherman, 1981.
Alexandria Coastal Dunefield, South Africa	X		Fishermen	Dune breeding birds	Quantifying beach use through data and observations	50% of activity was in dune bird area. Potential for impact is high above the MHWS.	Watson *et al.*, 1996.
San Francisco Bay, USA	X			Vegetation and soil	Investigate the impacts of vehicles on vegetation and soil	Loss of vegetation cover promotes erosion. Erosion exceeds US standards.	Wilshire *et al.*, 1978.

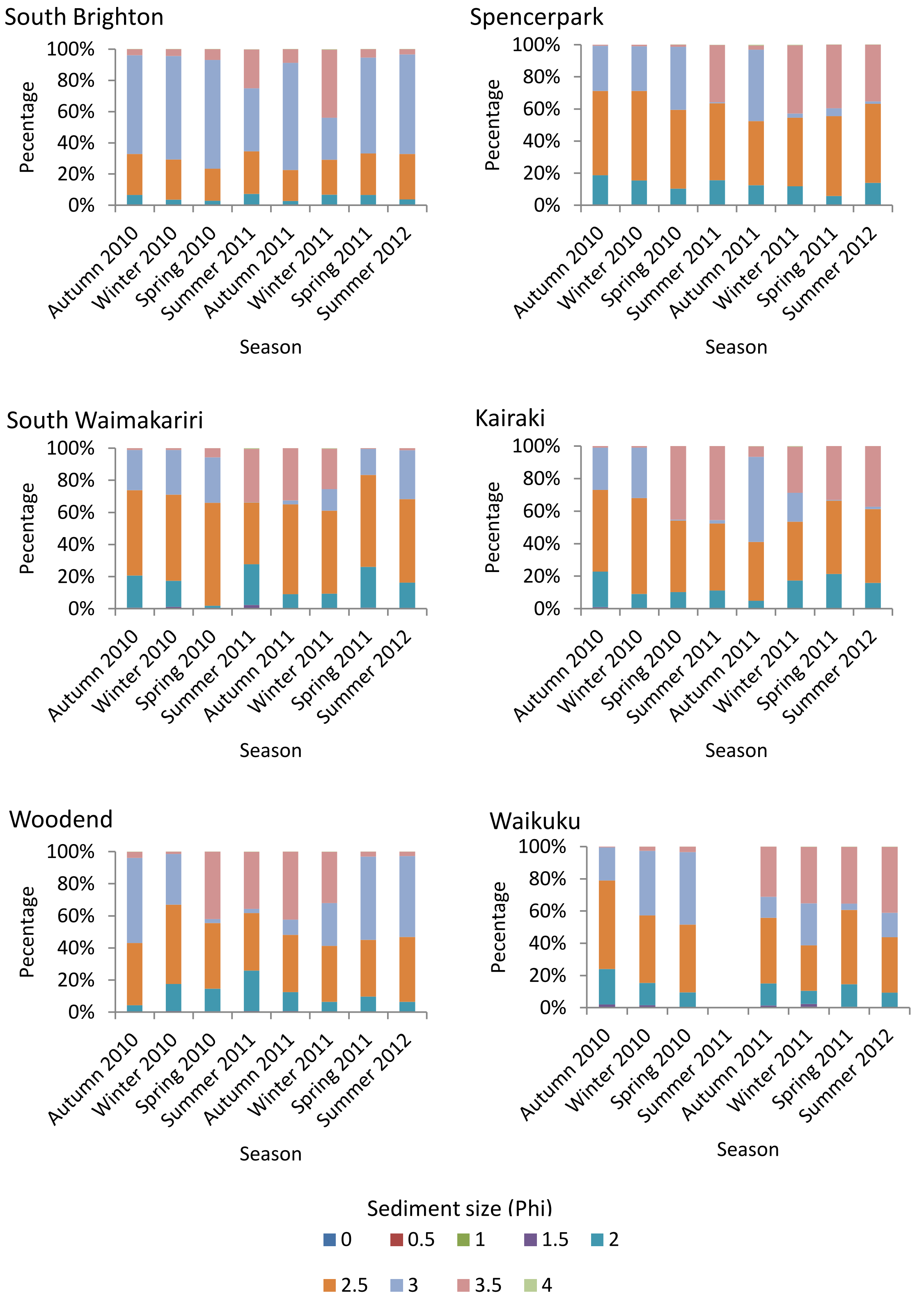
Appendix 2.3 Table of reviewed management policies

		Activity management covers					
Location	**Document name**	**V**	**H**	**Other**	**Management control method**	**Positive outcomes for shellfish**	**Negative outcomes for shellfish**
East of south Island, New Zealand	Tuatua Quota for PDO3			Fisheries	Sets TACC for adult tuatua	Stops overfishing	Limits could be too high for certain areas. Dredging is an acceptable method of gathering.
Hurunui, New Zealand	Hurunui District Plan			All district issues	Puts policies in place to control activities	Aims to maintain natural values and prevent contamination of water.	No mention of shellfish in policies.
Hurunui, New Zealand	Hurunui Northern Pegasus Bay Bylaw 2010	X	X	Pedestrians	Defines where each activity can occur	Does not allow vehicles in all areas of the beach.	Horses are allowed everywhere. Vehicles and horses allowed in the intertidal zone= condensing of traffic
Waimakariri district, New Zealand	Waimakariri District Plan			All district issues	Uses policies to control activities	Prevents contamination. Aims to prevent loss of integrity	No focus on vehicles, want to improve access. Only mention of vehicles is in the dune area.
Waimakariri District, New Zealand	Waimakariri Northern Pegasus Bay Bylaw, 2010	X	X	Pedestrians	Defines where each activity can take place	Prevents vehicles from driving over all the beach	Horses are allowed everywhere. Vehicles and horses allowed in the intertidal zone= condensing of traffic.
Christchurch, New Zealand	Christchurch City Council City Plan	X		All city related issues	Policies	Aims to increase public access so vehicles are not needed	No other mention of activities despite the zoning being extended below the MHWS line
Canterbury, New Zealand	Regional Coastal Environment Plan	X		Other regional issues	Policies	Prohibits vehicles in certain areas. Give Pegasus Bay Beaches “Area of significant value” status.	Large focus on dunes. Still allows 4wd clubs to use areas in winter when authorised
Canterbury, New Zealand	Regional Environment Statement			Regional Issues	Policies	Focuses on protection of indigenous species, biodiversity and erosion.	No mention of shellfish protection, only mentioned in relation to mahinga kai
New Zealand	New Zealand Coastal Policy Statement			All national priorities	Policies	Precautionary approach to be taken. Mentions protection at vulnerable life	No mention of horses. Left up to regions to decide how to interpret this.

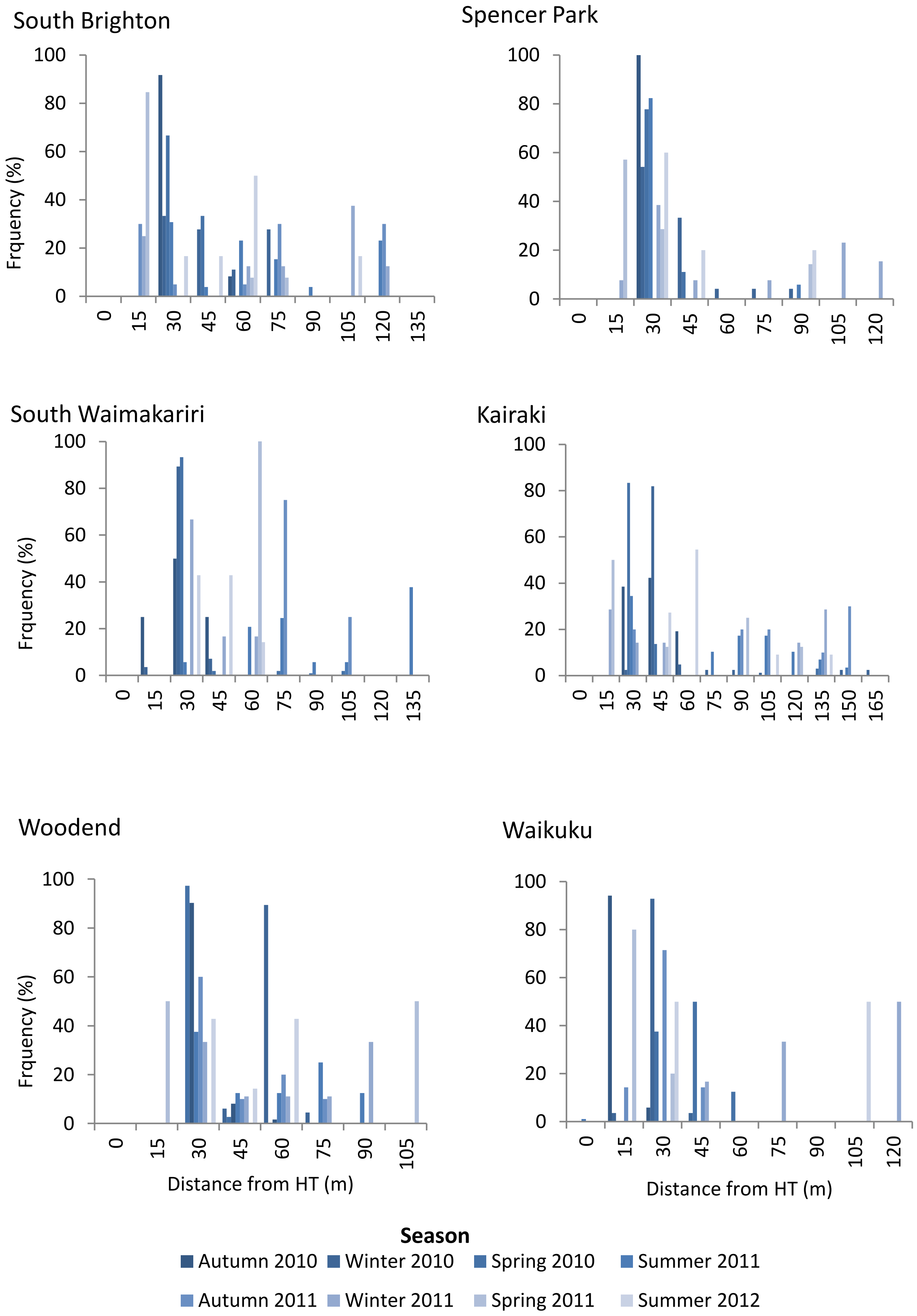
						stages. States vehicles to be controlled where ecological harm may be caused	
New Zealand	Resource Management Act, 1991			All national priorities	Policies that guide other documents	Mention of shellfish for water quality and gathering.	No specific mention of activities.
New Zealand	Fisheries Act, 1996			Fisheries	Policies	Stops overharvesting of shellfish for an area by setting a quota	Areas are often large which could result in some areas becoming depleted
Australia	Coastal Protection and Management Act 1995			National coastal issues	Give direction for management authorities to control activities	States that conservation should also be taken into account	States that public access must be considered.
Queensland, Australia	Queensland Coastal Plan, 2011	X	X	All state activities	Policies and principles	Vehicle use is unsupported and states that protection of foreshore species is important. Lists many beaches where it cannot occur due to erosion	Still states that vehicles are allowed if managed.
South-East Queensland, Australia	South-East Queensland Regional Coastal Management Plan, 2006	X		All regional activities	Policies	Vehicle use is same as for State coastal Plan	
New South Wales, Australia	Vehicle Access general Policy, 2010	X			Policies	Vehicle use is not to be expanded if a national park is gazetted. Not allowed if environmental damage will occur.	Is still allowed, no mention of where it is allowed.
South Africa	Guidelines on the implementation of regulations pertaining to the control of vehicles in the coastal zone, 2004	X			Policies	Complete ban on vehicles for recreational use.	Exceptions are made, areas can be declared by the Deputy Director-General.
France	La Loi Littoral,	X			Policies	Complete ban	

	1986					of vehicles on beaches.	
Whangarei, New Zealand	Vehicles on beaches bylaw, 2008	X			Bylaw	Vehicles not allowed in Safe zones (Near surf clubs). Also allowed anywhere on the beach face.	Allowed along most of the beach.
Kapiti Coast, New Zealand	Kapiti Coast District Council Beach Bylaw 2009	X	X	Other beach activities	Bylaw	Some areas are prohibited from use by vehicle and horses (at certain times of the year). Motor bikes are prohibited everywhere.	All traffic is on the foreshore. Horses are allowed everywhere apart from in the summer.
Tauranga, New Zealand	Tauranga City Council Beaches bylaw 2007	X	X	All other activities	Bylaw	No vehicles allowed, with few exceptions Activities allowed on whole beach face.	Horses are allowed almost everywhere.
Cape Cod, USA	No name (Web page)	X			Rules	No vehicles allowed on the foreshore.	Some allowed if track is cut off.
Cape Hatteras, USA	Cape Hatteras National Seashore Off-Road Vehicle Negotiated Rulemaking and Management Plan/EIS, 2010	X			Rules	Vehicles managed by permits and are not allowed during certain months around bird and turtle nests.	Horses are still allowed without permit.
Cannon Beach, Oregon, USA	Website	X			Rules	Vehicles only allowed with a permit for a specific reason.	Permits could vary.
Crane Beach, Massachusetts, USA	Website		X		Policies	Only allowed from Oct 1-Mar 31.	Have to stay in the intertidal zone. Up to 50per day.
Donegal County, Ireland	Donegal County Council (Regulation and Control of certain Beaches) Bye-Laws 2009	X			Policies	No vehicles allowed on most beaches. Horses not allowed in certain months without permit.	Horses are allowed.

Appendix 3.1 Sieve graphs of sediment phi size in samples throughout the study period.



Appendix 3.2 Position of tuatua on shore graphs for each site



Appendix 3.3 Table of tuatua densities at each shore level within six sites

Tuatua density (per m^2)

South Brighton

Distance from high tide (m)	Autumn 2010	Winter 2010	Spring 2010	Summer 2011	Autumn 2011	Winter 2011	Spring 2011	Summer 2012
0	0	0	0	0	0	0	0	0
15	0	0	0	0	30	10	55	0
30	50	30	10	40	5	0	0	5
45	0	25	5	5	0	0	0	5
60	5	10	0	30	5	5	5	15
75	0	25	0	20	30	5	5	0
90	0	0	0	5	0	0	0	0
105	0	0	0	0	0	15	0	5
120	0	0	0	30	30	5	0	0
135	0	0	0	0	0	0	0	0

Spencerpark

Distance from high tide (m)	Autumn 2010	Winter 2010	Spring 2010	Summer 2011	Autumn 2011	Winter 2011	Spring 2011	Summer 2012
0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	5	20	0
30	30	65	62	70	0	25	10	15
45	0	40	9	0	0	5	0	5
60	0	5	0	0	0	0	0	0
75	0	5	0	0	0	5	0	0
90	0	5	0	5	0	0	5	5
105	0	0	0	0	0	15	0	0
120	0	0	0	0	0	10	0	0

Tuatua density (per m²)

South Waimakariri

Distance from high tide (m)	Autumn 2010	Winter 2010	Spring 2010	Summer 2011	Autumn 2011	Winter 2011	Spring 2011	Summer 2012
0	0	0	0	0	0	0	0	0
15	5	5	0	0	0	0	0	0
30	10	121	490	15	0	20	0	15
45	5	10	10	0	0	5	0	15
60	0	0	0	54	0	5	5	5
75	0	0	10	64	15	0	0	0
90	0	0	5	15	0	0	0	0
105	0	0	10	15	5	0	0	0
120	0	0	0	0	0	0	0	0
135	0	0	0	100	0	0	0	0

Kairaki

Distance from high tide (m)	Autumn 2010	Winter 2010	Spring 2010	Summer 2011	Autumn 2011	Winter 2011	Spring 2011	Summer 2012
0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	10	20	0
30	48	10	275	50	10	5	0	0
45	53	340	45	0	0	5	5	15
60	24	20	0	0	0	0	0	30
75	0	10	0	15	0	0	0	0
90	0	10	0	25	10	0	10	0
105	0	5	0	25	10	0	0	5
120	0	0	0	15	0	5	5	0
135	0	0	10	10	5	10	0	5
150	0	10	0	5	15	0	0	0
165	0	10	0	0	0	0	0	0

Tuatua density (per m²)

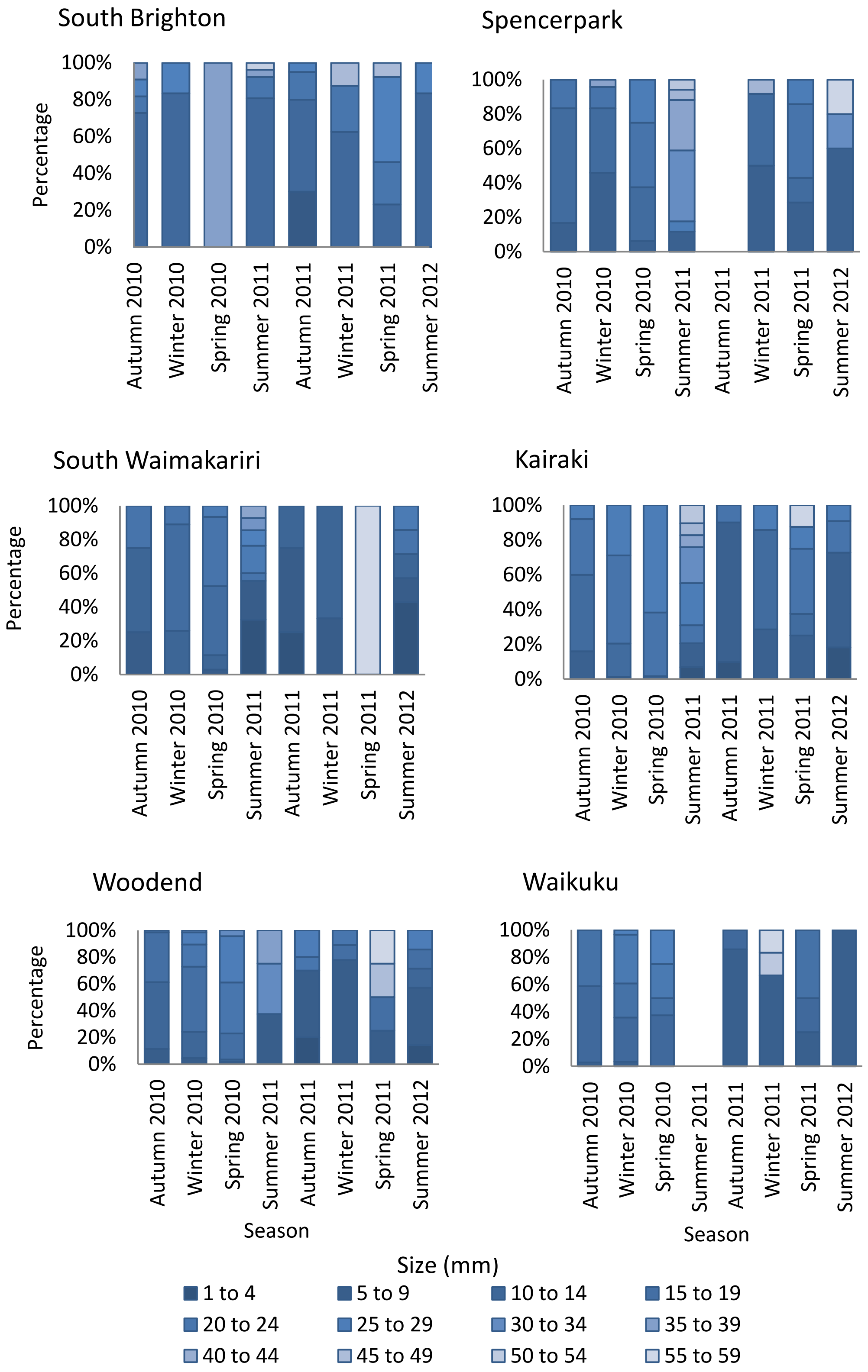
Woodend

Distance from high tide (m)	Autumn 2010	Winter 2010	Spring 2010	Summer 2011	Autumn 2011	Winter 2011	Spring 2011	Summer 2012
0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	10	0
30	280	0	550	15	30	15	0	15
45	25	20	15	5	5	5	0	5
60	5	295	0	5	10	5	0	15
75	0	15	0	10	5	5	0	0
90	0	0	0	5	0	15	0	0
105	0	0	0	0	0	0	10	0
120	0	0	0	0	0	0	0	0

Waikuku

Distance from high tide (m)	Autumn 2010	Winter 2010	Spring 2010	Summer 2011 (NA)	Autumn 2010	Winter 2011	Spring 2011	Summer 2012
0	0	0	0	0	0	0	0	0
15	160	5	0	0	5	0	20	0
30	10	130	15	0	25	0	5	5
45	0	5	20	0	5	5	0	0
60	0	0	5	0	0	0	0	0
75	0	0	0	0	0	10	0	0
90	0	0	0	0	0	0	0	0
105	0	0	0	0	0	0	0	5
120	0	0	0	0	0	15	0	0

Appendix 4.1 Size class distributions at each site and season of sampling.



Appendix 5.1 Vehicle effects data

Table of sediment and tyre characteristics

No. of Passes	Pore water (%)		Width (mm)		Depth (mm)		Volume (mm^2)	
Day 1	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**
0	21.48055	22.31489	0	0	0	0	0.0	0.0
1	20.68786	21.17477	187.5	195	2	3	37.5	58.5
10	20.20878	21.35751	262.5	262.5	15.5	19	407.0	498.0
25	20.08025	20.82663	270	270	29.5	30.5	796.5	822.8
40	19.7227	20.00526	277.5	277.5	39.5	37	1096.5	1026.5
50	20.17179	20.5322	280	282.5	40	41	1120.0	1158.0
Day 2								
0	21.7911	20.65595	0	0	0	0	0.0	0.0
5	20.97002	20.3952	255	255	11	11	280.5	282.0
10	20.58855	20.64398	260	262.5	18	16	468.0	419.5
25	20.34117	20.28618	285	270	29.5	25	840.8	675.0
30	20.30571	20.98969	290	270	31.5	28.5	913.5	769.5
50	19.43107	19.27889	290	275	35	37	1015.0	1019.0
Day 3								
0	22.86353	21.7134	0	0	0	0	0.0	0.0
1	20.42657	20.54039	200	187.5	3	3.5	60.0	65.8
20	19.76314	20.81247	267.5	275	20	30	535.5	825.0
30	19.69461	20.10596	277.5	290	25	36	693.8	1044.0
40	19.4141	21.1383	287.5	295	31	45	891.5	1327.5
50	19.13678	19.54115	287.5	295	32	45	920.3	1327.5
Day 4								
0	21.21831	22.90656	0	0	0	0	0.0	0.0
5	21.15257	23.07233	237.5	247.5	20	10	475.0	247.5
15	19.97588	20.62563	270	255	27	20	734.0	510.0
20	20.06527	21.01679	270	262.5	33	24	891.0	629.8
35	19.66826	21.63394	275	287.5	33.5	31	921.3	891.0
50	19.36526	21.06759	280	290	33	34	924.0	986.0

Table of tuatua mortality results

No. of Passes	Tuatua Mortality (%)		Reburied immediately (%)		Reburied 24hrs (%)	
Day 1	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**
0	11.76471	0	53.333	93.33333	60	86.66667
1	9.52381	17.64706	80	100	86.667	100
10	10	15	33.333	93.33333	80	80
25	16	10.52632	53.333	100	100	86.66667
40	14.28571	22.22222	80	93.33333	80	93.33333
50	20	15.78947	26.667	86.66667	66.667	93.33333
Day 2						
0	0	0	66.667	93.33333	93.333	100
5	4.255319	9.677419	66.667	100	66.667	100
10	3.846154	7.5	60	86.66667	66.667	100
25	4.672897	8.333333	40	93.33333	86.667	100
30	6.097561	23.80952	53.333	66.66667	93.333	93.33333
50	2.298851	20	53.333	80	80	93.33333
Day 3						
0	2.564103	3.846154	53.333	93.33333	66.667	93.33333
1	7.692308	0	80	100	66.667	100
20	12.82051	14.28571	40	73.33333	93.333	86.66667
30	20	25.80645	73.333	93.33333	100	80
40	20	33.33333	53.333	73.33333	66.667	40
50	17.14286	29.78723	60	66.66667	93.333	80
Day 4						
0	0	0	80	100	60	86.66667
5	2	2.298851	73.333	100	86.667	86.66667
15	8.695652	3.658537	80	93.33333	73.333	66.66667
20	13.7931	4.255319	73.333	93.33333	80	80
35	1.785714	13.63636	66.667	93.33333	80	33.33333
50	3.658537	13.51351	93.333	80	73.333	40

Appendix 6.1 Summarised Observational Horse Data

Woodend Beach							
Date sampled	**No. of horses**	**Distance from HT (m)**	**Width (m)**	**No. of shellfish per hoof**	**Average hoofs per 10 m**	**Average mortality (%)**	**Distance of tracks (km)**
5/11/2010	20	47	19	12	0	11	4.5
	39	24	50	0	15	NA	
	37	39	32	3	14	0	
6/12/2010	2	39	7	0	12	NA	6
	32	19	27	9	22	11	
	24	23	24	6	19	26	
31/01/2011	3	31	15	0	11	NA	5.6
	31	25	20	0	10	NA	
	19	28	19	2	14	11	
19/04/2011	9	30	28	4	12	6	7
	39	25	35	0	17	NA	
	17	36	20	0	10	NA	
30/06/2011	37	28	30	0	12	NA	3.8
	30	38	22	0.3	11	100	
	17	31	27	0.3	10	100	

Spencer Park Beach							
Date sampled	**No. of horses**	**Distance from HT (m)**	**Width (m)**	**No. of shellfish per hoof**	**Average hoofs per 10m**	**Average mortality (%)**	**Distance of tracks (Km)**
6/11/2010	10	37.8	17		12	14	6.6
	10	31	16	0	9	NA	
	12	38	23	1	16	0	
6/12/2010	4	30	4	0	19	NA	6
	14	25	26	0	9	NA	
	10	25	19	0	13	NA	
31/01/2011	4	32	9	0	14	NA	4.1
	4	35	8	0	14	NA	
	4	40	4	0	14	NA	
19/04/2011	8	29	17	0	11	NA	6.7
	10	19	10	1	19	0	
	6	30	12	0	11	NA	
30/06/2011	2	27	1	0	10	NA	4.7
	2	30	3	0	27	NA	
	4	26	4	0	19	NA	

Appendix 6.2 Summarised horse preliminary and disturbance intensity data

Preliminary experiments

Table of mortality and reburial results from preliminary experiments. Reburial was tested using the same individuals immediately and 24 hours after being runover.

	Tuatua mortality (%)	Standard Error	Pore water content (%)	Standard Error	Tuatua buried immediately (%)	Tuatua buried after 24 hours (%)
Control	0	0	21.3	0.5	60	73.3
Walk	8.3	4.8	22.5	0.1	33.3	73.3
Trot	31.5	8.0	22.2	0.1	40	66.7
Gallop	31.5	10.0	22.0	0.2	66.7	53.3

Disturbance intensity experiments

Table of mortality and reburial results from finalised experiments. Reburial was tested using the same individuals immediately and 24 hours after being runover.

	Tuatua Buried immediate (%)	Standard Error	Tuatua Buried after 24 hours (%)	Standard Error
Control	44.3	15.7	34.3	5.7
Walk 1	29.2	29.2	70.8	29.2
Walk 5	67.5	7.5	47.5	27.5
Trot 1	70	3.3	44.4	22.2
Trot 5	20.8	4.2	90	10