Green-lipped Mussels in GLM 9

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CONTENTS

EXECUTIVE SUMMARY

Alfaro, A.C.; Jeffs, A.G.; Gardner, J.P.A.; Bollard Breen, B.A.; Wilkin, J. (2011). Green-lipped Mussels in GLM 9

New Zealand Fisheries Assessment Report 2011/48.

The green-lipped mussel (*Perna canaliculus*) is the most valuable aquaculture species in New Zealand, valued at $260 million of production in 2009. The industry is almost 100% reliant on seed mussels, or spat, caught from the wild. The majority of these wild seed mussels (more than 80%) are harvested from fisheries management area GLM 9, mostly from Ninety Mile Beach in the far north of the North Island. At certain times of the year, drifting spat material arrives in the surf zone just offshore from the beach. The material consists of detached seaweeds and hydroids, as well as other debris, to which the mussel spat are attached, often at more than a million mussels per kilogramme of material. An excess of 100 tonnes of mussel spat material is harvested from the beach each year and distributed to mussel farms around New Zealand.

Despite the enormous economic value to seafood production and sales that this small volume spat fishery underpins, there is remarkably little known about the source of these mussels in GLM 9. Therefore, the purpose of this report is to review existing information about the GLM 9 resource, including the associated drift material, and to evaluate potential future research directions to best aid management of the resource. This includes evaluation of various scientific methods that could be used to determine the extent of the wild green-lipped mussel populations where the spat originates from, connectivity amongst these individual populations and connectivity between these populations and the supply of harvestable spat in GLM 9.

The review has identified five significant knowledge gaps in the green-lipped mussel fishery in GLM 9 and recommends corresponding research avenues in order to address each of these gaps.

These five knowledge gaps are recommended as five key topic areas for future research to guide the management of this important resource in the following order of priority.

1. The location of source green-lipped mussel populations, and their relative contribution to the spat harvested in GLM 9.

2. The location of source populations of hydroids, seaweeds and other debris, and their relative contribution to the spat material harvested in GLM 9.

3. The status of populations of broodstock mussels, hydroids, seaweeds and sources of other debris that are important contributors to the arrival of mussel spat that is harvested in GLM 9.

4. The functioning of the biological and physical pathways between populations of broodstock mussels and settlement material (hydroids, seaweed and other debris) and spat material harvested in GLM 9.

5. The impact of spat harvesting in GLM 9 on natural coastal mussel populations, including potentially important broodstock populations.

1 INTRODUCTION

Although the GLM 9 commercial fishery is of only a comparatively small size and value, it is the major source of mussel seed, or spat, for an aquaculture industry with more than $260 million of sales in 2009. The endemic green-lipped mussel, *Perna canaliculus*, is now the single most important seafood export species for New Zealand by value ($202 million in 2009), and this industry employs the equivalent of 2500 people (Ministry of Fisheries 2010). The mussels are sold under the trade name Greenshell, and are mostly exported to North America and Europe.

The industry has grown relatively quickly since its origins (Figure 1) and is currently planning for significant growth in order to meet the aquaculture sector growth target of $1 billion of production by 2025 (Figure 2) (New Zealand Aquaculture Council 2006).

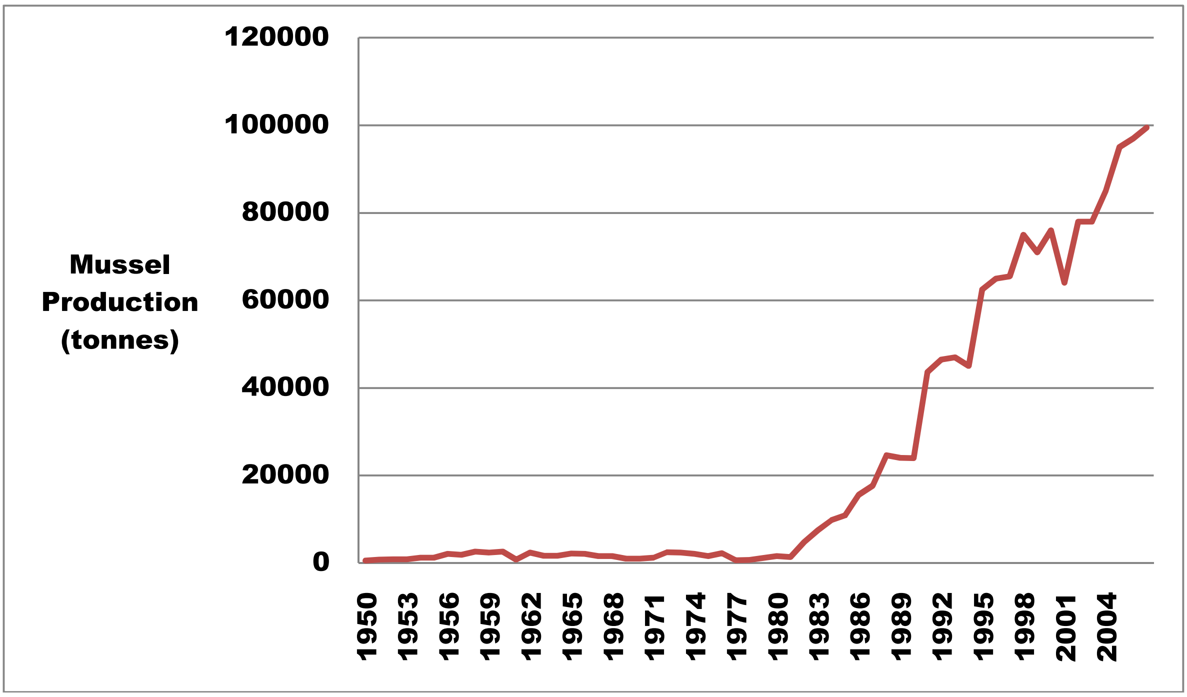

Figure 1: History of aquaculture production of *Perna canaliculus* in New Zealand (Ministry of Fisheries 2010).

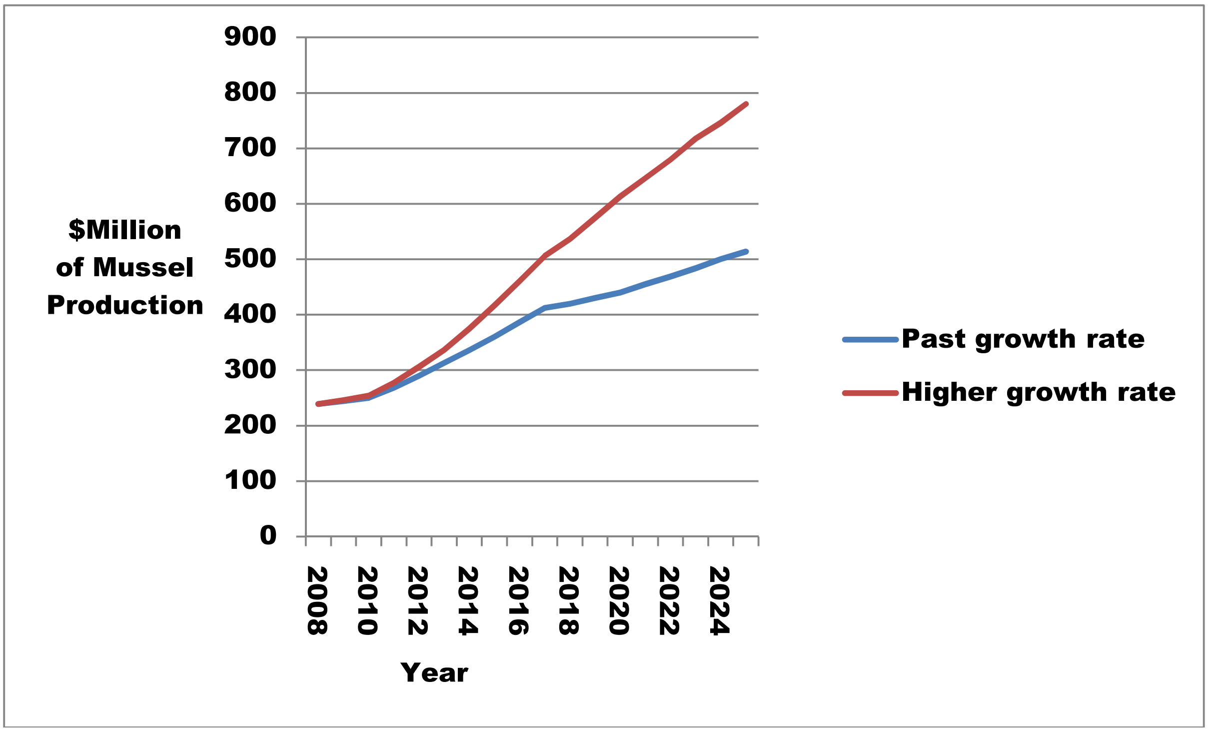

Figure 2: Projections of future value of aquaculture production of *Perna canaliculus* in New Zealand based on two scenarios – continuation of existing mean growth rate, or higher growth rate associated with meeting the aquaculture sector growth target of $1 billion of production by 2025 (New Zealand Aquaculture Council 2006).

There are 1018 authorised mussel farms in New Zealand, mostly concentrated in the Marlborough Sounds and Coromandel areas (Ministry of Fisheries 2010). Currently, the Greenshell aquaculture industry is almost 100% reliant on seed mussels collected from the wild, with only a small volume being supplied from hatchery production. The largest supply of mussel spat for aquaculture is from harvesting over 100 tonnes of spat a year in GLM 9 (more than 80% of all spat used by the industry), with the balance mostly caught on spat catching ropes in Golden Bay and Marlborough Sounds.

Mussel farmers, particularly in the Marlborough Sounds, like to use a combination of spat from Ninety Mile Beach and Golden Bay for their farms, because the breeding cycles of these mussel populations appears to be different allowing for an extended period for harvesting mussels with full gonads (commonly referred to as "fat" mussels). Mussels grown from spat sourced from GLM 9 tend to fatten and spawn from around August until January, whilst those mussels grown from Golden Bay spat fatten and spawn later, usually starting around January and ending later in the summer.

Almost all the spat harvested from GLM 9 is taken from Ninety Mile Beach in the Far North, where it occasionally washes into shallow waters along the beach. Once in the surf zone, it is easily collected by hand in scoop nets, although one major harvester also uses a mechanical harvester consisting of a large scoop net mounted on the front of a tractor that can be driven into the water. The spat material is loaded onto trailers and towed off the beach to a nearby depot, where the material is sorted to remove debris and material not covered with mussel spat. Commercial harvesters often return up to 50% of the harvested material to the beach after sorting (Ministry of Fisheries 2004).

The mussel spat are attached to drifting and detached seaweeds, hydroids and other flotsam, often at densities exceeding a million mussels per kilogramme of material (Hickman 1976; Alfaro & Jeffs 2002; Alfaro et al. 2004). The harvested spat are mostly shipped in refrigerated trucks to mussel farms around the country, including as far away as Big Glory Bay on Stewart Island (Jeffs et al. 1999). Once at farms, the spat with associated seaweeds and other material are placed on farm nursery lines, and then held in place by a surrounding biodegradable mesh stocking (Figure 3). Within a few weeks, the stocking degrades and the spat migrate onto the farm rope. After a few months, when the juveniles are securely attached to the ropes and have grown to a larger size (approximately 3 to 4 cm), the mussels are stripped from the lines and re-seeded at lower densities onto grow-out lines to reduce densities and maximise production (Figure 4).

Figure 3: Spat and seaweed held next to farm line with a degradable stocking (Photo by A. C. Alfaro).

Mussel larvae originate from adult mussel beds then settle upon filamentous substrates (predominantly seaweed and hydroids) in a process called primary settlement. These primary settlers then actively drift away from these substrates as juveniles (1–2 mm) to settle upon rocky substrates (secondary settlement) where they can then grow to adults. The spat industry at Ninety Mile Beach relies upon primary settlers attached to seaweed or hydroids being transported and accumulated along the seafloor and being cast up on the beach, from where they are harvested. The locations of source adult mussel beds and primary settlement substrates as well as the details of transport mechanisms of both larvae and primary settlers are largely unknown.

Some of the rocky intertidal outcrops that host mussel beds in GLM 9 are more easily accessible and form the basis of an important non-commercial fishery, especially for customary Maori purposes (e.g., hui, tangi). The importance of non-commercial use of mussels in GLM 9 was recognised when the species was introduced into the Quota Management System (QMS) in 2004 with allowances of 39 and 59 tonnes for recreational and customary harvests respectively (Ministry of Fisheries 2004).

The commercial harvesting of juvenile green-lipped mussels as seed for aquaculture began at Ninety Mile Beach on a small scale in the early 1970's and was conducted initially under a fishing permit (section 63, Fisheries Act 1983) (Ministry of Fisheries 2004). Legislative changes resulted in the introduction of spat catching permits 67Q2(b) issued under the Fisheries Act 1993. Between 2004 and 2005 the harvesting of green-lipped mussel spat was brought into the QMS after considerable discussion with interested parties (Ministry of Fisheries 2004). In particular, there was a need to include mechanisms to recognise that harvesting mussel spat, included the harvest of associated drift seaweed, and that a proportion of the harvest spat and seaweed material could be returned to the sea after sorting.

Previous work has demonstrated that mussel juveniles have a strong selectivity of attachment for these natural filaments (Buchanan & Babcock 1997; Alfaro & Jeffs 2002), and the attachment process is determined by the physical structure (Alfaro & Jeffs 2002, 2003), chemical composition (Alfaro et al. 2006; Young et al. 2008), and bacterial biofilms (Ganesan et al. 2008; Ganesan et al. 2010) of the substrates.

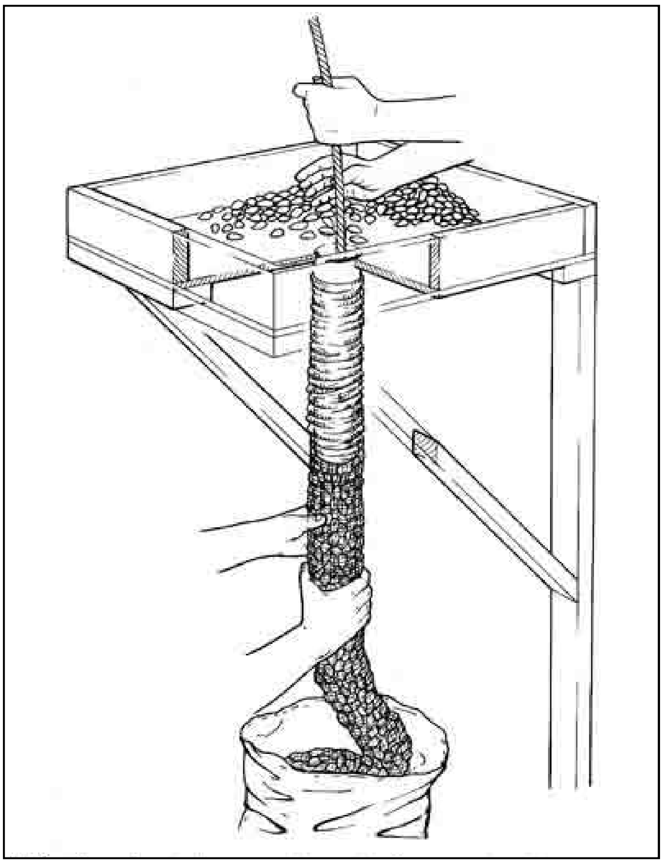

Figure 4: Re-seeding mussel juveniles on ropes surrounded by degradable stockings (Source: Jenkins 1985).

Although macroalgae and hydroids provide a critical primary settlement substrate for mussel larvae, little is known about the potential sources and turnover rates (sustainability) of these macroalgae and hydroids, the mechanisms that dislodge and transport them, and their life span in the water before and after mussel larvae settle upon them. Thus, it is important that future investigations answer questions about the location, size and distribution of these macroalgal and hydroid populations, the source of the associated debris and their combined role in mussel spat transport and arrival to coastal areas. Most importantly, still largely unknown is the location of the mussel broodstock populations that supply the large quantities of spat harvested in GLM 9 and which are a significant basis for producing this burgeoning aquaculture product.

This report reviews a range of methodologies to investigate population connectivity of this green-lipped mussel spat resource, and identifies knowledge gaps so that future research may be targeted in the most appropriate and beneficial areas. The Ministry of Fisheries intends that this review would help to facilitate the direction for future management and research activity, particularly given the potential demands on the resource with further expansion in the mussel aquaculture industry, whilst also recognising that the spat resource also supports an important local non-commercial fishery.

Overall Objectives:

1. To determine the best method(s) for investigating population connectivity of the green-lipped mussel resource and associated algal species at Ninety Mile Beach and adjacent coastal areas (GLM 9).

Specific Objectives:

1. Undertake a desk-top study to identify, review and evaluate various scientific methods (e.g., acoustic mapping, aerial photography, 2-dimensional hydrodynamic modelling, elemental fingerprinting, side-scan sonar swath mapping) that could be used to determine the extent of and relationship between populations of green-lipped mussel at Ninety Mile Beach and adjacent coastal areas.

2. Identify potential knowledge gaps in the green-lipped mussel fishery in GLM 9 and evaluate future research directions to best aid management objectives.

2 MUSSEL BIOLOGY AND ECOLOGY

The mussel genus *Perna* differs from the more diverse genus *Mytilus* by its geographic distribution and by morphological characteristics, such as position of muscle scars, soft tissue morphology, and shell colouration (Siddall 1980; Wood et al. 2007). There are three species in the *Perna* genus. *Perna canaliculus* (Gmelin 1791) is endemic to New Zealand, while *P. perna* (Linnaeus 1758) is found throughout South America and Africa, and *P. viridis* (Linnaeus 1758) is present in the Indo-Pacific.

In New Zealand, *P. canaliculus* is distributed widely throughout the three main islands (Figure 5), but is more common in the warmer northern parts of the country (Powell 1979). Dense beds of up to 100 individuals m^{-2} can be found in northern coastal areas (Stead 1971; Flaws 1975; Hickman 1991), which can include rocky reefs, wharf piles, and soft bottom habitats (Morton & Miller 1973). Intertidal (mid-littoral) populations are limited by aerial exposure (Paine 1971; Kennedy 1976; Marsden & Weatherhead 1998), while subtidal (down to 50 m; Powell 1979) populations are limited by predation pressure (Paine 1971). Environmental parameters, such as temperature and salinity, are strong determinants of the distribution of this species. Whilst its temperature range is from 5.3 °C in the south to 27 °C in the north (MacDonald 1963; Hickman 1991), *Perna canaliculus* appears to prefer the warmer waters of bays and estuaries in northern coastal areas. A wide range of salinities are tolerated by this species, although the optimum range is 30 to 35 PSU (Flaws 1975).

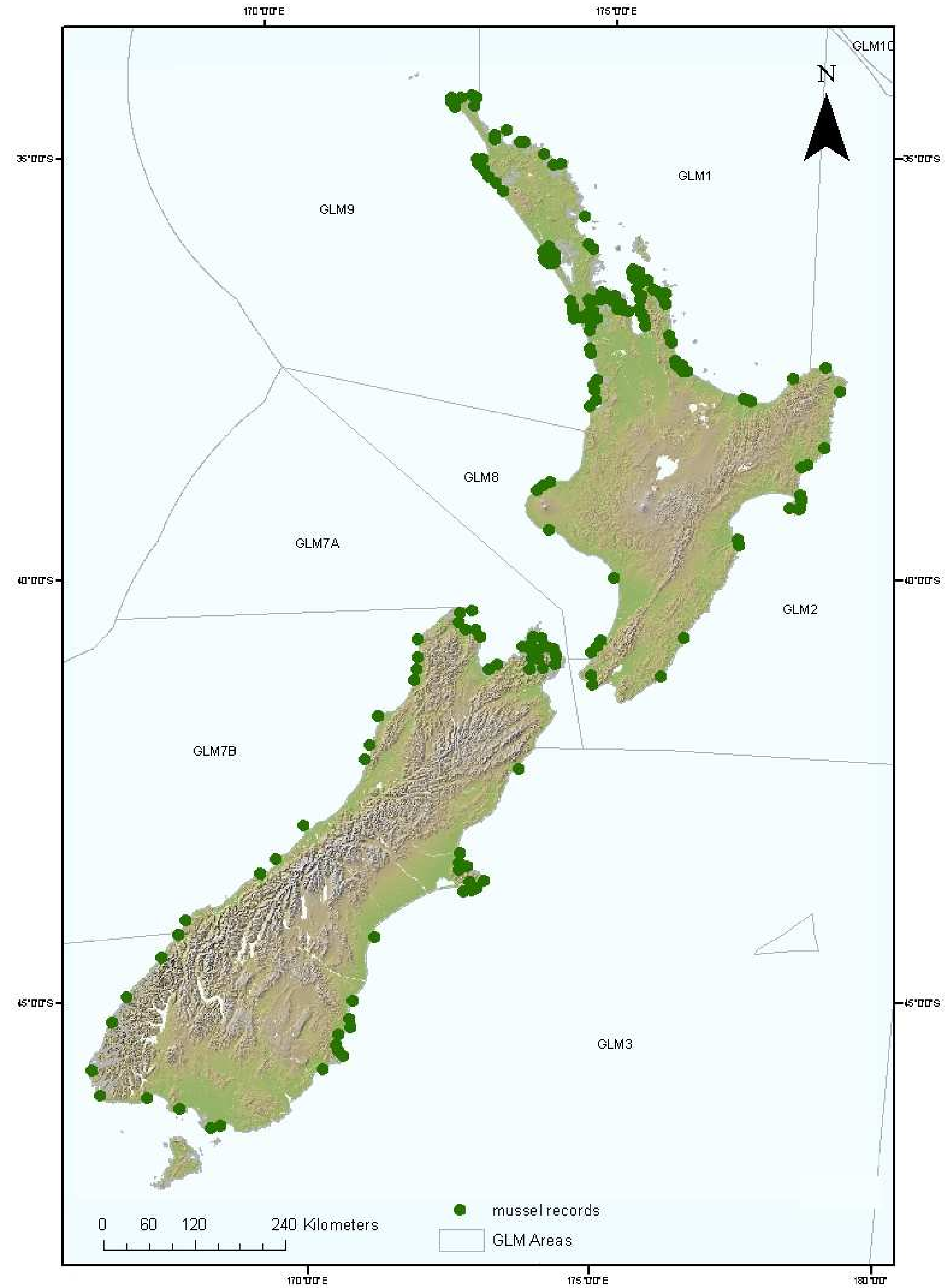

Figure 5: Map of New Zealand showing the known locations of *Perna canaliculus* complied from the records of the New Zealand Oceanographic Institute, Te Papa – National Museum of New Zealand, and the Auckland Institute and Museum (Source: Jeffs et al. 1999).

2.1 Reproduction

Perna canaliculus is a dioecious broadcast spawner (Jenkins 1985), and generally spawns in late spring to early autumn (Ministry of Fisheries 2010). However, differences in spawning times and durations may be apparent between northern and southern New Zealand populations. At Ninety Mile Beach in Northland, mussels mostly spawn between June and December (Alfaro et al. 2001; Alfaro et al. 2003), while two distinct spawning periods in early summer and autumn-spring are observed in the Marlborough Sounds (northern South Island) (Flaws 1975; Tortell 1976; Buchanan 1998). These variations in spawning activity have been attributed to regional temperature differences (Alfaro et al. 2001). For example, Alfaro et al. (2001) found that the water temperature at Ninety Mile Beach rarely dropped below 14 °C, whereas temperatures in Marlborough Sounds are between 10–11 °C in winter and 20–21 °C in summer (Tortell 1976; Jenkins 1985). In general, gametes can be released throughout the year (Jenkins 1985; Hayden 1995), but gonadal development only occurs at temperatures above 11 °C and is also closely related to food availability (Jenkins 1985; Redfearn et al. 1986; James & Ross 1997).

Variation in reproductive behaviour of green-lipped mussels has been found over relatively small spatial scales, including between intertidal versus adjacent subtidal populations, and amongst intertidal populations at Ninety Mile Beach (Alfaro et al. 2003). Marked differences in condition indices also have been identified for mussels transferred from Ninety Mile Beach to other growing locations around New Zealand, indicating that these differences in reproductive cycles are environmentally driven rather than genetically determined (Hickman & Illingworth 1980). Similar localised variability in reproductive activity has been observed for many other individual populations of these mussels (e.g., Ninety Mile Beach and Marlborough Sounds) (Flaws 1975; Tortell 1976; Buchanan 1998; Alfaro et al. 2001). At Ninety Mile Beach, subtidal populations of mussels were found to be larger in size than adjacent populations of intertidal mussels, which is thought to be due to higher growth rates. This is a potential explanation for the prolonged spawning period in subtidal beds compared to adjacent intertidal beds, which only have two to three short spawning periods during the year (Alfaro et al. 2003).

Wild *Perna canaliculus* populations have a 1:1 sex ratio and may have a high degree of spawning synchrony between sexes and amongst sites, including intertidal and subtidal populations (Flaws 1975; Tortell 1976; Buchanan 1998; Alfaro et al. 2001; Alfaro et al. 2003). In a single season, a female can produce up to 100 million eggs (Jenkins 1985) of about 56–62 µm in diameter, and males can produce countless sperm of about 54 µm in length (Redfearn et al. 1986). Fertilization takes place in the water column, and within hours the fertilized eggs progress to lecithotrophic trochophore larvae (Redfearn et al. 1986; Buchanan 1994).

2.2 Larval Development and Dispersal

Within 24 to 48 hours after fertilization, the trochophore larva develops into a D-shaped veliger larva (prodissoconch I) (Redfearn et al. 1986) (Figure 6). Veligers remain in the plankton for at least 3 to 5 weeks depending on water temperature, food availability and settlement cues, whilst in the laboratory the pediveligers usually settle around 30 days after hatch (Redfearn et al. 1986; Jeffs et al. 1999). During this planktonic phase, larvae may be transported up to several hundred kilometres by nearshore currents.

The larvae feed on phytoplankton, which may be supplemented with detritus (Manahan & Crisp 1983), bacteria (Douillet & Langdon 1993; Moal et al. 1996), and dissolved organic matter (Hayden

1995). At this stage it is believed that the veliger can migrate vertically in the water column; however, the factors that influence this behavioural movement are unknown.

The veliger shell grows (prodissoconch II, 100–250 µm) with a rounded umbo and highly angular shoulders (Booth 1977). Once this stage is complete, the pediveliger develops (at 4 to 6 weeks) to a shell length of 220 to 350 µm (Booth 1977). Settlement of pediveligers takes place when appropriate substrates for attachment are found, or they may remain in the plankton for several more weeks if settlement substrates are not encountered (Buchanan 1994; Hayden 1995). Settlement is complete once the mussel has attached by byssal threads, metamorphosis occurs and growth of the dissoconch begins (Buchanan 1994).

The settled larvae are known as plantigrades, or colloquially as mussel spat or seed. The settlement process takes place within minutes to 24 hours, and is mediated by chemical and biological cues (Young 2009). *Perna canaliculus* larvae prefer to settle on filamentous substrates, such as fine-branching macroalgae, hydroids, and other debris (Alfaro & Jeffs 2002, 2003; Alfaro et al. 2004) (Figure 6).

From a dispersal perspective, the time spent in the water column by larvae is very important for the potential movement of mussels (as larvae, spat or as juveniles) from site to site. It is widely believed that mussel spat are passive particles with the potential to be dispersed by currents over distances of 500 km or more, depending on local hydrodynamic conditions. Given the sessile adult lifestyle, the larval dispersal period maintains connectivity amongst populations, and therefore needs to be better understood in order to identify the nature of the links between source populations and migrating larvae.

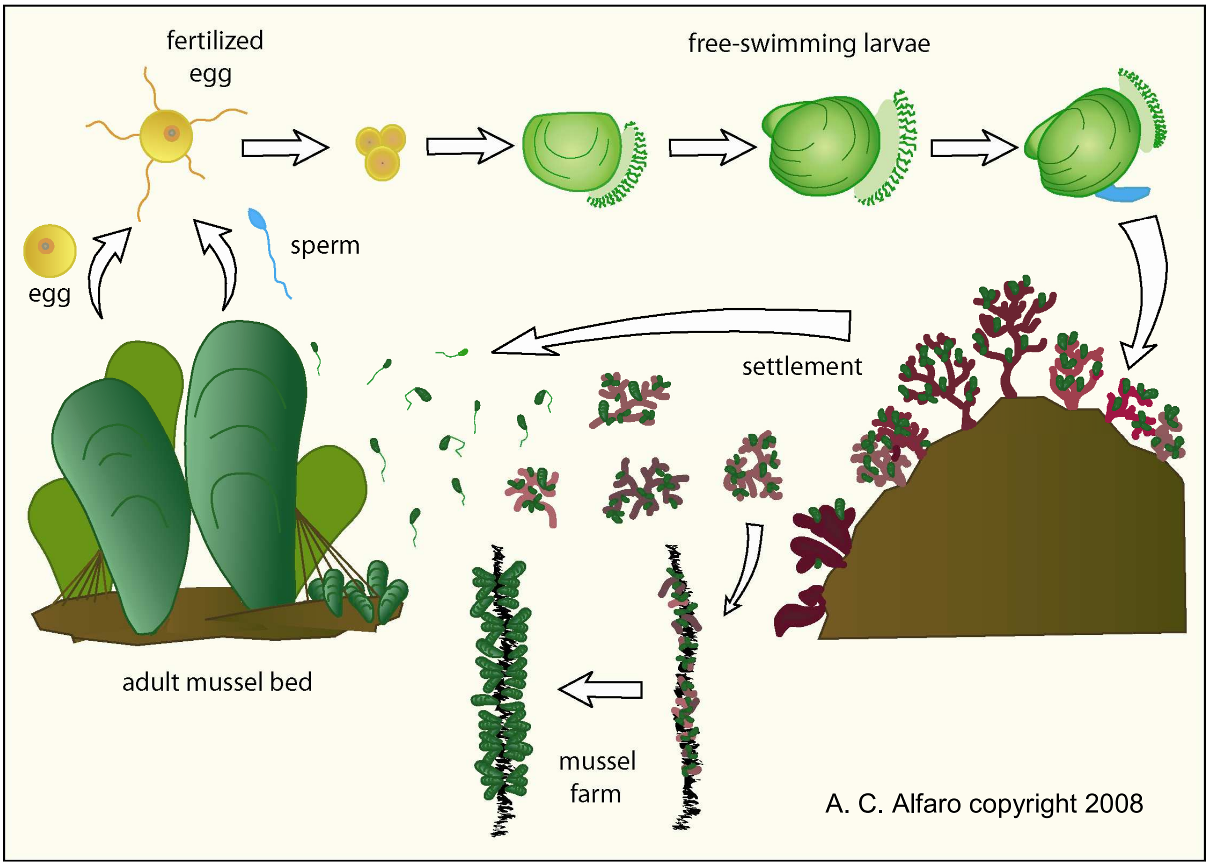

Figure 6: Life cycle of *Perna canaliculus*, including planktonic and benthic stages in the wild and farms. Primary settlement takes place on filamentous red seaweeds and then mussels transfer onto the rocky shore (adult population) as secondary settlers. Seaweeds with spat are harvested to seed the mussel ropes, from which they are harvested after 12–18 months (Diagram by A. C. Alfaro).

2.3 Settlement Processes

Bayne (1964) first described primary and secondary settlement processes after studying European blue mussel (*Mytilus edulis*) larvae, and noted that they settle initially on filamentous substrates (primary settlement) and then move to adult mussel beds (secondary settlement) as early juveniles (1–2 mm). This dual-stage transfer of mussels from a pelagic to a benthic existence is thought to be an evolutionary strategy to avoid predation, intraspecific competition and/or ingestion by adult mussels. Furthermore, Sigurdsson et al. (1976) and Lane et al. (1985) documented the use of a long mucus thread by *Mytilus edulis* to facilitate transport of juveniles from primary settlement sites to the adult mussel beds. This process has been termed "bysso-pelagic drifting", and may take place several times until the larvae settle successfully onto hard substrates. Primary and secondary settlement processes have been confirmed for *Perna canaliculus* through a range of field and laboratory experiments (Buchanan 1994; Buchanan & Babcock 1997; Alfaro & Jeffs 2002; Alfaro 2006c).

Field experiments on *Perna canaliculus* of Auckland's west coast beaches by Buchanan (1994) showed that mussel juveniles were distributed on algal substrates according to mussel size and degree of branching of the filamentous macroalgae. Thus, finely-branched macroalgae, such as *Laurencia thyrsifera*, *Champia laingii*, *Corallina officinalis*, and the hydroid, *Amphisbetia bispinosa* contained the highest number of "primary settlers" (smaller than 0.5 mm). Moderately-branched macroalgae (*Gigartina albeata*, *G. cranwellae*, *Pterocladia lucida*) had moderate numbers of primary settlers, "dispersers" (0.5–5.5 mm) and "stable" (larger than 5 mm) mussels. In addition, coarsely-branched macroalgae (*Melanthalia abscissa*, *Pachymenia himantophora*) and the rocky shore had a high number of dispersers, a moderate number of stable mussels, and only a few primary settlers (Table 1; Buchanan 1994; Table 1; Buchanan & Babcock 1997).

Buchanan (1994) also conducted laboratory and field choice experiments to test larval settlement preferences on various cleaned algal substrates. Both laboratory and field studies confirmed that primary settlers (smaller than 1.5 mm) preferentially settle on finely-branched macroalgae, and secondary settlers (larger than 1.5 mm) are more likely to settle on coarsely-branched macroalgae and upon the rocky shore.

Analyses of drift material with attached spat collected from the surf zone along Ninety Mile Beach also showed a significant inverse relationship between mussel size and degree of branching of the substrate (Alfaro & Jeffs 2002). Small mussels (smaller than 0.5 mm) were more abundant on fine-branching macroalgae (*Champia laingii*, *Plocamium costatum*, *Haliptilon roseum*, *Corallina officinalis*) and hydroids (*Amphisbetia bispinosa*, *Dictyocladium moniliferum*, *Crateritheca insignis*, *Aglaophenia acanthocarpa*, *Lytocarpia incisa*); whereas, larger mussels (1.5–2.0 mm) were more common on coarse-branching macroalgae (*Osmundaria colensoi*, *Carpophyllum angustifolium*, *Rhodymenia dichotama*). This settlement pattern was corroborated in laboratory experiments where artificial substrates (standard aquarium plastic plants) of different branching degrees were used as settlement substrates for different-sized mussels (Alfaro & Jeffs 2002). In addition, micro-scale settlement sites were investigated within natural and artificial substrates, and results revealed a strong preference of settlement in node areas (joints where branching takes place) over inter-node areas (straight branches without joints). These results were interpreted to reflect micro-scale selectivity by mussels to improve physical stability during the settlement process (Alfaro & Jeffs 2002).

Table 1: Different abundances of primary settlers of green-lipped mussels (<0.5 mm), secondary settlers (0.5-5.5 mm), and stable mussels (>6 mm) on various species of substratum. The greater the size of the circle, the greater the abundance of mussels found to be present (Source: Buchanan 1994; Source: Jeffs et al. 2005).

Substratum	**Primary settlers (<0.5 mm)**	**Secondary settlers (0.5 – 5.5 mm)**	**Stable mussels (>6 mm)**
Finely-branched hydroid			
Amphisbetia bispinosa	⬤	⬤	•
Finely-branched algae			
Corallina officinalis	⬤	⬤	•
Laurencia thyrsifera	⬤	⬤	•
L. botrychoides	⬤	⬤	•
Medium-branched algae			
Champia laingii	●	●	●
Gigartina alveata	●	●	●
G. cranwelliae	●	●	●
Coarse-branched algae			
Pterocladia lucida	•	⬤	●
Melanthalia abscissa	•	⬤	●
Pachymenia himatophora	•	⬤	●

Extensive manipulative experiments were conducted in the field to elucidate primary and secondary settlement processes at three rocky intertidal sites along Ninety Mile Beach (Alfaro 2006c). Short-term (daily) and long-term (monthly) settlement experiments were undertaken within quadrats that were cleared of all mussels in both the mussel bed and adjacent algal habitats (Figure 7). At all three sites, primary settlement (smaller than 0.5 mm) was highest in the algal habitats and settlement patterns on artificial mesh material mimicking macroalgae in both bare rock and algal habitats were similar to the natural substrates. These results support the hypothesis of strong selectivity by small mussels to settle on filamentous substrates. Secondary settlement was highest within the cleared quadrats on the mussel beds, this supports the hypothesis that a proportionally greater number of secondary settlers recruit amongst adults on the rocky shore.

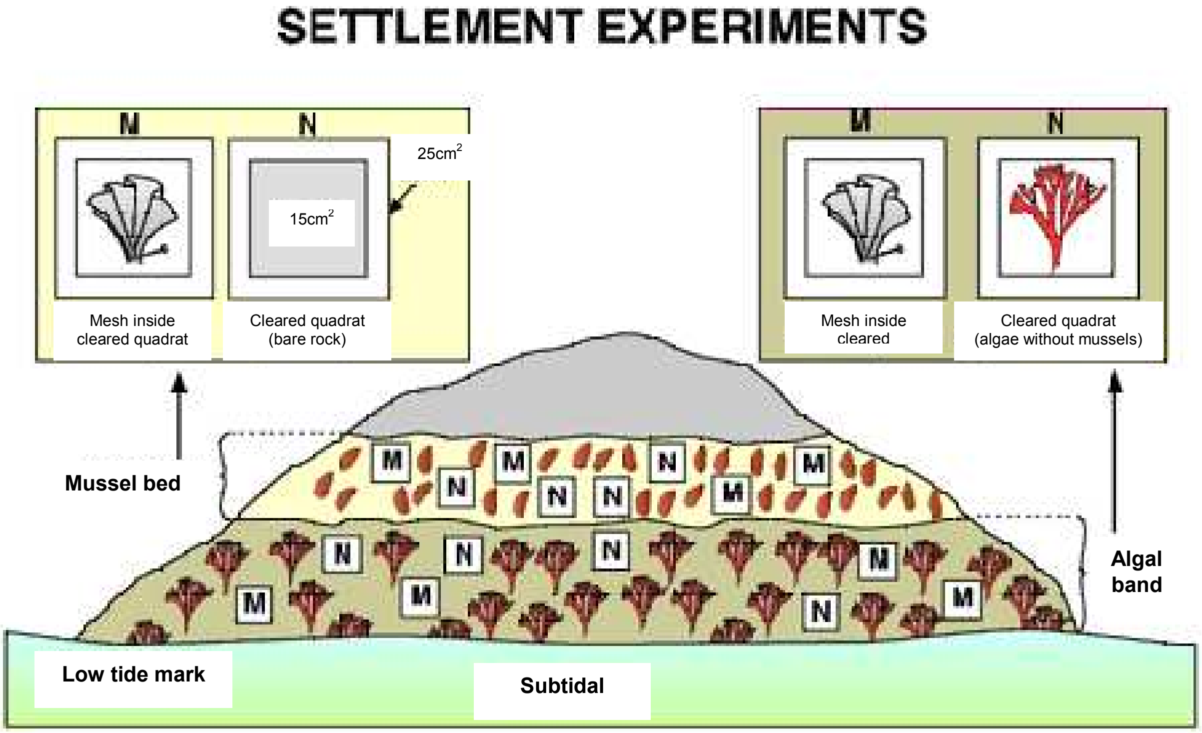

Figure 7: Arrangement of larval settlement experiments conducted at Ninety Mile Beach which revealed patterns of primary and secondary settlement of mussels of different size ranges (Source: Alfaro 2006c).

Extensive mussel larval settlement studies have not been undertaken elsewhere in GLM 9. A commercial spat collection initiative at the entrance to Whangape Harbour in the Far North collected some data on the effectiveness of various physical structures for spat catching. Similar small-scale studies on the potential for commercial spat catching also have been conducted at a number of other locations in GLM 9, including the Hokianga, Kaipara, Manukau, Aotea and Kawhia harbours. Aotea Harbour was a focus for spat collecting research for a number of years by the Ministry of Agriculture and Fisheries in the 1980's (Bartrom 1984; Bartrom 1985a,b; Bartrom & Potaka 1986). The research found that the seasonal pattern of settlement of mussel larvae on collecting ropes was similar to Ninety Mile Beach, with the majority arriving in late winter and early spring, but with some presence of settling spat throughout much of the year.

2.3.1 Settlement Inducers – Physical

Both the physical structure of the substrate and the environmental conditions have an influence on primary and secondary settlement, respectively. Not only are mussel larvae able to "investigate" the physical structure of surfaces, but they also can choose to move to new sites by detaching and re-attaching until a suitable recruitment site is encountered. In addition, laboratory experiments have shown that byssal attachment by spat to hard substrates is enhanced with increasing water motion (Alfaro 2005; Alfaro 2006a), oxygen concentration (Alfaro 2005), and air bubbles (Alfaro 2006a). Hatchery-reared (pediveliger) larvae and juveniles (0.5–3.0 mm) collected from Ninety Mile Beach were reported to have greater settlement in high water flow rates (10 cm s^{-1}), while higher oxygen concentrations (12 mg l^{-1}) increased larval settlement only, compared to lower water flows and oxygen concentrations, respectively (Alfaro 2005). Furthermore, mortality of larvae and juveniles was highest under low flow rates (1 cm s^{-1}) and decreased with increasing flow rate. However, increasing oxygen concentrations caused a decrease in mortality of larvae but not juveniles.

Further experiments by Alfaro (2006a) showed that juvenile mussels (3–5 mm) exposed to a combination of different water flow regimes (approximately 1, 5, and 10 cm s^{-1}) and with and without air bubble treatments settled in higher numbers in treatments with higher water flows and air bubbles. The higher water flows together with air bubbling also resulted in stronger byssal attachment by the spat (i.e., greater number of byssal threads) compared to those in slower flow rates and no air bubbles. These results support observations that mussel spat are more strongly attached to drifting material collected in the surf zone and nearshore along Ninety Mile Beach, compared to similar material dredged from sandy seafloor areas just offshore in 10–35 m water depth (Alfaro et al. 2004; Alfaro 2005). In addition, ongoing experiments by Young and Alfaro (unpublished data) have shown that increased surface roughness and colour (e.g., yellow) on plastic plates elicit greater larval settlement within hatchery-rearing environments.

While there has been quite a lot of research on larval settlement processes and subsequent spat behaviour, the natural larval settlement and post-settlement processes which are vital to providing the commercially harvestable spat supply in GLM 9 remain largely unknown.

2.3.2 Settlement Inducers – Chemical

The ability of *Perna canaliculus* to respond to chemical settlement cues was first documented by Alfaro et al. (2006). Crude organic extracts from macroalgae (*Scytothamnus australis*, *Melanthalia abscissa*, *Corallina officinalis*, *Carpophyllum maschalocarpum*, *Plocamium costatum*, *Osmundaria colensoi*, *Gigartina alveata*) were mixed with phytogel (neutral gelling compound), poured into Petri plates and tested for their ability to induce settlement of mussel larvae in field experiments conducted in the waters off Ninety Mile Beach. The results of these field experiments and similar laboratory experiments showed that the chemical extracts from *Scytothamnus australis* and *Melanthalia abscissa* significantly enhanced larval settlement compared to control plates.

Further research has tested 16 pharmacologically active compounds for their ability to induce settlement in *Perna canaliculus* larvae in 48-hour laboratory assays (Young 2009). Among the chemicals tested, potassium chloride, acetylcholine, atropine, epinephrine, L-DOPA, hydrogen peroxide, and cyclic adenosine monophosphate induced larval settlement with minimal acute toxic effects. High settlement was also recorded when larvae were exposed to potassium metabisulphite, sodium metabisulphite, ascorbic acid, caffeine, L-tryptophan, L-phenylalanine, and L-tyrosine, although these chemicals also were acutely toxic to the larvae (Young 2009). Conversely, exposure to gamma aminobutyric acid inhibited larval settlement. These findings have provided valuable information to deduce biochemical signalling pathways controlling larval settlement for *Perna canaliculus*, and to highlight similarities and differences between this and other mussel species.

Further experiments are currently underway to investigate the ability of surface-bound chemicals to induce and retain mussel larvae and juveniles on artificial surfaces, such as farming ropes (Young and Alfaro unpublished data). Initial results have shown that mussels have a significant attachment preference to positively charged surfaces, although retention of spat on the surfaces does not seem to be affected by surface charge (Young and Alfaro unpublished data).

2.3.3 Settlement Inducers – Biological

The ability of bacterial biofilms and biofilm exudates to induce *Perna canaliculus* larvae to settle was investigated by Ganesan et al. (2010). Marine bacteria were isolated from marine seaweeds, seawater and mussels, and cultured on marine agar plates. Three main strains (*Macrococcus* sp. AMGM1, *Bacillus* sp. AMGB1 and *Pseudoalteromonas* sp. AMGP1) were selected, and used for mussel settlement assays. Bacterial biofilms and biofilm exudates from *Macrococcus* sp. AMGM1 and *Bacillus* sp. AMGB1 significantly increased larval settlement (over 60%) compared with controls. Conversely, *Pseudoalteromonas* sp. AMGP1 did not induce larval settlement in the treatments, and resulted in extremely high larval mortality. These results suggest that settlement cues for *Perna canaliculus* may be produced by some bacterial biofilm cells and/or their biofilm exudates that probably cover the surface of settlement materials.

Further larval settlement work (Ganesan et al. 2010) with various bacterial phases (planktonic cells versus biofilm) and exudates of *Bacillus* sp. AMGB1 demonstrated that the planktonic phase did not induce mussel settlement, compared to the bacterial surface biofilm phase and exudates. Characterisation of the exudates revealed that the molecular weight of the settlement inductive cue was at least 10 k Da. In addition, exudates treated at 70 °C were still able to induce settlement, indicating that the inductive cue is thermally stable.

2.4 Larval Abundance

Analyses of plankton tows conducted off the southern end of Ninety Mile Beach showed a good agreement between spat abundance and the reproductive cycle of intertidal and subtidal adult populations in the area (Alfaro et al. 2004). Plankton samples taken at nearshore and offshore sites indicated that there were higher mussel larval abundances during the spawning period in July 1999 compared to subsequent samples taken over the following 6 months. Higher abundances of planktonic larvae were found inshore and at the southern end of Ninety Mile Beach. These patterns of distribution were attributed to local hydrodynamic conditions, including an eddy that may retain larvae at the southern end of the Ninety Mile Beach.

Concentrations of pelagic mussel stages in seawater samples collected near three intertidal mussel beds along Ninety Mile Beach (Scott Point, The Bluff, and Tonatona Beach) also reflected the reproductive cycle of the local mussel populations (Alfaro 2006c). Small larvae and post-larvae (smaller than 0.25 mm) were more abundant in the water samples at the beginning of the spawning season in August 2000 and least abundant at the end of the spawning season in December 2001. Conversely, larger size classes of mussels (larger than 0.5 mm), made up primarily of drifting secondary settling spat, were more abundant in March 2001. In addition, all mussel size classes were more abundant at Scott Point (northern end of the beach) and least abundant at The Bluff, a rocky intertidal reef on Ninety Mile Beach, 55 km north of Ahipara. It is unknown if these reproductive patterns are similar for other populations throughout the North Island, but they do appear to differ from populations in Marlborough Sounds, South Island (Alfaro et al. 2001, 2003).

2.5 Spat and Algal Abundances

The size and number of spat present in commercially harvested spat and associated beach-cast material along Ninety Mile Beach were analysed over a period of 19 months from October 1998 to April 2000 (Alfaro et al. 2004). A distinct cycle of spat abundance was observed, with lowest values (21 x 10^3 mussel spat kg^{-1} of beach-cast material) in March-April, increasing over winter to a maximum (1516 x 10^3 mussel spat kg^{-1} of beach-cast material) in August. The smallest mussels (smaller than 0.5 mm) were most abundant in August and the largest mussels (larger than 2.0 mm) were most abundant in January. There was a clear shift in the abundance of mussels in progressively larger size classes over time (less than 0.49, 0.5–0.99, 1.00–1.49, 1.50–1.99, and greater than 2.0 mm) indicating that most spat are generated from a single spawning period in June-July. The same progression in the size of spat found in this study was also evident in mussel spat material dredged from off the coast of Ninety Mile beach.

Bottom-drifting material (e.g., macroalgae, hydroids and debris) with associated spat was also sampled by dredge from near the sandy seafloor offshore Ninety Mile Beach from October 1998 to April 2000 (Alfaro et al. 2004). Monthly samples of the material were obtained from three inshore (5 km) and three offshore (15 km) locations at the southern end of the bay. The sampled clumps of mostly filamentous red macroalgae contained almost exclusively attached *Perna canaliculus* spat. In general, spat were more abundant at the southern and inshore sites compared to offshore and more northerly sampling sites. The greatest quantity of algal material (about 7 kg m^{-2}) was dredged from the southern end of the beach in July and August, and subsequently decreased. Nearshore water flow that runs in a northward direction along Ninety Mile Beach was thought to have a significant effect on the algal and spat composition of drifting material over time. Distinct rafts of bottom-drifting spat material that were not harvested were sampled daily during their north-bound movement. Analyses of these samples indicated that this bottom-drifting material was sorted by natural physical processes as it was moved along the beach by water currents. Heavier, fine-branching macroalgae covered with small spat were found in greater proportions at the southern end of the dispersed raft, and lighter coarse-branching macroalgae (mostly brown macroalgae with air bladders) were transported farther north with the current flow. These results corroborated the direct relationship between spat size and algal branching degree reported in previous studies (Alfaro & Jeffs 2002,2003; Alfaro et al. 2004).

The direct settlement of larval mussels onto spat-collecting ropes placed in the water column at the southern end (inside and outside of Ahipara Bay) of Ninety Mile Beach was recorded during two spawning seasons in 1999 and 2000 (Alfaro & Jeffs 2003). In general, small mussels (less than 0.5 mm) were found to be more abundant on rope collectors at shallow depths (2 m) in August-September, and larger early juvenile mussels (larger than 1.0 mm) were more abundant on collectors at greater depths (18 m) in December.

2.6 Composition of Spat Material

The composition of harvested spat material from Ninety Mile Beach is extremely variable. Eleven samples of spat material taken from spatfall events at the beach between October 2004 and January

2005 were analysed (Jeffs et al. 2005). Algae, especially fine filamentous red seaweeds, were the dominant component of the spat material, making up on average nearly half by wet weight (Figure 8). Mussel spat was the second major component of the spat material comprising 26% by wet weight of the samples. Sediment made up around 19% of the wet weight, while the remainder was made up of hydroids, land plant material (wood and leaves), shells, and other material (egg cases, plastics, etc.) which were all only minor contributors, making up on average 3%, 2%, <1% and <1% by wet weight of the total sample (Figure 8).

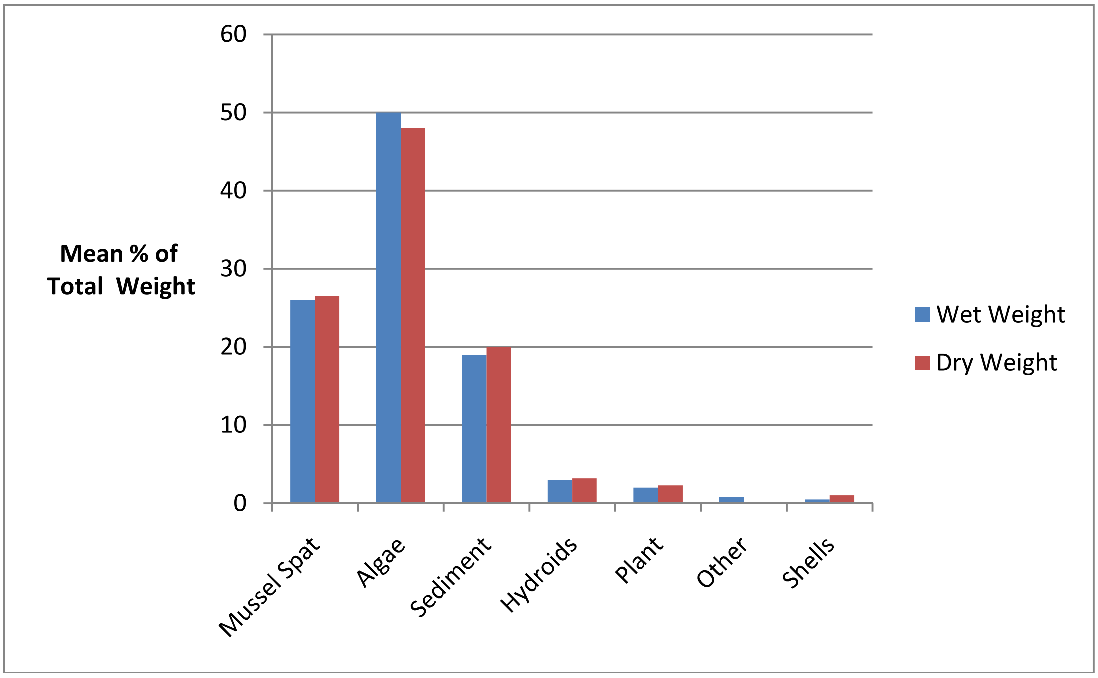

Figure 8: Proportional composition of mussel spat material sampled from commercial harvests from Ninety Mile Beach from October 2004 and January 2005 (Source: Jeffs et al. 2005).

2.7 Natural Movements of Spat Material

Research to date clearly indicates that distributions of mussel larvae and juveniles at Ninety Mile Beach have a close association with spawning cycles and some of the properties of the macroalgal, hydroids and debris with which they are associated (i.e., abundance, morphology and chemistry). In addition, as the spat material is moved along the sandy coastline, spat and drift seaweed associations are sorted spatially and temporally by local hydrodynamic processes, e.g., along-shore transport and possibly localised coastal eddies (Alfaro et al. 2004).

It is still unclear whether mussels settle primarily on attached or detached biological material, such as seaweeds and hydroids, but it is evident that mussels have the ability to “re-distribute” themselves across the available substrates (bottom-drifting material) possibly to improve their dispersal success (Alfaro et al. 2004). This bottom-drifting transport process also retains potential secondary settlers in close proximity to the seafloor to improve the chances of the juveniles encountering suitable hard substrates upon which to colonize and recruit to benthic adult mussel beds.

Oceanographic and weather patterns undoubtedly also play an important role in the aggregation and transport of drift material. At Ninety Mile Beach, spat dispersal is associated with “loose-lying” or bottom-drifting detached macroalgae, hydroids, and debris. This bottom-drifting material, often densely covered with spat (up to 100% cover, or 200 million kg^{-1} of drift material) is neutrally or negatively buoyant, and requires a subsurface transport mechanism for dispersal (Alfaro et al. 2004). In addition, as a consequence of strong water movements associated with turbulence and wave-induced bottom stresses during storm events, attached algae and hydroids may become dislodged and accumulate into clumps that tumble near the bottom, where mussel spat may continue to attach to this material.

In an attempt to better understand the daily, monthly, and inter-annual patterns of the arrival of spat at Ninety Mile Beach, the records of spat harvesters from 1990 to 1999 were analysed in relation to historical records of wind speed and direction, tidal range, water temperature, and modelled swell height and direction (Alfaro et al. 2010). For the long-term data set, the number of spatfall events and amount of spatfall material per event increased markedly with strong offshore winds. On days with a large tidal range, there tended to be an increase in the amount of spatfall, but this trend was not significant statistically.

Daily and seasonal water temperature records did not show a significant effect on the timing or scale of spatfall events. However, low swell height in the onshore direction was associated with a significant increase in spatfall events and spatfall amounts. Within the 9 year data set, storm events (wind speeds greater than 20 m s^{-1}) were most frequent during May to October. An average lag time of 4 months was found between peak storm events and the subsequent peak in spatfall events and amounts of spatfall occurring in September to October. Years with a greater number of storm events (La Niña episodes) also were associated with significantly higher numbers of spatfall events and amounts of spatfall.

Away from Ninety Mile Beach, there is no information on natural movement of spat material, although it has been observed to wash up in small quantities on rare occasions on other west coast beaches within GLM 9, such as Bayley's Beach near Dargaville, and Miti Miti Beach north of Hokianga Harbour.

2.8 Adult Mussel Beds in GLM 9

A small number of the accessible intertidal and subtidal adult mussel populations adjacent to Ninety Mile Beach have been studied in some detail (Alfaro 2006b; Alfaro 2006c). The individual beds were found to differ markedly in their ability to produce larvae, and their larval production and population turnover rates were highly dependent on variables such as reproduction (Alfaro et al. 2001; Alfaro et al. 2003), settlement and recruitment processes (Alfaro 2006c), as well as other biological factors, such as larval residence time and cannibalism (Alfaro 2006b). However, the contribution and importance of these localised mussel beds to spatfall events on the adjacent Ninety Mile Beach is unknown. Indeed, the locations and extent of the adult mussel beds providing the large quantities of mussel spat harvested at Ninety Mile Beach remain unknown.

The population dynamics of three intertidal mussel beds (Scott Point, The Bluff, and Tonatona Beach) along Ninety Mile Beach were investigated over a 2-year period (Alfaro 2006c) (Figure 9). Monthly mussel abundances and size-frequency distribution analyses indicated that peak recruitment (juveniles of 5–24 mm) coincided with high mortality of existing resident mussels in the established mussel beds during August.

Of the three sites, Scott Point had the most dynamic population turnover and a distinctive annual cycle. The cycle involved high recruitment in August through to December, following local spawning events. Afterwards, mussels continued to grow from December to July, at which time they "peeled off" from the rocky shore in high mortality events, creating empty spaces for new recruits. During this time, established mussels were overgrown and smothered by numerous small recruits. A similar, but less pronounced pattern was observed at Tonatona Beach and The Bluff.

The easily accessible adult intertidal mussel beds in GLM 9, including Scott Point, The Bluff, and Tonatona Beach (located at Reef Point), are also popular locations for non-commercial harvesting of mussels. Customary harvest of mussels in this area is especially common given the continuing strength of the Maori community and customs in this area. Therefore, the mussel spat resource also plays an important role in replenishing this important non-commercial fishery in GLM 9.

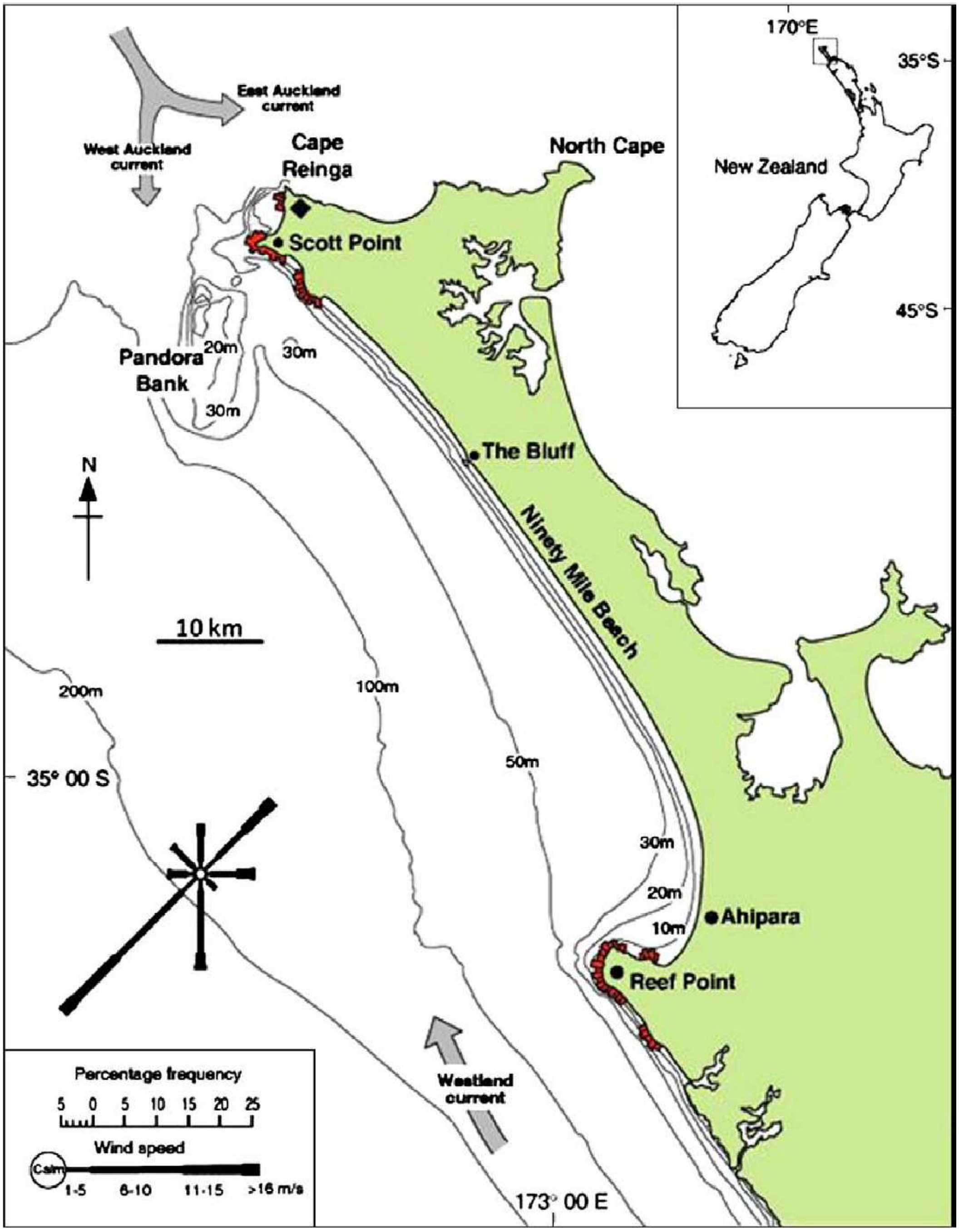

Figure 9: Map of the study site at Ninety Mile Beach, northern New Zealand. Three major intertidal mussel populations are found at Reef Point (including Tonatona Beach, The Bluff, and Scott Point. Two major currents that affect the area are the West Auckland Current and the Westland Current. Predominant winds are from the southwest direction. The location of the Cape Reinga meteorological station is identified with a black diamond (Source: Alfaro et al. 2010).

The growth and health of mussels in these intertidal populations along Ninety Mile Beach also were investigated by Alfaro et al. (2008). This study involved a mark and recapture experiment with young mussels (15–35 mm), and an evaluation of the growth of adult mussels (70–80 mm) over a one-year period. Fast-growing mussels with high condition indices and low levels of shell parasitism were found at Scott Point. Conversely, The Bluff contained mussels that were slow-growing, with low condition indices, and a high degree of shell parasitism. In addition, population turnover rates were calculated to be 2.5, 1.6, and 1.1 years for Scott Point, The Bluff, and Tonatona Beach, respectively. Differences amongst the three sites were suggested to be due to variations in food availability, sediment loads, and human disturbance (Alfaro et al. 2008).

Gaining new information about subtidal mussel populations at Ninety Mile Beach has been limited by difficulties in accessing these sites. However, sonar remote sensing tools (QTC-View) used in conjunction with underwater drop cameras offshore from Ahipara Bay found adult mussels at 25 m depth, a much greater depth than previously associated with this mussel (Morrison et al. 2010). This recent finding greatly extends the potential range of the source broodstock populations of mussels for the spat harvested at Ninety Mile Beach. In addition, sampling at two subtidal sites (Wizard Rock and Blue House) between Ahipara and Reef Point at the southern end of Ninety Mile Beach has shown that these mussel beds have the potential to yield a great number of mature individuals with high reproductive output, prolonged spawning periods (Alfaro et al. 2001; Alfaro et al. 2003), and fast growth rates compared with nearby intertidal populations (Alfaro 2006b).

Anecdotal information suggests that extensive mussel beds are located not only just off Tauroa Point (southern end of Ninety Mile Beach), but also off of Scott Point (northern end of the beach) and around Matapia Island, which is 1.6 km offshore and 12 km north of The Bluff. Anecdotal reports also intimate that extensive subtidal mussel beds extend further afield throughout GLM 9 including the margins of Columbia Bank to the north, and south around the entrances of the Whangape, Hokianga, Kaipara, and Manukau harbours, as well as offshore of many of the rocky intertidal reefs and islets found along the west coast of GLM 9. However, the extent of these beds and their potential contribution to spat and macroalgal resources at Ninety Mile Beach and other locations in GLM 9 is not known.

There are few studies of adult mussel populations at other locations within GLM 9, especially at accessible intertidal populations near Auckland City. Experimental removal of the predatory starfish, *Stichaster australis*, on a rocky intertidal reef at Anawhata over a 9 month period resulted in *Perna canaliculus* extending its vertical distribution down the shore by 40% and increasing its overall shore coverage by as much as 78% (Paine 1971). The conclusion of this study was that the presence of the starfish predator was critical in limiting the population expansion of the mussels on intertidal shores. Results of this study also suggest that broodstock mussel populations of green-lipped mussels could be vulnerable to population explosions or introduction of invasive species of predatory starfish, such as the northern Pacific seastar, *Asterias amurensis* (Ross et al. 2004). For example, introduction of this starfish species together with the European green crab, *Carcinus maenas*, into Tasmanian waters has had a dramatic impact on native bivalve species through predation.

Green-lipped mussels were also observed as a major occupier of space in artificially cleared areas on rocky intertidal reefs at Piha Beach, west of Auckland (Luckens 1976). However, human harvesting was responsible for suppressing the size of the population, as has been observed in other studies of these populations west of Auckland City (Barrett 2001). Settlement of juvenile mussels was observed throughout much of the year, especially during late winter and spring. Piha Beach was later used for settlement behaviour experiments in green-lipped mussels by Buchanan (1994), who explored settlement behaviour in relation to morphology of different species of macroalgae.

3 ORIGIN AND BIOLOGY OF DRIFT MATERIAL

There is virtually no information regarding the sources of drift seaweed and other materials that constitute the settlement substrate for mussel spat harvested at Ninety Mile Beach. Other than the commercial harvesting of beach-cast material along the beach for mussel farming, small collections of seaweeds (mostly *Pterocladia lucida*) for chemical extraction (i.e., agar, carrageenans) are undertaken along the southern end of the beach and south of Tauroa Point to Whangape Harbour.

Extensive surveys of intertidal areas along Ninety Mile Beach did not identify any significantly large macroalgal beds of any of the drift algal species and, given the typical habitats of the algal and hydroid species mostly found in the spat material, it is highly likely that the drift material is subtidal in origin (Alfaro 2001).

Subtidal macroalgae and hydroids (Table 2) associated with subtidal reefs have been observed by drop video camera and divers off Tauroa Point, but their extent is unknown (Alfaro 2001; Morrison et al. 2010). The source of the land plant debris included in the spat material is also unknown, but is likely to originate from either wind-blown material, or riverine sources, such as rivers leading into the harbours south of Ninety Mile Beach.

Table 2: Species of drift algae and hydroids found with attached mussel spat on Ninety Mile Beach (Source: Jeffs et al. 2005).

Algal type	Species	Reference
RED ALGAE	*Champia laingii*	Alfaro 2001
	Gigartina alveata	Hickman 1976
	Gigartina marginifera	Alfaro 2001
	Haliptilon roseum	Alfaro 2001
	Laurencia thyrsifera	Alfaro 2001
	Melanthalia abscissa	Alfaro 2001
	Osmundaria (*Vidalia*) *colensoi*	Alfaro 2001; Hickman 1976
	Pachymenia himantophora	Hickman 1976
	Pachymenia lusoria	Alfaro 2001
	Plocamium costatum	Alfaro 2001
	Rhodymenia dichotoma	Alfaro 2001
	Pterocladia lucida	Alfaro 2001
	Pterocladia capillacea	Alfaro 2001
GREEN ALGAE	*Codium fragile*	Hickman 1976
BROWN ALGAE	*Carpophyllum maschalocarpum*	Hickman 1976
	Carpophyllum angustifolium	Alfaro 2001
	Cystophora retroflexa	Hickman 1976
	Cystophora torulosa	Hickman 1976
	Durvillaea antarctica	Hickman 1976
	Ecklonia radiata	Hickman 1976
	Lessonia variegata	Hickman 1976
HYDROIDS	*Amphisbetia bispinosa*	Alfaro 2001
	Dictyocladium moniliferum	Alfaro 2001
	Crateritheca insignis	Alfaro 2001
	Alaophenia acanthocarpa	Alfaro 2001
	Lytocarpia incise	Alfaro 2001

4 SPAT SUPPLY

4.1 History of Spat Collections at Ninety Mile Beach

Commercial harvesting of mussel spat from Ninety Mile Beach began on a very small scale in the early 1970's by the Wedding family, who supplied it to McFarlane's Fisheries Ltd., a company that had begun experimenting with mussel farming in the Hauraki Gulf in the late 1960's (Dawber 2004). In August 1974, Bob Hickman from the Fisheries Research Division of MAF and fisheries officer, Frazer McLean, were on Ninety Mile Beach doing routine sampling when they discovered beach-cast seaweed that was encrusted with great numbers of *P. canaliculus* spat (Hickman 1976; Dawber 2004).

Sampling and subsequent experimentation with the spat in the rapidly growing mussel aquaculture industry in Marlborough Sounds led to regular commercial harvesting of spat material from Ninety Mile Beach. For example, in mid-September of 1978 a total of 67 consignments of mussel spat were sent to Marlborough Sounds following a large stranding of spat material at Ninety Mile Beach. Initially the spat material was air-freighted to the South Island, but methods for chilling and land-freighting the spat were then developed. The discovery of the spat supply at Ninety Mile Beach, and subsequent development of efficient methods for transferring it onto mussel farming ropes, have facilitated the rapid growth in production of the Greenshell mussel aquaculture industry.

The volume of spat collected from Ninety Mile Beach has continued to increase, together with the growth in production of this aquaculture industry. Nonetheless, the annual harvest of spat has been highly variable, often affected by availability of sufficient spat material arriving at Ninety Mile Beach (Figures 1 and 10). For example, a reduced harvest of spat in 1999–2000 resulted in substantially decreased aquaculture production in 2001–2002. The decrease in harvesting spat during this period was due to concerns about the transfer of cysts of the toxic microalgae *Gymnodinium catenatum* from Ninety Mile Beach to mussel growing areas around the country with the transfer of spat for seeding farms (Jeffs et al. 2005). A similar event occurred in 1991–1992 for the toxic microalgae *Gymnodinium breve*, which also resulted in a reduction in the harvest of spat and subsequent mussel production.

After 2002, there was a general reduction in the total volume of spat harvest at Ninety Mile Beach due to farmers making more efficient use of spat, as well as the development of alternative sources of spat for security as a result of the toxic algal event (e.g., line-caught spat in Golden Bay and hatchery production). Unfortunately, accurate harvesting records for this fishery are not available so it is difficult to be entirely confident of the harvest history (Ministry of Fisheries 2004). More recent figures of total annual landings for GLM 9 recorded against Individual Transferable Quota holdings appear to be below the records of pre-QMS landings that were based mostly on access to commercial invoice records of fishers (Figure 10).

Anecdotal information from Greenshell aquaculture industry personnel suggests that the harvest of spat from the fishery has been increasing, as it is generally believed that using wild spat from Ninety Mile Beach is the most cost effective method for seeding mussel farms. Certainly, the increased production from the Greenshell aquaculture industry would suggest an increased use of mussel spat (Figure 1). Landing data for the fishery does not support the proposition that total spat catches from GLM 9 have been increasing in recent years (Figure 10). However, discussions with industry personnel indicated that there has been an increasing amount of sorting of harvested spat material, with material containing small amounts of spat being returned to Ninety Mile Beach as a quota sparing measure. Mussel farmers are also reported to be attempting to make more efficient use of spat material when seeding their farms.

The management of the spat resource in GLM 9 has changed since the inception of the commercial fishery in the early 1970's. Initially, management was under a fishing permit (section 63, Fisheries Act 1983) and later a spat catching permit 67Q2(b) issued under the Fisheries Act 1993. Between 2004 and 2005 the harvesting of green-lipped mussel spat was brought into the QMS with a total allowable commercial catch (TACC) of 250 tonnes per annum set based on available knowledge at the time (Ministry of Fisheries 2004). At this time the Ministry believed that "the harvest of juvenile green-lipped mussel is unlikely to affect the productive capacity of the stock, because if juvenile green-lipped mussel is not harvested it lands on the beach and dies, or floats off into the Tasman Sea" (Ministry of Fisheries 2004). The TACC was based on the estimate that juvenile green-lipped mussel greenweight is on average 50% of the weight of the landed material and the Ministry expected that commercial fishers would use the same 50% of the weight of landed material to report mussel greenweight landings as was used to set the TACC (Ministry of Fisheries 2004). The introduction of the QMS also removed method controls for the harvesting of green-lipped mussel spat at Ninety Mile Beach because the Ministry considered that there was a lack of evidence to show the risk posed to the environment by harvesting methods other than hand gathering was high enough to justify regulating for method controls (Ministry of Fisheries 2004).

Under the QMS a further 39 and 59 tonnes of catch were allocated to recreational and customary fishers respectively (Ministry of Fisheries 2004). These allowances were based on a recreational fisheries survey conducted in 2002, with an additional 50% increase made for calculating customary harvest (Ministry of Fisheries 2004).

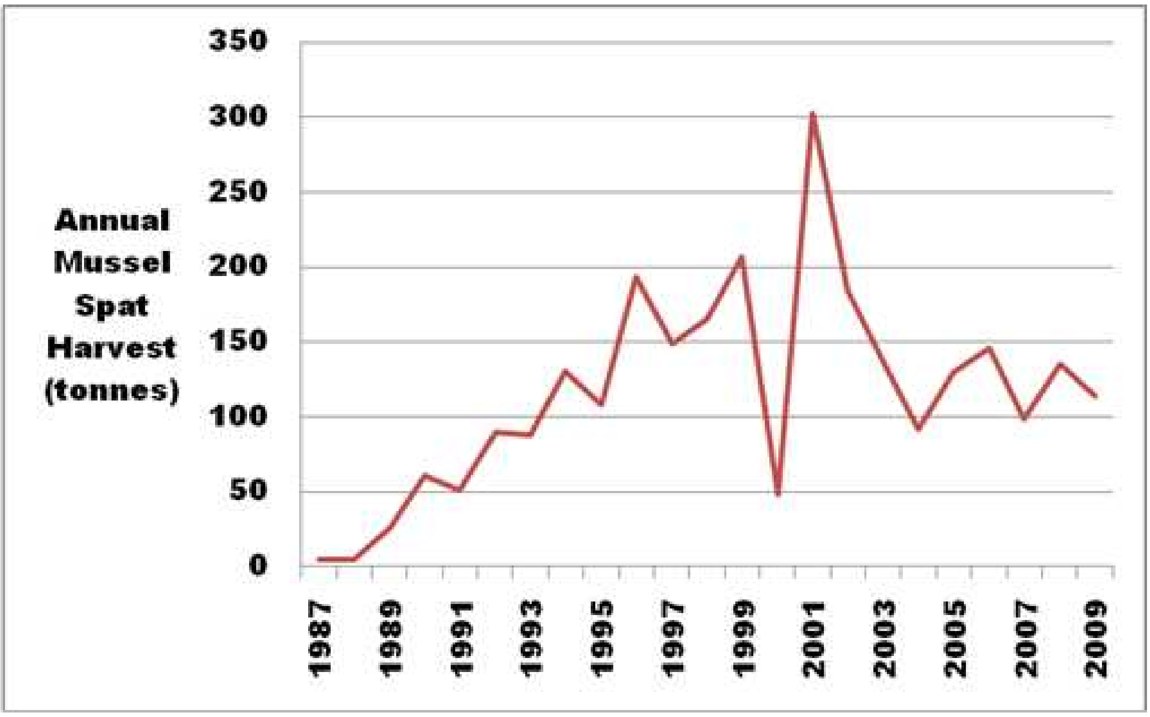

Figure 10: Annual harvest of mussel spat from Ninety Mile Beach (Source: Jeffs et al. 1999). Ministry of Fisheries catch data have been included in this graph.

4.2 Issues for Spat Supply from GLM 9

A number of threats to the harvesting of spat from GLM 9 have been identified: toxic microalgae, parasites and viruses, invasive species, oil spills, climate change and depletion of broodstock populations.

Toxic microalgae can kill shellfish or cause restrictions on transfer. For example, in 1998 a bloom of *Karenia brevisulcata* (synonymous with *Gymnodinium brevisulcatum*) in southeastern North Island caused mass mortalities of marine organisms, including *P. canaliculus*, and cultured shellfish larvae (Tong 1998; Wear & Gardner 2001).

A number of parasites and a viral disease have been found to be associated with *Perna canaliculus*. Probably of greatest concern is an RNA virus which has been associated with mortality of larvae, spat and adults from a number of locations around New Zealand (Hay & Hooker 1994; Jones et al. 1996). It appears that the virus only causes severe mortalities when mussels are stressed or vulnerable, and natural rates of adult mussel mortalities due to the virus are low.

The introduction of invasive species of bivalve predators, such as the northern Pacific seastar, *Asterias amurensis*, or the European green crab, *Carcinus maenas*, poses a significant risk to native shellfish beds. For example, the introduction of these two species into Tasmanian waters has had a dramatic impact on native bivalve species through predation (Ross et al. 2004).

Broodstock populations in GLM 9 are likely to be located in shallow coastal waters or intertidally, where an oil spill could most likely cause an impact, especially because the prevailing winds and swell on this coast are onshore (Alfaro 2001; Jeffs et al. 2005). If dispersants are used to suspend and disperse oil droplets into the water column, this could exacerbate the problem by exposing benthic feeding mussels to oil residues. A large portion of the waters covered by GLM 9 are currently under consideration for oil exploration as an extension of the petroleum developments off the Taranaki coast further south.

A vessel incident on this coastline also could cause a petroleum spill. For example, a regular visitor to the west coast of North Island, the *Taharoa Express*, a 146,000 tonne bulk carrier, became incapacitated off the west coast of North Island on three occasions between 2003 and 2007 (Figure 11). In April 2003, when the vessel was stalled by a broken propeller shaft, it was reported by the NZ Herald to be carrying 1100 tonnes of heavy fuel and 370 tonnes of diesel. No single tug in New Zealand was capable of towing the stricken vessel.

The impact of climate change on mussel populations in GLM 9 is unclear. However, climate change models predict that mean westerly wind flow over Northland will increase by around 10% by 2050, which is likely to result in a reduction of the delivery of spat into the shallow waters of Ninety Mile Beach (Mullan et al. 2001; National Institute of Water and Atmospheric Research 2004).

Mussel spat has been harvested from Ninety Mile Beach in relatively large volumes for thirty years with no markedly obvious effects on continued supply. It is unlikely that any impact would become apparent unless it had an extreme effect on the wild broodstock populations responsible for the ongoing production of spat. Nonetheless, experience has shown that the recovery of benthic green-lipped mussel populations following their loss or removal can be very slow or non-existent, even after decades (McLeod 2009). The exact cause of this slow recovery of naturally occurring mussel populations is not clear and may be due to interrupted recruitment processes or increased sedimentation from land erosion (Jeffs 1997; Morrison et al. 2009).

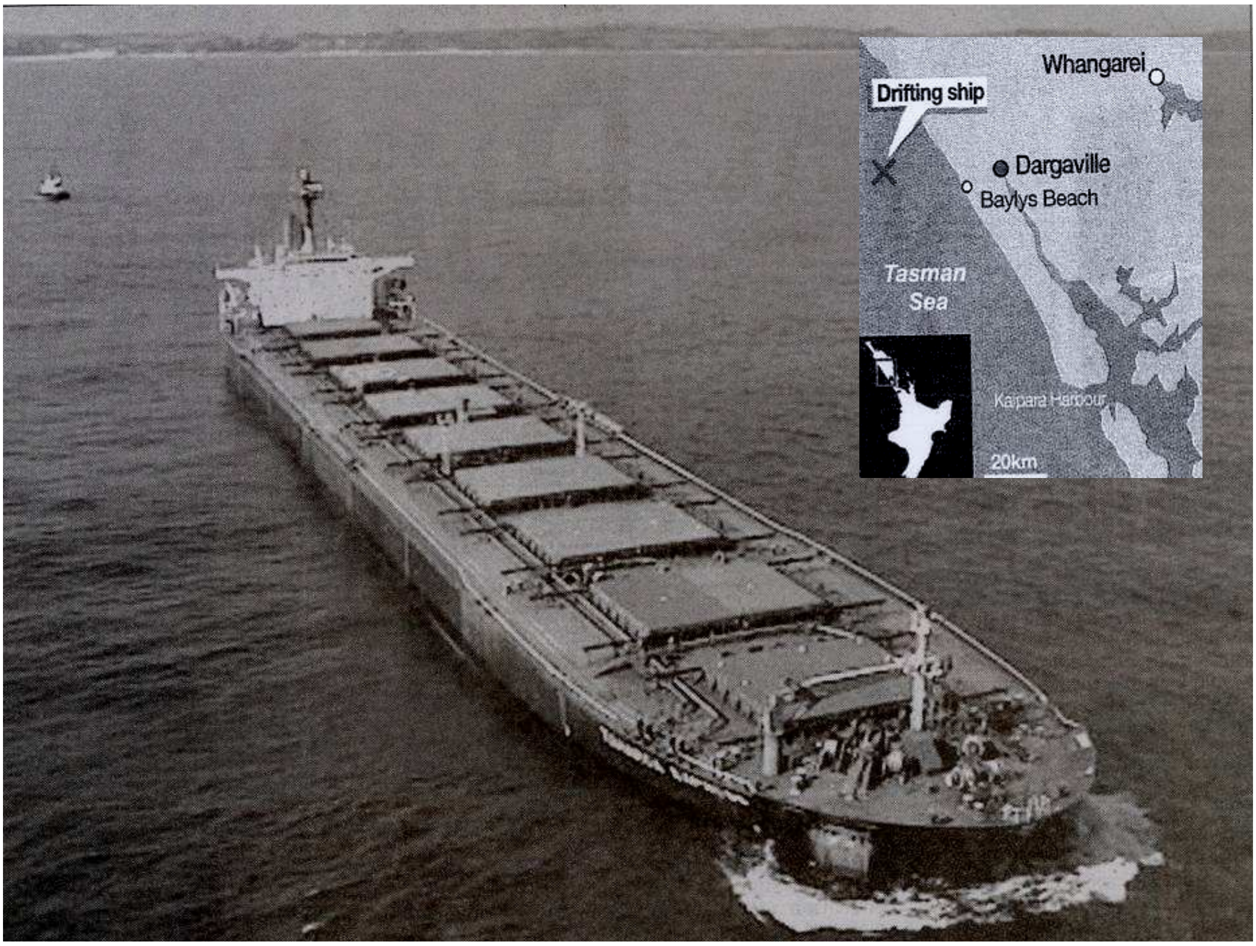

Figure 11: The vessel Taharoa Express drifting offshore of Dargaville while attempts were being made to hold the vessel in position with a local tugboat (New Zealand Herald 2 April 2003).

5 METHODOLOGIES TO INVESTIGATE POPULATION CONNECTIVITY OF MUSSELS AND ASSOCIATED SPECIES

The direct tracking of all but a few invertebrate taxa using visual observation or a variety of artificial tagging methods has been challenging, with very few successful examples (see reviews by Levin 1990; see reviews by Thorrold et al. 2002). However, a number of techniques for tracking the connectivity among populations of sessile marine invertebrates are now beginning to emerge. Some of these techniques have potential for application to green-lipped mussels.

5.1 Chemical Marking of Larvae

Chemical marking of larvae, followed by release, and then their subsequent recapture is one potential method for attempting to determine the larval trajectories of marine organisms (Thorrold et al. 2002). These chemical marking methods have been known and used for many applications where living animals need to be marked so they can be distinguished from all other wild individuals (Loosanoff & Davis 1947).

Three relatively inert chemical stains have been the most predominantly used for marking a variety of marine taxa, especially the early juvenile stages – calcein, oxytetracycline and alizarin red S (Tables 3-5). Recently chemical staining methods on larval shells have been tested and applied to larval *P. canaliculus*. The ultimate aim of the study was to determine whether marine reserves can provide recruitment cross subsidy, whereby chemically marked larvae were released inside a reserve and attempts were made to catch them again on spat collectors located outside the reserve (Fitzpatrick 2010).

The chemical calcein, was found to be effective for marking the larval shell, or prodissoconch, of cultured *P. canaliculus* of ages 10, 15 and 19-days post fertilisation (Fitzpatrick 2010). Larvae were marked by culturing them in seawater with the addition of between 50 and 200 mg l^{-1} of calcein for a 24 hour period. Generally, the treatment resulted in no subsequent increase in mortality or decrease in growth of larvae, suggesting that this staining does not compromise viability of the larvae. These results concur with a great number of other studies where calcein solutions, as well as other inert chemical markers, have been used to mark a wide range of molluscs and fishes (Tables 3-5). The marking of larval shells of *P. canaliculus* with calcein was generally more pronounced in older larvae at the time of treatment, as well as when a higher concentration of the chemical marker was used (Fitzpatrick 2010).

The techniques developed were utilised to successfully tag 15.6 million hatchery-reared *P. canaliculus* larvae that were 17-days old. The tagged larvae were released in the Cape Rodney to Okakari Point Marine Reserve, where an array of moored mussel spat collecting ropes had been deployed previously over a 5 km stretch of coast and up to 1.5 km offshore. Subsequent recovery and analyses of 64 of the spat collectors failed to find any chemically marked mussel spat. The reasons for the failure to recover any marked mussels were unclear, but may be related to a significant storm which hit this coast shortly after the release of the marked mussels.

If this methodology can be proven to work effectively to track larvae, it may have merit for elucidating the source of broodstock mussels in GLM 9. The process would involve releasing chemically tagged larvae at different locations and then examining subsequent spat that arrive at Ninety Mile Beach to determine whether tagged larvae are amongst the materials which might indicate larval transit connectivity between the two locations.

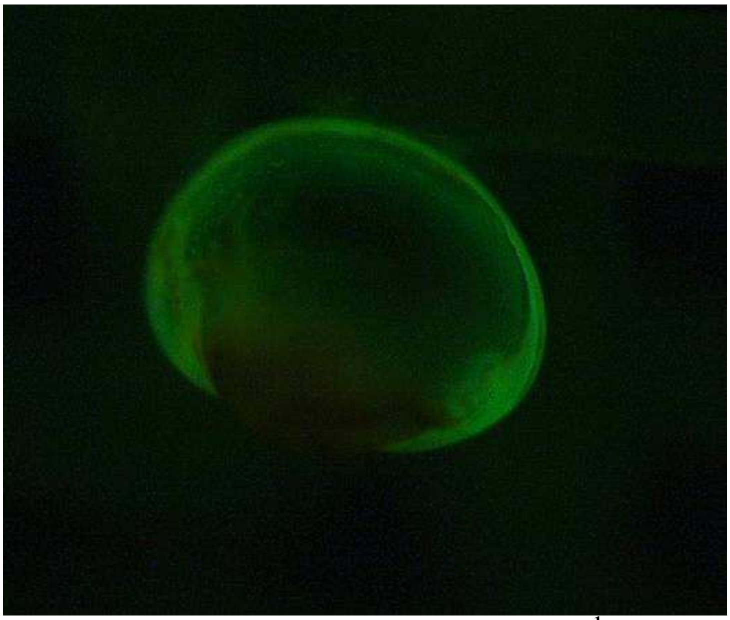

Figure 12: A single *P. canaliculus* larva after being immersed in 100 mg l^{-1} solution of calcein for 24 h, producing a fluorescent mark in the prodissoconch (Source: Fitzpatrick 2010).

Table 3: Studies investigating the use of calcein for the chemical marking of a range of marine species (Source: Fitzpatrick 2010).

Author (Year)	Immersion Time	Concentration of calcein solution	Additional Experimental Notes	Species and life stage
			Teleosts	
Wilson et al. (1987)	2 h	125 mg l^{-1}	- Mark detected in otolith. Calcein was dissolved in tap water at a concentration of 6.25 g l^{-1}, with the pH buffered to 5–6 using sodium bicarbonate to facilitate its solubility, then added to seawater	*Sciaenops ocellatus, Micropogonias undulates* & *Leiostomus xanthurus* **Adults and Juveniles**
Bashey (2004)	24 h	250 mg l^{-1}	- Mark detected in skeleton & otolith. pH buffered utilising sodium hydroxide	*Poecilia reticulata* **Juveniles**
Klesius et al. (2006)	4 h	500 mg l^{-1}	- Mark detected in the skeletal head and fins. pH was not buffered, but did drop after 1 hour	*Oreochromis niloticus* **Juveniles**
			Gastropods and Bivalves	
Day et al. (1995)	12 h	120 mg l^{-1}	- Mark detected on the shell edge; little on the spire	*Haliotis rubra* **Adults and juvenilles**
Moran (2000)	12 h & 24 h	100 mg l^{-1}	- Mark most detectable just beyond the protoconch -teleoconch boundary. Calcein was dissolved in distilled water, at concentration 6.25mg l^{-1}, buffered to pH6 using sodium bicarbonate to facilitate solubility, then added to filtered seawater.	*Nucella ostrina* **Hatchlings (0.9 mm-2 mm)**
Moran & Marko (2005)	48 h & 72 h	50 mg l^{-1} & 100 mg l^{-1} respectively	- Mark detected parallel to the concentric growth rings of the larval shell. Calcein was dissolved in distilled water, at concentration 6.25mg l^{-1}, buffered to pH6 using sodium bicarbonate to facilitate solubility, then added to filtered seawater.	*Argopecten irradians* & *Mytilus trossulus* **Larvae**
Riascos et al. (2007)	3 h & 6 h	50 mg l^{-1} & 100 mg l^{-1}	- Mark detectable in a prepared cross-section of the shell, most brightly toward the shell edge. Kept in a dark room to minimise UV effects of fluorochrome	*Concholepas concholepas* & *Mesodesma donacium* **Adults**
			Holothurians	
Purcell et al. (2006)	17 h	250 mg l^{-1}	- Mark detectable in the spicules within the body wall	*Holothuria scabra* **Juveniles**

Table 4: Studies investigating the use of oxytetracycline for the chemical marking of a range of marine species (Source: Fitzpatrick 2010).

Author (year)	**Immersion time**	**Concentration of oxytetracycline solution**	**Additional Experimental Notes**	**Species and life stage**
			Teleosts	
Hettler (1984)	1–2 h	100 mg l^{-1}, 250 mg l^{-1} and 500 mg l^{-1}	- Mark detectable in the otolith - Utilised 1% NaCl solution as opposed to seawater	*Leiostomus xanthurus* & *Lagodon rhomboides* **Larvae**
Szedlmayer & Howe (1994)	15 h	250 mg l^{-1}	- Mark detectable in the otolith	*Sciaenops ocellatus* **Juveniles**
Beltran et al. (1995)	Hyperosmotic: 3.5–12.5 minutes. Freshwater: 6–18 h	Hyperosmotic: 1% or 10 g l^{-1} Freshwater: 200 and 400 mg l^{-1}	- Mark detectable within the otolith and the caudal vertebrae - 5% NaCl hyperosmotic solution to induce osmotic shock was tested against a freshwater solution. Mortality post-immersion was greater in the prolonged immersion in weaker solution than in the short immersion in a hyperosmotic solution.	*Coregonus lavaretus* **Larvae+**
			Gastropods	
Day et al. (1995b)	48 h optimal	100 mg l^{-1} optimal	- Mark detected on the shell edge; little on the spire - pH adjustment using sodium hydroxide	*Haliotis rubra* **Adults and juveniles**
Pirker & Schiel (1993)	30 h minimum	600–800 mg l^{-1}	- Mark detectable most clearly at the anterior margin of the shell, mainly absent at the posterior end	*Haliotis iris* **Adults and juveniles**
			Bivalves	
Lucas et al. (2009)	2 and 7 d	200 and 300 mg l^{-1} optimal	- Compared OTC, ARS and calcein. OTC mark was detected on the shell 10 m post-immersion and OTC was identified as the optimal fluorochrome.	*Amusium balloti* **Spat**
			Holothurians	
Purcell et al. (2006)	17 h	200 mg l^{-1}	- Mark detectable in the spicules within the body wall	*Holothuria scabra* **Juveniles**

Table 5: Studies investigating the use of alizarin red S for the chemical marking of a range of marine species (Source: Fitzpatrick 2010).

Author (Year)	Immersion Time	Concentration of alizarin red S solution	Additional Experimental Notes	Species and life stage
			Teleosts	
Beckmann & Schulz (1996)	12–24 h	200–300 mg l^{-1}	- Mark was detectable on the otoliths. pH rose after the initial drop; when it didn't sodium bicarbonate was added to buffer the solution.	*Campostoma anomalum, Phoxinus erythogaster* & *Catostomus commersoni* **Larvae and juveniles**
Lagardere et al. (2000)	24 h	400 mg l^{-1}	- Mark was detectable on the otoliths. Tested in pH buffered and unbuffered solutions.	*Scophthalmus maximus* **8-month-old**
Eckmann (2003)	24 h	1000 mg l^{-1}	- Mark was detectable on the otoliths. pH buffered to ~8 using tris buffer.	*Coregonus lavaretus* **Embryos 5–66 days after hatching**
Bashey (2004)	24 h	250 mg l^{-1}	- Mark detected in skeleton & otolith. Conditioned water was used to make solution.	*Poecilia reticulate* **Juveniles**
Simon & Dorner (2005)	3 h	150 mg l^{-1}	- Mark was detectable on the otoliths	*Anguilla anguilla* **Adults**
			Gastropods	
Riascos et al. (2007)	6 h	100 mg l^{-1}	- Mark detectable in a prepared cross-section of the shell, most brightly toward the shell edge.	*Mesodesma donacium* **Adults**
	3 h and 6 h	100 mg l^{-1} and 50 mg l^{-1} respectively	- Mark detectable in a prepared cross-section of the shell, most brightly toward the shell edge.	*Concholepas concholepas* **Adults**

5.2 Elemental Signatures

The elemental signatures of larval shells can be analysed with laser ablation inductively coupled mass spectrometry (LA-ICP-MS), a technique that has the potential to be used to help localise the broodstock populations of *P. canaliculus* which are the basis of the commercial harvest of spat in GLM 9 (Becker et al. 2005; Dunphy et al. 2010). Becker et al. (2007) used elemental analysis to reveal patterns of larval exchange in two mussel species, *Mytilus californianus* and *M. galloprovincialis*, in southern California. They found regional differences in dispersal for both species, with export of larvae occurring from southern populations, and self-recruitment in northern populations. The results are significant because they show that coastal mussel larvae, previously thought to be highly dispersed, can be retained within 20–30 km of their natal origin. These results demonstrate the effectiveness of this technique for identifying patterns of larval transport on a scale of more tens of kilometers.

More recently some initial research has examined elemental signatures from the shells of settled early juvenile *P. canaliculus* sampled from six sites on the west coast of the Northland and Auckland regions of northern New Zealand (Dunphy et al. 2010). Eleven elemental ratios were analysed from these shells and of these, seven (Zn:Ca, Mn:Ca, B:Ca, Sr:Ca, Mg:Ca, Ba:Ca and Cu:Ca) exhibited sufficient spatial variation for a discriminate function analysis to assign the juvenile mussels to their region and site of collection with reasonable reliability. However, amongst open coast sites, analyses for these seven ratios were unable to distinguish between juvenile mussels taken from sites that were 11 km apart, revealing that there are limits to the resolving power of elemental signatures for *P. canaliculus.*

Sampling of early juveniles at one site (Maori Bay) at four different times over six months revealed temporal stability in elemental signatures, with early juveniles able to be correctly assigned to the collection location regardless of month of collection. Given the spatial resolution of the techniques suggested by this study, it is anticipated that the location of broodstock populations could be determined within a range of around 12 km. While this will not serve to pin-point the exact location of the broodstock populations, it would enable other expensive field survey tools to be targeted more effectively (Morrison et al. 2010). Alternatively, even at the spatial scale provided by elemental signature data from larval shells, it would be possible to proceed to implement legal measures to protect the broodstock populations, such as banning inshore bottom-trawling, which also would provide a sufficiently wide buffer zone. In addition, spat arriving at Ninety Mile Beach could be fingerprinted to determine if they are composed of larvae transiting from a variety of locations. Some initial samples indicate that there is some variability in mussel spat samples from Ninety Mile Beach which could be indicative of widely separated, multiple larval source populations (B. Dunphy pers. comm.).

5.3 Isotopic Signatures

Carbon and nitrogen isotopes of invertebrate tissues can fingerprint characteristics of local food sources. For example, measurements of mussel tissues sampled along the coast of South Africa were consistent with their broad geographic zone of origin (Hill & McQuaid 2008). While the tissue isotope signatures reflected the isotopic profile of the locally available food sources, experiments showed that profiles change slowly and only after the mussels had been feeding in waters with a different isotopic signature for over 3 months (Hill & McQuaid 2009).

Earlier studies of the isotopic profile of suspended particulate matter which is consumed by filter feeders, over a 10 km inshore to offshore transect, found that the isotope profile changed markedly over the transect and with season (Hill et al. 2006; Hill & McQuaid 2008). The technique does not appear to have been applied to attempt to determine the source of larvae.

It is possible to use chemical isotope markers that are detected amongst elemental signatures using LA-ICP-MS in order to trace the geographic origins of marine organisms. The technique has been used successfully in larval fish by dosing breeding female fish with unnatural isotopes of barium which then leave a chemical signature in the otoliths (ear bones) of the larvae that can be detected by LA-ICP-MS (Thorrold et al. 2006; Almany et al. 2007). However, it is doubtful this technique would have potential for use with green-lipped mussels because it is unlikely that a maternal contribution of minerals would show up in the larvae. Furthermore, it would be difficult to locate and dose a potential parental population of mussels with an isotope marker.

5.4 Genetic Markers

Genetic markers are defined here as either: (1) a DNA sequence (a coding gene or a non-coding length of DNA) which have been, or potentially can be, traced to specific locations on a chromosome; or as (2) protein markers, such as allozymes, which are expressed (protein products from genes) DNA sequences. Where such markers are expressed, then they are associated with a regulatory function or with a particular gene or trait, although it often is the case that the actual gene itself is unknown (i.e., both its identity and chromosomal location are unknown) and/or that the trait under control is unknown.

Generally, the most informative genetic markers are highly polymorphic (variable), although those which are fixed within populations but are different between regions also can be extremely informative. Such markers may be applied to the mitochondrial genome (mtDNA) which is usually maternally inherited, to the nuclear genome (nDNA), or to the chloroplast genome (cDNA - in plants only).

There is an array of genetic markers available to researchers, including allozymes, RFLPs, RAPDs, AFLPs, microsatellites, ISSRs, SNPs, and ESTs (see Table 6 for full names). Each of these marker types has advantages and disadvantages, as reviewed by Liu & Cordes (2004), Anne (2006), and Gardner et al. (2010) (see Table 6). Of these, RFLPs, AFLPs, ISSRs, microsatellites and SNPs are all highly polymorphic (very variable) and therefore are informative in terms of differentiating among populations and sometimes among individuals within populations (Liu & Cordes 2004; Anne 2006), and potentially can be used to provide the resolution required for identifying genetic differences between broodstock populations of green-lipped mussels, the ultimate sources of spat harvested in GLM 9.

Most marine invertebrates are assumed to have open populations, because their larvae tend to spend some time in the plankton (minutes to months). Thus, gene flow between and among populations may be extensive and widespread (Hellberg et al. 2002; Palumbi 2004; Bay et al. 2006; Cowen et al. 2006; Levin 2006). In its ultimate expression, this has resulted in the view that all new settlers must be recruited from distant populations (Tracey et al. 1975). However, more recent research across a range of different taxa now indicates that many populations are only semi-open (restricted gene flow) and some may indeed be closed (i.e., they rely on self-recruitment (Almany et al. 2007; Planes et al. 2009).

With the advent of new genetic markers (e.g., the move away from protein-based markers, such as allozymes, to molecular-based markers, such as microsatellites), it is now possible to demonstrate that self-recruitment and long distance dispersal are both important factors in explaining genetic connectivity among populations (Ross et al. 2009; Kelly & Palumbi 2010; White et al. 2010).

The scale of dispersal of a marine organism will depend on a number of different factors including the species in question, its life-history characteristics, the history of its populations, local hydrographic conditions, and the geographic scale of its distribution. In addition, it is now possible to identify "source" and "sink" populations (Bell 2008). Source populations are defined as those populations that contribute to the supply of settling larvae which recruit successfully to other locations. In contrast, sink populations are defined as populations that receive new recruits from elsewhere, but do not supply larvae to other populations. In general, the larger the geographic area under investigation, the easier it is to quantify gene flow (most usually larval dispersal) among populations, and also to identify source and sink populations. Thus, at a New Zealand-wide level it is possible to identify genetic structuring across regions and to quantify genetic connectivity (Gardner et al. 2010). However, at the smaller spatial scale of GLM 9, it may not be possible to identify genetic structure among populations using existing markers. However, it may be possible to narrow down the location of the source of spat collected at Ninety Mile Beach, whether those spat are derived from populations within GLM 9 or from neighbouring sites outside the region.

Table 6: An overview of genetic marker types and their properties with examples of their use in the assessment of genetic variation for the New Zealand green-lipped mussel, *Perna canaliculus*. * studies in bold relate specifically to research on *Perna canaliculus*. Table contents are modified from Gardner et al. (2010).

Marker type	**Dominant or codominant?**	**Advantages**	**Disadvantages**	**Examples of use for *Perna canaliculus***
Allozymes (also called isozymes). Protein products expressed by genes	Codominant	Quick and cheap to run. Reasonably informative. Assumed to be selectively neutral. Widely distributed throughout the (nDNA) genome.	Generally not highly polymorphic and therefore not highly informative. May be under direct selective pressure.	Smith (1988) Gardner et al. (1996) Apte & Gardner (2001) Apte et al. (2003)
RFLPs – Restriction Fragment Length Polymorphisms	Codominant or dominant depending on circumstances	Quick and cheap to run. Reasonably informative. Assumed to be selectively neutral. Widely distributed throughout the (nDNA, mtDNA and cDNA) genome.	Generally not highly polymorphic and therefore not highly informative.	Apte et al. (2003)
RAPDs – Randomly Amplified Polymorphic DNA	Dominant	Quick to run. Highly informative. Widely distributed throughout the (nDNA, mtDNA and cDNA) genome.	Uncertainty about what exactly is being amplified (coding, non-coding?). Questions about reproducibility and accuracy of scoring. Moderately expensive to run.	Apte et al. (2003) Star et al. (2003)
AFLPs	Dominant	Quick to run. Highly informative. Widely distributed throughout the (nDNA, mtDNA and cDNA) genome.	Uncertainty about what exactly is being amplified (coding, non-coding?). Questions about reproducibility and accuracy of scoring. Moderately expensive to run.	
ISSRs		Widely distributed throughout the (nDNA, mtDNA and cDNA) genome. Assumed to be selectively neutral. Highly informative.	Moderately expensive to run.	
SSCPs	Dominant	Highly informative. Widely distributed throughout the (nDNA, mtDNA and cDNA) genome.	Can be time-consuming and expensive to develop. Moderately expensive to run.	Apte & Gardner (2002)
DGGE	Dominant	Highly informative. Widely distributed throughout the (nDNA, mtDNA and cDNA) genome.	Can be time-consuming and expensive to develop. Moderately expensive to run.	Apte & Gardner (2002)

DNA sequencing	Codominant or dominant depending on circumstances	Highly informative. Targets gene (coding regions) and/or non-coding regions. "Universal" primers exist for many genes and non-coding regions. Has spin-off advantages if whole genome sequencing is carried out.	Can be time consuming and expensive May require specific primers or modification of "universal" primers.	Wood et al. (2007)
Minisatellites. Short simple sequence repeats of 20 to 50 base pairs	Codominant	Highly variable and highly informative. Widely distributed throughout the genome. Generally assumed to be selective neutral. Several probes such as 33.6 and 33.15 work across many different taxa.	Time consuming and expensive to develop from scratch. Unless properly characterised, are prone to null alleles and allele drop out. May need to be developed for each new species.	
Microsatellites. Short simple sequence repeats of 2 to 20 base pairs.	Codominant	Highly variable and highly informative. Widely distributed throughout the genome. Generally assumed to be selective neutral.	Time consuming and expensive to develop. Unless properly characterised, are prone to null alleles and allele drop out. Generally are species-specific and need to be developed for each new species.	MacAvoy et al. (2008) Wei et al. (In press)
SNPs Single nucleotide polymorphisms	Codominant	Highly variable and highly informative. Widely distributed throughout the genome. Assumed to be selective neutral if in non-coding regions; assumed to be under selection if in coding regions.	Time consuming and expensive to develop. Is often the case that the user does not know if the SNP is a coding or non-coding region for groups of taxa which are not well characterised. Generally are species-specific and need to be developed for each new species.	
ESTs Expressed sequence tags	Codominant	Highly variable and highly informative. Widely distributed throughout the genome – they are from genes. Assumed to be under selection because they are genes or parts of genes.	Time consuming and expensive to develop. Generally are species-specific and need to be developed for each new species.	

This table is a qualitative assessment of marker types, and is based on a comparative approach to assessing each marker's pros and cons. Terms can be interpreted as follows:
"quick to run" – results are available in a single day.
"time consuming and expensive to develop" – may require several weeks (e.g., 2–10) and thousands of dollars to develop markers and to test their utility before actual genetic testing can commence.
"reasonably informative" – provides poor discrimination among individuals (because not enough genetic differentiation) which may translate to information enough to differentiate among populations.
"highly variable and highly informative" – provides maximum information content or highest level of discrimination.
"widely distributed throughout the genome" – found on all or most chromosomes and across all regions of each chromosome: not localised to specific part of the genome (for molecules such as mitochondrial DNA and chloroplast DNA this would mean that they can be found anywhere on the molecule: not restricted to one region alone).

The earliest surveys of population genetic structure in *Perna canaliculus* employed allozymes (biochemical markers) and reported partial isolation between northern and southern populations at about 38° S (Smith 1988), or an isolation-by-distance population structure (Gardner et al. 1996). A subsequent and far larger allozyme survey found no evidence for either the north-south split or the isolation-by-distance results of earlier studies (Apte & Gardner 2001). Low population subdivision as a consequence of high levels of gene flow indicated that a single panmictic (random mating within a breeding population) model best explained population genetic homogeneity in the green-lipped mussel over its entire range in New Zealand (Apte & Gardner 2001). That is, all sites within New Zealand are genetically very similar (cannot be differentiated using standard statistical approaches) and are therefore viewed as belonging to one homogenous gene pool.

Application of a range of different molecular markers to the analysis of green-lipped mussel populations changed the view of genetic connectivity and genetic structuring for this species, which is widely distributed around the coast of New Zealand (Apte & Gardner 2002; Apte et al. 2003; Star et al. 2003). These studies revealed the existence of a pronounced genetic break just south of Cook Strait at approximately 42° S, which has subsequently been confirmed for other species, such as brittle-stars of the genus *Amphipholis* (Sponer 2002), sea-stars of the genus *Patiriella* (Waters & Roy 2004; Ayers & Waters 2005), and limpets of the genus *Cellana* (Goldstien et al. 2006). Most recently the application of microsatellite markers to the genetic structuring of green-lipped mussel populations has confirmed these findings (Wei et al. 2010).

While microsatellites are a good method for examining population connectivity, the markers developed by MacAvoy et al. (2008) and applied by Wei et al. (In press) showed little differentiation within the northern group that includes GLM 9. The utility of these markers for differentiating between populations within GLM 9 is untested and unknown, as all studies so far have only examined one population/site from within GLM 9. In light of new statistical assignment tests (Piry et al. 2004), it would seem worthwhile to test the existing markers against mussel populations within GLM 9 and in adjacent regions, to better understand the performance of the microsatellites in differentiating amongst populations.

Assignment tests may provide enough power to help identify or at least narrow down the general area of the source population(s). If this approach does not yield the necessary level of differentiation, then development and testing of new marker types may provide a higher resolution to discern the source population(s) required for the study of beach-cast spat at Ninety Mile Beach. Regardless, the application of these methods will require identification of the location of potential broodstock populations for supplying the spat in GLM 9 so that these mussels can be sampled to provide genetic reference material for comparison.

5.5 Hydrodynamic and Larval Dispersal Modelling

5.5.1 Introduction

Marine population connectivity *via* larval dispersal is inherently a coupled bio-physical problem. Amongst the relevant physical processes on continental shelves and nearshore regions are wind- and buoyancy-driven currents, fronts and associated jets, tides (including residual currents, internal tides and bores), and surface and bottom boundary layers (Scotti & Pineda 2007; Werner et al. 2007). In addition, waves induce Stokes drift that transports pelagic larvae and eggs floating at the sea surface, and wave radiation stress induces along-shelf currents and across-shelf exchange in shallow water *via* vertical exchange and rip currents (Monismith et al. 2007; Fewings et al. 2008; Lentz et al. 2008). In terms of the relative significance of these various forces within GLM 9, and especially in the vicinity of

Ninety Mile Beach, winds and waves, possibly moderated by tides, are mostly likely to be the dominant hydrodynamic forces in this region.

This conjecture is supported by the statistical model of Alfaro et al. (2010) who considered a range of oceanographic and climatic parameters in association with the arrival of spat material at Ninety Mile Beach. This study identified that swell conditions, wind direction, and El Niño/La Niña events were significant indicators for periods of presence/absence of spat material on the beach. However, physical processes alone do not determine population connectivity. Spawning, larval development and behavioural characteristics, including vertical migration and spatially explicit environmental differences, play important roles (Boehlert & Mundy 1988; Tremblay et al. 1994; Hare et al. 1999; Bode et al. 2006).

Modelling the dispersal of planktonic invertebrate larvae by coupling hydrodynamic models of ocean circulation with larval development and behaviour models has proven useful for delivering fresh insights into population connectivity (Cowen et al. 2006; Gallego et al. 2007; Werner et al. 2007).

5.5.2 Physical Processes

Assuming the dominance of local winds and waves on the occurrence of spatfall events, there are two probable mechanisms by which these are impacted by ocean circulation. These are: (1) broad scale transport during the pelagic phase by ocean currents in relatively deep water (i.e., well beyond the surf zone) that carries larvae from their source beds to regions presumably adjacent to Ninety Mile Beach; and (2) cross-shore transport of pediveligers shortly prior to settlement, or of mobile substrates upon which the pediveligers already may have settled.

Often, larval dispersal modelling emphasizes the former mechanism, but does not consider the nearshore processes involved in transporting larvae to shore. However, these nearshore processes can have a substantial influence on transport trajectories in many species (Pineda 2000; Gawarkiewicz et al. 2007).

In the case of spat material at Ninety Mile Beach, whereby larvae are effectively brought on to the beach itself, the importance of the latter mechanism may be paramount to understanding the connection between adult broodstock populations and the delivery of harvestable spat material. Analysis of these *physical* circulation processes can be considered independently, even though it is likely that they may co-vary due to correlated forcings (i.e., local winds and waves).

Ocean circulation affecting larval dispersal during the pelagic phase can be examined using relatively well established observational and hydrodynamic modelling approaches. The observations required to characterize this flow on a broad continental shelf are relatively long time series of ocean currents, waves, and the regional meteorology. Unfortunately, the northwest New Zealand shelf is a severely under-observed region; hence, making progress on green-lipped mussel larval dispersal modelling is likely to require new observational initiatives.

Established technologies for observing ocean currents in shallow seas are vector measuring current meters that are deployed on moorings or tripods standing on the seafloor, which give single point time series for durations of several months, or full water column velocity profiles from bottom mounted Acoustic Doppler Current Profiler (ADCP) instruments. These ADCP instruments can be configured to simultaneously provide information on the wave climate, which is of value in this situation. In either case, consideration for designing an observational strategy would include selecting the number of instruments to use, where to install them, their duration of operation, and ensuring the engineering of robust deployment technologies on this heavily swell impacted and exposed coast with a mobile sediment regime.

Newer technologies for measuring ocean surface currents over a broad swath are high frequency (HF) radar systems, such as Coastal Ocean Dynamics Applications Radar (CODAR) and Wellen Radar (WERA). Such systems are a key component of the Australian Integrated Marine Observing System (IMOS), with installations in place on sectors of the South Australia and Queensland coasts, and proposed for areas of New South Wales. HF-radar is a mature technology in U.S. ocean observing, with near complete coverage on the U.S. east coast routinely providing surface current estimates at 3 to 6 km resolution, hourly, to a range of 100 km from shore. It should be noted that HF-radar observes surface current only and lacks the precision of conventional *in situ* measuring systems, but offers greater spatial coverage and consists of land-based transmitter/receiver antennas requiring no in-water infrastructure.

Circulation processes on the scale of several tens of kilometres will be relevant to the dispersal of larvae immediately post-spawning, and in this pelagic phase lasting several weeks, the mussel larvae may be widely dispersed both along-shelf and out to sea. The processes by which larvae in late stages approaching settlement may be transported across the shelf towards the coast are likely to be more complicated because of the joint action of winds and waves that drive turbulent mixing, sea level set-up, and Lagrangian Stokes transport.

5.5.3 A Case Study

An ocean circulation regime with similarities to Ninety Mile Beach, where these processes have been studied in detail, is the long, straight sandy coast at Duck, North Carolina, USA, where the U.S. Army Corps of Engineers Field Research Facility (FRF) is located. For example, Reniers et al. (2004) described observations of alongshore and across transport from a 5-week field programme termed *Sandy Duck* during summer 1997, and compared these data with model predictions.

The shelf at Duck is some 90 km wide but less than 40 m deep, with a sandy seafloor and open exposure to the North Atlantic wind and wave climate. Research at Duck has led to significant advances in our understanding of momentum balances on straight, gently sloping, shallow shelves, due to energetic wind and waves, including across shelf two-layer exchange transports and upwelling.

Observations during *Sandy Duck '97* were considered by Feddersen & Guza (2003), who showed that the flow exhibited substantial alongshore uniformity and could be described by a relatively simple alongshore momentum balance. Integrated oceanographic and sediment transport studies at Duck (e.g., Lee et al. 2002) have enabled analysis of the ability of models to infer turbulent mixing rates, and suspended sediment concentrations under wave regimes from storms to swell, which have similarities to Ninety Mile Beach conditions.

The inner shelf at Duck becomes density stratified in summer. Whether this is a characteristic shared by the Ninety Mile Beach regime is difficult to say given the lack of *in situ* observations. Lentz (2001) found that the presence or absence of stratification significantly affected wind-driven, cross-shelf circulation, and this should be a priority for any future observation efforts at Ninety Mile Beach. Both wind-driven and wave-driven turbulent mixing have the potential to de-stratify the water column, and observations of these forcing processes in concert with ocean circulation observations are required. Wind-driven, across shelf circulation processes at Duck have been connected to larval dispersal in work by Shanks & Brink (2005) and Garland & Zimmer (2002).

Shanks & Brink (2005) presented an interesting example of how simultaneous observations of velocity shear, stratification and vertically resolved plankton abundances can be informative with regards to cross-shelf transport of pelagic larvae. In the case of Ninety Mile Beach, it is necessary to also consider exchange processes associated with larvae already settled upon substrates that may move differently from neutrally buoyant particles or larvae with limited ability to control their vertical position in the water column.

Augmenting observations at Duck with data from a cabled observatory on the Massachusetts coast (bottom mounted ADCP current measurements, directional wave observations, and wind data), Fewings et al. (2008) and Lentz et al. (2008) further considered the role of waves and wind in driving cross-shore exchange circulation. Seaward of the surf zone in water depths on the order of 10 m, wave-driven Stokes drift at the surface (above the average depth of wave troughs) becomes compensated by a vertically sheared undertow.

Correctly modelling the vertical structure of shear in horizontal cross-shore velocity, which would impact the cross-shore transport of larval mussels depending on where they are located vertically in the water column, requires consideration of the Coriolis force and its influence on wave momentum flux (the so-called Hasselman wave stress). Lentz et al. (2008) concluded that the fundamental nature of wave-driven transport makes it likely that undertow will be present on most inner shelves exposed to waves, and that this process will frequently dominate over exchange flows driven by along-shelf wind. As determined in earlier work (Lentz 2001), vertical density stratification can significantly modify vertical turbulent mixing and vertical shear.

Hunt et al. (2009) employed results from modelling bedload sediment transport to consider how bivalve larvae are transported within an estuary, but this is a process rather different from the transport of GLM 9 pediveligers which have settled upon drifting substrates. In our review, we have not located any references to efforts quantifying or modelling the movement of macroalgal substrates in the surf zone or shallow inner shelf. Studies have considered macroalgal propagule transport, or the effects of specific organisms on water flow in shallow environments (e.g., attached bull kelp), but not the movement of detached clumps or accumulated mats of material, which are central to GLM 9 spatfall.

5.5.4 Combining Physical and Biological Processes

Physical processes alone do not determine scales of population connectivity in sessile marine organisms generated through larval dispersal. Time scales of larval development and behavioural characteristics, including vertical migration and spatially explicit environmental differences, play important roles (Boehlert & Mundy 1988; Tremblay et al. 1994; Hare et al. 1999; Bode et al. 2006). Larval dispersal modelling must work hand-in-hand with field and laboratory studies to test model predictions and assumptions, better parameterise and initialise the models, and iteratively strengthen model capabilities.

The most simple population connectivity models base projections on planktonic larval duration (PLD) and assume that larvae are passive particles transported by oceanic currents. This approach has been found to over-estimate dispersal distances (Sponaugle et al. 2002; Largier 2003). Modelling approaches that allow for the inclusion of biological factors, such as spawning times and swimming behaviour, have proven to be more accurate (Werner et al. 2007). Furthermore, some success has been seen with relatively simple 2-dimensional models. For example, Gilg & Hilbish (2003) measured dispersal distances of *Mytilus* sp. by taking advantage of the strong genetic differences between mussel populations, and their simple 2-dimensional model accurately predicted general patterns of larval dispersal rates, directions and distances.

Using wind and surface current data, McQuaid & Phillips (2000) found that they could predict dispersal distances of the mussel *Perna perna* in South Africa. This led them to conclude that mussel larvae within that region are dispersed like passive particles. They also sampled larvae from the water column to test for diel vertical migration, for which they found no evidence. Thus, they suggested that the good match with estimates from wind data implies that the mussel larvae in that region were dispersed passively.

Successfully modelling population connectivity of the green-lipped mussel is presently hampered by their relatively complex life history, in particular, their association with bottom-drifting settlement material, and tendency to settle and detach possibly multiple times, as well as our incomplete knowledge surrounding their larval behaviour in the plankton. At early stages of their life history, green-lipped mussel larvae are dispersed much like passive drifting particles, possibly also undertaking directed vertical migration in response to environmental cues or to avoid predation. In later stages, they can no longer be treated as individual particles because there is ample evidence they also move *via* byssopelagic migration or mucous drifting, and as particles attached to drifting algae. They may attach, detach and reattach an unknown number of times in response to largely unknown factors.

A maximum plankton larval dispersal (PLD) of 6 weeks has been estimated, but this period may differ with different environmental conditions (Jenkins 1985). Estimates of PLDs determined by culturing larvae in the laboratory cannot take into account the flexibility of larval life history that may vary with environmental conditions (Scheltema 1986). Even so, it is known that taking into account factors such as larval mortality, habitat availability, and diffusion within models of transport can lead to much lower estimates of larval transport rates (Scheltema 1986; Cowen et al. 2000; Largier 2003; Shanks et al. 2003). In most cases when reported PLDs are compared with empirically determined mean transport distances, larvae do not travel as far as would be expected by simple advection (Shanks et al. 2003). Clearly, studies of GLM 9 are needed to gain a greater understanding of these processes, or to at least formulate hypotheses on behaviour that may be explored further using eco-hydrodynamic simulations.

The timing of spawning (on seasonal or tidal scales) of a species can lead to great differences in simulated transport trajectories, especially if the circulation regime is seasonally dependent (Kingsford et al. 2002; Sponaugle et al. 2002). In the case of green-lipped mussels, we do have reasonably focussed estimates of spawning season, but unfortunately we lack a complementary certainty in the circulation regime.

The length of time that larvae are in the plankton and their flexibility in settling time after competence is a major determinant of transport distances and therefore connectivity (Sponaugle et al. 2002). The behaviour of larvae during coastal transport has been shown to greatly alter their resulting trajectories (Sponaugle et al. 2002; Paris & Cowen 2004), and it is unlikely that the veligers can control their transport in most horizontal flows. However, there is evidence that the larvae of *Mytilus* spp. can swim strongly enough to affect vertical position (Bayne 1976).

It may be that the heart of elucidating the complex dynamics of the mussel spat resource at Ninety Mile Beach will be in the identification of links between the pelagic and benthic components within the system. The transition entails transformation of veligers in the offshore environment with limited ability to actively swim, to pediveligers ready to settle in response to uncertain environmental cues or habitat preferences. This is complicated by the fact that initial larval settlement may not be permanent. The integration of ecological modelling that expresses different hypotheses regarding these behaviours, with well resolved hydrodynamic modelling of wind and wave driven cross-shelf circulation which is supported by observation of ocean circulation, stratification and mixing for validation, holds promise for understanding the factors controlling spatfall events in GLM 9.

5.6 Oceanographic Information

As outlined in the previous section, any effective hydrodynamic and larval dispersal modelling for GLM 9 will rely on in-depth information about the oceanographic processes operating in this area. The west coast of Northland is dominated by sandy beaches, with backdrops of Pleistocene and Holocene dune systems from the Kaipara Harbour mouth to Maunganui Bluff, and behind Ninety Mile Beach (Shaw et al. 1990). South of Ninety Mile Beach, from Maunganui Bluff to Ahipara, and north of Scott Point, sandy beaches are intermixed with rocky headlands and associated intertidal reefs. Subtidal reefs are quite limited, but occur off Tauroa (Reef) Point as large bedrock platforms out to 35–40 m water depth, and off Cape Maria van Diemen down to 6 m (Brook & Carlin 2000; Brook 2002).

The few islands present are located close to the shore (Matapia Island, northern end of Ninety Mile Beach; Motuopao Island, Cape Maria van Diemen), along with the Three Kings Islands, located 55 km to the northwest of Cape Reinga (Shaw et al. 1990). New Zealand's largest estuary, the Kaipara Harbour, opens to this coast, along with the smaller Hokianga Harbour, and two very small estuaries (Whangape and Herekino Harbours) to the north. Large and extensive intertidal sand and mud flats are defining features of these harbours. There are no islands or reefs to shelter this coast from almost continuous oceanic swell originating from the Tasman Sea and Southern Ocean. As a result, wave induced turbulence and along-shelf wave-induced currents generate significant sediment movement along this exposed open coastline (Shaw et al. 1990).

The large scale oceanographic regime in deep water west of Northland is ill-defined due to an extreme paucity of observations. In terms of physical oceanographic observations, this is arguably the least observed of any sector of the New Zealand continental shelf. The existence of a southward flowing West Auckland Current was supposed by Garner (1961) on the basis of drift card evidence, but contradicted by Stanton (1973) who inferred weak northward geostrophic flow from hydrographic observations along a section offshore of Tauroa (Reef) Point.

Stanton (1973) reanalysed Garner's drift card data, and proposed that if a West Auckland Current exists, it forms south of Tauroa Point. Drift cards released near Cape Reinga travelled eastward into the East Auckland Current (EAUC), while those released off Kaipara moved southward. This ambiguity in the direction of the mean flow is consistent with observation of ocean flows made from satellites. In addition, calculations for the waters off Northland from satellite data and from the CSIRO Atlas of Regional Seas (CARS) further suggests that if a West Auckland Current exists it is extremely weak most of the time, or is possibly only a weak seasonal feature (Ridgway et al. 2002; Ridgway & Dunn 2003).

Chiswell & Rickard (2006) computed a climatological mean circulation using a nested ocean model and obtained similar results. They complemented their modelling study with an analysis of surface velocity observations from satellite tracked drifters from the Global Drifter Program, but found that too few drifters reach the ocean immediately west of Ninety Mile Beach to make a reliable estimate of the current. Rather, the trajectories of drifters that cross the Tasman Sea from west to east diverge at Lord Howe Rise, with those that cross the West

Norfolk Ridge in the Tasman Front passing north of Cape Reinga to enter the EAUC, while others move south, evidently steered by the Lord Howe Rise and Challenger Plateau toward the Taranaki coast.

The absence of any significant mean flow offshore, the considerable width of the continental shelf, and the inability of drifters originating offshore to cross the continental shelf break, collectively suggest that inner shelf circulation in this region is largely insulated from the influence of any remotely generated forcing. As with any shallow coastal ocean, the candidate local forces probably driving local ocean currents are tides, winds, waves and buoyancy input from coastal runoff.

Semi-diurnal tides around New Zealand are dominated by a coastally-trapped wave response to tide potential forcing. The sense of propagation is anticlockwise around the shelf (i.e., phase advancing with the coast on the left), with elevation amplitudes seldom more that 1–2 m and a tidal current amplitude of about 0.1–0.2 m s^{-1} (Heath 1985; Walters et al. 2001). The lunar semi-diurnal tide dominates along the Ninety Mile Beach coast with a range of about 1.5 m, with the other three semi-diurnal constituents (N2, S2 and K2) having elevation amplitudes on the order of 0.3, 0.22 and 0.1 m, respectively (Walters et al. 2001).

All four semi-diurnal constituents exhibit a rapid progression of phase around amphidromic points close to Cape Reinga and, as a result, this drives famously large tidal currents over the Columbia Bank. However, the magnitudes of these currents quickly diminish away from the Cape and are modest along Ninety Mile Beach itself. Although their results were not conclusive, Alfaro et al. (2010) observed a tendency for higher spatfall during periods of higher tides.

The predominant winds affecting shelf waters at Ninety Mile Beach are from the southwest (Reid 1982; Alfaro et al. 2010) (Figure 9) and have been observed to create upwelling in the area. These were the conditions at the time of the hydrographic observations of Stanton (1973) off Tauroa (Reef) Point, and may be the origin of the northward flow he observed on that occasion.

El Niño climate conditions in New Zealand are associated with lower sea surface temperatures (Gordon 1986), which have been attributed to increasing southerly winds from the Antarctic, and a large-scale diffusive upwelling phenomenon caused by reduction in the source of tropical water to the Australasian region (Sprintall et al. 1995).

In association with southeasterly winds, swell from the southwest creates a high level of exposure to the coastline (Moir et al. 1986), and wave action is undoubtedly a factor in the regional dynamics. However, in summer, strong easterly and northeasterly winds also can occur, and are associated with the passage of tropical cyclones to the north of New Zealand (Moir et al. 1986). Indeed, offshore winds are recognised as being correlated with the amount of spatfall (Alfaro et al. 2010), so these evidently play a role in inner shelf circulation *via* a dynamic mechanism that has yet to be determined.

Observations of a recurring northward flowing, along-shore current at Ninety Mile Beach in association with northward winds (Alfaro et al. 2004) during spatfall events suggest that considerations of local wind forcing should be paramount in formulating hypotheses regarding ocean circulation processes on this coastline. Whether the role of wind is to act directly on the ocean *via* wind stress, or indirectly through wind-wave radiation stress and wave set-up, or a combination of the two, will require further analyses.

The few rivers that flow to this coast discharge into the estuaries (Hokianga and Kaipara, Manukau), where their buoyancy input is tidally mixed to almost oceanic salinity values and therefore will not represent significant dynamic forcing of inner shelf circulation. There are no gauged river flow data in the NIWA Environmental Data Explorer database for the Far North peninsula, but given its small catchment area immediately adjacent to Ninety Mile Beach, it is difficult to conceive that river flows here could play any role in coastal ocean dynamics.

On shelf-wide scales, wind driven surface currents and wave-driven Stokes drift have the potential to mediate dispersal of mussel larvae in the veliger stage. In the pediveliger stage when the larvae have the potential to settle, the dispersal processes become complicated by (possibly temporary) settlement on mobile filamentous substrates that may constitute floating algal rafts or debris moved by circulation in the bottom boundary layer.

6 METHODOLOGIES TO INVESTIGATE LOCATION AND EXTENT OF POPULATIONS OF MUSSELS AND ASSOCIATED SPECIES

6.1 Remote Sensing

Due to the spatial scale and hundreds of kilometres of coastline in GLM 9, conventional methods of habitat characterisation, such as video camera drops and diver census, are neither practical nor cost effective ways to identify subtidal benthic habitats at Ninety Mile Beach (Morrison et al. 2010). Remote sensing systems offer potential solutions to this problem and allow for rapid mapping of seafloor characteristics.

A number of different remote sensing systems are available that operate across the electromagnetic spectrum and in the acoustic energy range that can usefully detect and identify marine benthic habitats (Table 7). These include systems that operate in the visible and near infrared range (e.g., aerial photography, satellite imagery, hydrographic lidar) and sonar (e.g., single-beam, side-scan and multi-beam sonar).

High resolution aerial photography to map detailed coastal and intertidal areas has been in use since the 1970s (Smith et al. 1975; Kelly 1980; Walker 1989; Pasqualini et al. 1998; Malthus & Mumby 2003). For example, the majority of digital maps available for coral reef ecosystems have been derived through interpretation of aerial photos or multispectral satellite imagery (Battista et al. 2007).

Satellite imagery is used increasingly for a variety of applications, ranging from cartography, to mapping temporal changes in coastal areas and environments, bathymetry and fisheries management (Jupp et al. 1985; Mumby et al. 1997). Since the early satellites, there have been vast improvements in the quality of spatial resolution and availability of different wavelengths that can be captured (Mumby et al. 1997; Mumby & Edwards 2002; Blaschke 2010). As a result, more accurate mapping of coastal areas has occurred. Mumby & Edwards (2002) compared the use of the new generation IKONOS satellite to lower spatial and spectral resolution satellites, such as the range of LandSat satellites that were launched during the 1990s. Their findings showed that IKONOS was able to significantly improve habitat discrimination compared to Landsat imaging methods.

The latest satellites have an even higher resolution than IKONOS. The satellites launched and owned by DigitalGlobe, Inc., have a spatial resolution as high as 0.5 m, which gives increased detailed imagery compared to other satellites currently in use (DigitalGlobe 2009; Pittman et al. 2009; DigitalGlobe 2010). Digital Globe's latest satellite launched in 2009, the WorldView 2, is also able to receive 8 spectral bands at 1.84 m, which is more than any other commercially available satellite (DigitalGlobe 2009; DigitalGlobe 2010). This provides even more accurate mapping and analysis of the Earth's surface with the standard colours, blue, green, red and near infrared 1, and additional colours of coastal, yellow, red edge and near infrared 2 (DigitalGlobe 2010).

With the added spectral bands, more accurate mapping can be conducted in terms of nearshore and intertidal marine habitats (Table 8) (DigitalGlobe 2010). While aerial or satellite imagery may have the capability to identify contiguous beds of green-lipped mussels in shallow and sufficiently clear water, it is uncertain whether the technique would have the capability to identify locations of algal and hydroid beds which may be much more dispersed.

Table 7: Table showing the potential range of capabilities of different remote sensing technologies available for detecting sub-tidal benthic habitats, including beds of green-lipped mussels.

Remote Sensor	Depth Range	Horizontal resolution	Scan width (Swath)	Limiting factors & other issues
Aerial photography	<10 m in clear water	>0.5 m	Variable 2 – 0.2 km	Water clarity, cloud cover
Satellite images	<10 m in clear water	>1 m	Variable 500 – 0.5 km	Water clarity, could cover
Hydrographic lidar	<70 m in clear water	>0.01 m	Variable 2 – 0.2 km	Water clarity, could cover, instrument cost expensive
Single-beam sonar	>2 m	>0.01 m	Variable 0.1 km	Extensive vessel running
Side-scan sonar	>2 m	>0.1 m	Variable 0.5 – 0.05 km	Vessel running
Multi-beam sonar	>15 m	>0.03 m	Variable 1 – 0.1 km	Vessel running

Table 8: The 8 spectral bands that are collected by the WorldView 2 satellite and the marine habitats or species distributions that can be mapped from these spectral bands.

Spectral Band	Applications	Marine and coastal habitat
Coastal: 400 – 450 nm	Useful in conducting bathymetry studies	Nearshore and intertidal and depths up to 30 m
Blue: 450 – 510 nm	Penetration of water for bathymetry studies but not as deep as coastal	Mainly intertidal habitats but also nearshore
Green: 510 – 580 nm	Determines characteristics of water column	Seaweeds and phytoplankton
Yellow: 585 – 625 nm	Vegetation both on land and water	Aquatic vegetation
Red: 630 – 690 nm	Vegetation	Aquatic vegetation
Red Edge: 705 – 745 nm	Vegetation	Aquatic vegetation
Near-IR1: 770 – 895 nm	Effectively separates water bodies from vegetation	Islands
Near-IR2: 860 – 1040 nm	Enables broader vegetation analysis and biomass studies	Vegetation and biomass

While these passive remote sensing techniques may be relatively successful for mapping some marine habitats and ecosystems, they do not provide accurate and continuous topographic/bathymetric information (Costa et al. 2009). Topography is ecologically important because it influences the spatial distribution of marine organisms, especially for sessile species like mussels, which are more likely to attach to hard substrates such as emergent rocky reefs (Wilson et al. 2007; Wedding et al. 2008; Pittman et al. 2009).

In contrast, Lidar, single-beam, side-scan sonar (SSS), and multi-beam echo sounders (MBES) are active remote sensing systems that measure topography and physical characteristics of the seafloor by pulsing sound or laser light (Costa et al. 2009). The returning pulses are analysed to provide spatially continuous, high resolution bathymetric and intensity surfaces (Brock et al. 2004; Dartnell and Gardner 2004; Wilson et al. 2007).

Airborne light detection and ranging (Lidar) systems are currently being used to address the limitations of current technology. Lidar systems work by using laser light to illuminate a target area. They emit pulses of laser light and precisely measure the elapsed time for a reflection to return from the ground below. Hydrographic Lidar systems use dual frequency lidar methods to accurately measure depth in shallow waters. They can be used to map shallow waters, shoreline and topography simultaneously while travelling at 140 kn (as compared to 8 kn for multi-beam, side-scan and single beam sonar systems). The swath accuracy in shallow waters is independent of depth (Costa et al. 2009). This technology has been used recently to update nautical charts (McKenzie et al. 2001; Intelmann 2006), for a wide range of coastal applications (Venturato et al. 2007), and for developing spatially explicit seafloor complexity and biodiversity models (Kuffner et al. 2007; Wedding et al. 2008; Pittman et al. 2009). It is considered to be accurate up to 30 m in temperate marine ecosystems and to 70 m in clear waters, such as coral reefs (Costa et al. 2009).

Given the advantages of airborne Lidar surveys, it is likely that they will provide an alternative to multi-beam and side-scan sonar surveys for collecting datasets that simultaneously address benthic habitat mapping and nautical charting requirements in shallow coastal waters (Costa et al. 2009). However, the limited commercial availability of these systems has prevented their use in New Zealand and elsewhere. Furthermore, in the highly turbulent and phytoplankton rich waters of GLM 9, it is not clear how effective this technology would be for penetrating greater depths and for detecting algal and hydroid habitats given that they may be quite dispersed.

Single-beam sonar was the first sonar technology developed for bathymetric mapping. It functions by firing high frequency acoustic pulses from a single source, and measuring the time for the transducer on the hull of the vessel to receive a reflection signal from the sea floor. It produces sparse coverage (narrow swath), so more passes are required to map an area than for either side scan or multibeam sonar systems. However, the echo data are easily interpreted and require less storage than for the other systems. Vessels using this technology also can run at higher speeds - up to 15 kn - compared to some submerged towed survey systems. The nature of the return echo data can be analysed by using software, such as QTC IMPACT, to interpret benthic substrates and distinguish some habitat types with reasonable reliability, such as mussel beds and some types of larger attached algae (Morrison et al. 2010).

Side scan sonar systems use two banks of opposing sonar transducers mounted on a towfish, which flies close to the seafloor behind the survey ship. The sonar beams are directed at a low grazing angle to the seafloor in order to emphasise surface relief and, as a result, the method has a higher surface reflectivity resolution (Aronoff 2005; Le-Bas & Huvenne 2009). As the towfish moves forward, successive swaths are recorded to build up a continuous image, with achievable resolution of benthic objects at an elevation of as little as 3 cm. The system generates image swaths on each side of the towfish from the received sonar echoes. These swaths can range in size from 50 to 500 m wide depending on the distance of the towfish from the seafloor. To generate high quality mosaics of the seafloor, a side scan survey typically acquires 200% coverage, where the overlap between swaths is great enough that double coverage of the entire area is acquired (Aronoff 2005). The individual swaths are fitted together to produce an improved composite image of the entire survey area.

Post-processing software such as QTC SideView can be used with xtf output files from the side scan system to extract features from the bottom echoes and deliver a classification of seafloor type, such as identifying mussel beds. This approach has been successfully used by AUT scientists, Carle & Breen (2010), to derive accurate habitat classes for three broad geographic areas in the Hauraki Gulf, and by Wong et al. (2008) to investigate the impact of mussel farms on soft sediment habitats in the Hauraki Gulf. Wewetzer et al. (1999) also used side scan sonar augmented with echo-sounding to successfully identify mussel beds over soft sediments in a survey of Tay Estuary of eastern Scotland. It is not clear whether this technology would be able to detect algal and hydroid habitats given that they may be quite dispersed. However, preliminary results of a study by Carle and Breen (pers comm. 2010) suggest that this is possible.

Multi-beam sonar systems use an array of sound sources and echo receiving devices, usually mounted on the hull of the survey ship. The system works by sending a focused burst of acoustic energy to a narrow strip of seafloor perpendicular to the ship's direction of travel. The array of receivers on the hull of the ship simultaneously record sound reflected back from the seafloor. From the multiple echoes, a series of depth measurements can be generated at regularly spaced intervals along a profile perpendicular to the ship's track. As the ship moves forwards, bathymetric measurements along a swath of seafloor are collected. The width of the swath depends on the depth of the ocean below the vessel. The large array of receivers allows for more subtle detection of textural characteristics of the seafloor than is possible with single beam and side scan sonar systems. However, it is not clear whether this technology would be able to detect algal and hydroid habitats given that they may be quite dispersed.

Ship-based multi-beam sonar, while proven to be exceptionally useful in meeting a wide range of objectives, has several limitations, particularly while working in shallow water environments. These include: 1) navigation dangers; 2) inability to collect data in water shallower than approximately 15 m; 3) inability to create seamless, coastal topographic-bathymetric surfaces; 4) reduced efficiencies due to the proportional relationship between water depth and bottom coverage; and 5) the speed and cost of collecting the datasets (Costa et al. 2009).

6.2 Local Knowledge

Combining perceptions and local knowledge with scientific information can provide a more holistic view of the natural environment (Robertson et al. 2000; Breen 2006; Dinsdale & Fenton 2006). Studies have shown that repeat visitors to a natural environment are able to detect quite subtle changes in the condition of that area (Davis et al. 1995; Breen 2006; Dinsdale & Fenton 2006).

These stakeholders often have an enormous depth of knowledge about the condition and extent of natural resources, their ecology and the effects of management (Neis et al. 1999; Berkes et al. 2000; Webb et al. 2004; Johannes et al. 2008). Their perceptions of the environment can be used as a tool for evaluating general ecological trends, resource condition over time and to provide insight into a community's assessment of how well the management of an area or resource is working (Webb et al. 2004; Breen 2006).

Agrawal (2000) found that local residents are far more likely than visitors to have the longer term horizons that are necessary for adaptive management of marine resources. The involvement of local users in research can assist low cost data collection and enforcement, and has the potential both to generate far better information for management and to help extend the time horizon over which managers make decisions (Breen 2006).

With this in mind, a pilot survey of local knowledge was conducted between 19 and 20 March 2010 with key stakeholders involved in the mussel spat fishery in GLM 9. Five individuals representing iwi, fisheries officers and commercial interests were interviewed using a semi-structured questionnaire (Appendix 1); detailed findings from the survey are provided in Appendix 2. All five subjects had lived and worked in the Ninety Mile Beach area for more than 10 years, and were involved in harvesting spat, algae, or in managing the resource.

The interviews focussed on respondent's perceived locations of spatfall, seaweed and adult mussel beds in the region (Figure 13). In general there was agreement between their 'anecdotal' observations of the fishery and the scientific findings described in the general knowledge section of this report. There was concern expressed by some of the respondents as to the sustainability of the fishery, the need for protection of the adult mussel beds and seaweed beds, and the impacts of global warming on the prevailing wind patterns.

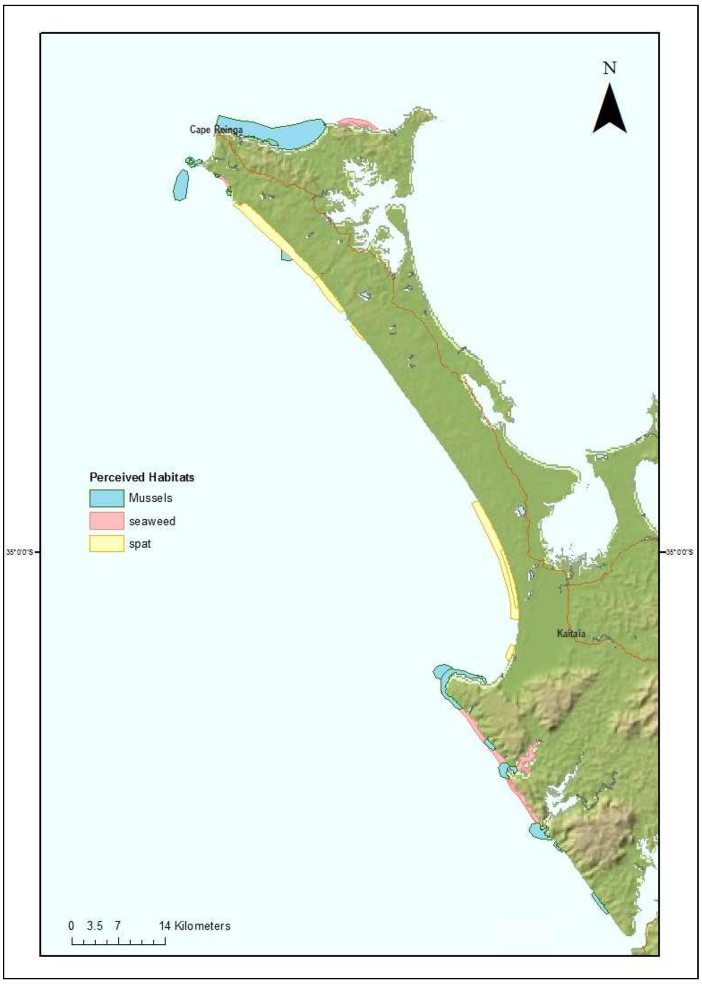

Figure 13: Map of the five survey respondents' perceived locations of adult mussel beds, seaweed and spatfall.

7 IDENTIFICATION OF KNOWLEDGE GAPS

From our review of the literature and local knowledge we have identified five key knowledge gaps with regards to GLM 9. The five knowledge gaps are presented below in decreasing priority order for future research efforts:

1. The location of source green-lipped mussel populations, and their relative contribution to the spat harvested in GLM 9, are unknown
2. The location of source populations of hydroids, seaweeds and other debris, and their relative contribution to the spat material harvested in GLM 9, are unknown.
3. The status of populations of broodstock mussels, hydroids, seaweeds and sources of other debris that are important contributors to arrival of mussel spat harvested in GLM 9 is unknown.
4. The functioning of the biological and physical pathways between populations of broodstock mussels and settlement material (hydroids, seaweed and other debris), and spat material harvested in GLM 9, is unknown.
5. The impact of spat harvesting on natural coastal mussel populations in GLM 9, including potentially important broodstock populations, is unknown.

8 ADDRESSING THE KNOWLEDGE GAPS

Given the range of research methods reviewed here, there are a wide variety of approaches that could be used for addressing these knowledge gaps. The five knowledge gaps are presented in decreasing priority order for future research efforts.

8.1 The location of source green-lipped mussel populations, and their relative contribution to the spat harvested in GLM 9

A range of effective seabed survey tools are available that can remotely distinguish mussel beds, but their effectiveness for identifying algal and hydroid beds is uncertain. Of the available remote sensing tools, side-scan sonar with post-processing of data to determine habitat types is probably the most suitable in terms of ability to cover a range of depths reliably and to determine habitats. However, using such a tool for undertaking a survey would only tell us the location and extent of populations, not their relative contribution to mussel spat in the GLM 9 harvests.

Currently available genetic markers (principally microsatellites in this instance) have not been tested at the spatial scale required to resolve the extent to which individual adult populations of mussels are providing spat harvested for GLM 9. To determine whether existing microsatellites are informative in identifying the source of spat at Ninety Mile Beach will require a test of genetic variability across small spatial scales (population by population) within the GLM 9 region, and immediately outside but adjacent to it. Statistical testing of multi-locus genotypes (possibly across different marker types) can then be employed using new assignment-based tests of the sort often used in human forensics.

This approach provides a probability or likelihood of match, which means that even if we could not identify with absolute certainty the source population(s) of the spat harvested at Ninety Mile Beach, we could say with a specific degree of confidence which population(s) is/are likely to be the source. This in itself moves us forwards a great deal in our state of knowledge because, at present, we simply do not have any knowledge of which mussel broodstock populations are contributing to the GLM 9 spat resource. The location and size of the region where the natal bed(s) exist(s) can be narrowed down quite considerably using this genetic marker approach, such that other approaches (modelling, satellite imagery, etc.) can then be better employed at a more localised and relevant geographic scale.

This genetics approach requires that mussel beds in different locations are sampled so that the adult mussels to be tested may provide a genetic basis for comparison with harvested spat from Ninety Mile Beach. Having tested the *P. canaliculus* microsatellite data using the new generation of assignment tests (Wei et al. In press), we can be reasonably confident that this approach will provide new and informative data. However, if this approach is unsuccessful then new genetic marker types, with the potential to provide high spatial resolution of populations, may need to be investigated and tested to determine their suitability for this application.

Appropriate marker types to test would include SNPs (single nucleotide polymorphisms) and also ISSRs (inter-sequence simple repeats). Given the present knowledge about population genetic structuring for *P. canaliculus* within New Zealand, it seems likely that these two methods (existing microsatellites and/or new markers) will provide the greatest marker-dependent approach to resolving the issue of the source of the Ninety Mile Beach spat.

An alternative and much larger scale approach involves genomics. Specifically, this would require the complete sequencing of the nuclear genome of the green-lipped mussel. While this is a large and expensive undertaking, it would provide the full DNA sequence of this mussel as a baseline for further use in this project and also in other potential applications.

Other tools, such as chemical larval marking and analyses of larval shell chemistry, may help to distinguish which populations contribute to harvested spat, but these techniques are largely unproven at the scale of resolution desired (i.e., chemical marking of spat, isotope tracing, and elemental fingerprinting). Furthermore, temporal variability in the contribution to harvested spat from different adult mussel populations is quite likely, and hence temporal replication of these methods would be necessary, which would compound the difficulty of undertaking the research and interpreting the results.

This temporal variability could be confirmed using elemental fingerprinting methods on the prodissoconchs of harvested larval spat, together with elemental fingerprinting of resident juvenile mussels sampled from along the coast, to determine the localised differences in elemental composition of water. These methods also may serve to identify the general location of parental populations of mussels.

Regardless, from our existing limited hydrographic knowledge, information on genetic structure of North Island mussel populations, our general knowledge of mytilid larval biology, and detailed knowledge of the reproductive biology of a small number of adult mussel populations that have been examined in GLM 9, all strongly suggest extensive larval mixing and therefore it is likely that green-lipped mussel populations over a wide area are contributing to GLM 9 harvests. Thus, surveying the location of adult mussel populations within a radius calculated on the basis of larval period and hydrographic information would provide an appropriate benthic survey range.

This range could be roughly estimated at a minimum of 50 km alongshore of Ninety Mile Beach and up to a depth of 60 m offshore (larval period of 35 days and mean maximum potential rate of passive drift estimated at 0.02 m s^{-1}). The scale of this survey could be reduced if more detailed information on hydrodynamic regimes in the area were available. However, the cost of obtaining this survey information through many of the methods available (high frequency coastal radar, current instrument deployment and modelling) is likely to be equivalent to undertaking a more extensive benthic survey.

This benthic survey information (bathymetry and habitat classification) would provide the basis for formulating protection of adult mussel populations, such as placement of harvesting restrictions or identifying areas as a priority for protection in the event of a significant coastal oil spill.

8.2 The location of source populations of hydroids, seaweeds and other debris, and their relative contribution to the spat material harvested in GLM 9

The same issues apply for filling this information gap as for identifying broodstock mussel populations (see section 8.1). However, because there is a wide variety of seaweed and hydroid species involved in contributing to spat material, many of which are small and inconspicuous and which may not form obvious benthic patches or beds, they could be extremely difficult to survey effectively.

Given that all of these organisms are normally attached to hard benthic substrates (rock), a remote survey method that reveals hard benthic substrates would help to isolate and reduce the extent of the areas needing to be examined more closely for the presence of seaweed and hydroid populations of significance to mussel settlement. Side-scan sonar with post-processing for habitat classification may be sufficient to determine potential areas of algae and hydroids. If not, it will very effectively identify benthic areas of hard substrate that could be surveyed for algae and hydroids using more conventional methods such as drop camera and video, or remotely operated vehicle video survey. Again, this would allow the location and extent of seaweed and hydroid populations to be determined, for consideration of how appropriate protection measures could be applied to them.

Such survey information would not provide information on the relative contribution of different seaweed and hydroid populations to GLM 9 harvests. Realistically, this would be very difficult to determine using existing scientific methods that are available because other unknown source populations for this material may still be present beyond the study area which may also contribute to the material harvested with spat in GLM 9. Advances might be possible using some of the genetic methods already outlined, to identify specific source populations for this material, but this type of project would be likely to constitute a significant research undertaking.

8.3 The status of populations of broodstock mussels, hydroids, seaweeds and sources of other debris that are important contributors to the arrival of mussel spat that is harvested in GLM 9

Assessing and then monitoring the status of populations of broodstock mussels, hydroids and seaweeds over the longer term would be a challenging task. From previous studies of other species of mytilids, and from the monitoring of intertidal populations in GLM 9, we know there is a great deal of flux in population parameters, in part due to the wave-exposed nature of this coastline.

Discerning long-term trends from this high level of short-term variability is difficult. Monitoring changes in subtidal populations of hydroids and seaweeds would be more challenging given both the ephemeral nature of many of these species, and the logistical difficulties of making any rigorous quantitative assessments that could form the basis of long-term comparisons, especially if the populations of these organisms are patchy, at low density, or widely dispersed.

If wider scale surveying of the extent of populations of mussels, hydroids and seaweeds proceeds, it could be used as a base-line for longer term changes, and/or for identifying populations that could be used for developing effective monitoring methods. If accessible mussel beds are identified with side-scan sonar methods it should be possible to accurately map the spatial extent of these populations, and take dredge samples to determine mussel sizes, density, and condition index, which could then be used to estimate bed biomass and turnover rates, and track any changes in the overall size of the mussel bed.

Any long-term monitoring of representative adult mussel populations should focus on populations most likely to be affected by the loss of a natural supply of spat through harvesting (i.e., subtidal and intertidal populations at The Bluff and the northern end of Ninety Mile Beach, i.e., Scott Point). Field-based assessment of population biology (e.g., recruitment, growth, mortality, turnover rates) derived from such studies would help to improve our understanding of the processes delivering the harvested spat material to GLM 9 and assist in refining the modelling of connectivity processes.

8.4 The functioning of the biological and physical pathways between populations of broodstock mussels and settlement material (hydroids, seaweed and other debris) and spat material harvested in GLM 9

Incremental studies of natural biology of larvae and spat, as well as studies of the hydrological features and processes of the coastline included in GLM 9, especially Ninety Mile Beach, will assist in addressing this knowledge gap. In addition, understanding these processes may be an important factor in re-establishing substantial and ecologically important wild populations of green-lipped mussels in other parts of the country which have previously been allowed to be fished to extinction (e.g., Hauraki Gulf, Marlborough Sounds, and Nelson Bay).

Incremental studies could include larval behaviour and nutrition, larval settlement substrate availability, larval settlement processes, post-settlement movement of spat, hydrodynamic processes involved in detaching and accumulating algae and hydroids together with spat, and transporting them to Ninety Mile Beach.

This could involve identifying the locations where the settling larvae and settlement substrate are brought together. More extensive collection of local *in situ* physical oceanographic data will be required to substantiate the reliability of these modelling efforts with respect to larval transport pathways and environmental conditions that impact development and behaviour during dispersal.

8.5 The impact of spat harvesting in GLM 9 on natural coastal mussel populations, including potentially important broodstock populations

One observation suggests that spat which otherwise would have been harvested have contributed to the renewal of an intertidal population at the northern end of Ninety Mile Beach at Scott Point (Alfaro 2006c). Tracing the eventual fate of un-harvested mussel spat in GLM 9 is challenging scientifically given the extremely exposed nature of this coastline, but is worthy of consideration as there are emerging techniques that could be utilised. For example, video drones could be used to provide low level aerial views of the progress of movement and eventual fate of un-harvested spat in algal mats at Ninety Mile Beach.

Currently there is very little monitoring of what spat material is being harvested, the composition of that material, what is being returned to the beach by harvesters (unsold spat material) to preserve quota, what spat material is left behind after harvesting and the eventual fate of un-harvested spat material. Some of this monitoring could be implemented with the co-operation of harvesters. Long term records of spat harvesting could be compared with patterns of recruitment to any adult mussel beds that are monitored.

9 CONCLUSIONS

While the GLM 9 fishery is relatively small, it is the critical basis for around $260 million worth of aquaculture production from the Greenshell aquaculture industry, with further growth in production likely. The value and importance of this fishery to New Zealand has been growing rapidly, despite only limited efforts to reduce the risk exposure of a large aquaculture industry to a wild and variable seed supply.

The GLM 9 resource has been brought into the Quota Management System and a Total Allowable Commercial Catch introduced for the stock which provides an upper harvesting limit. Overall, a relatively small amount of good scientific information is available on mussel population biology in GLM 9. This is despite the great economic importance of this fishery to New Zealand, and with respect to a number of potential risks to this fishery that have been identified in this study.

In contrast to other commercial fisheries of equivalent ultimate economic value to New Zealand (e.g., hoki at less than half the total value of Greenshell), very little research effort has been targeted at identifying the size and location of the stock, and the sustainability of the harvested resource in GLM 9.

The state of knowledge for the biology and oceanography of the west coast of the Far North region of New Zealand is not well developed. For example, the relatively recent development of scallop harvesting in Spirits Bay subsequently led to the discovery of unique biodiversity of benthic organisms, which was followed by implementation of protection measures from fishing. The area was found to have more than 200 species of sponges and 300 species of bryozoans, a number of which were unique to the area, or thought to have very limited natural distribution ranges (Cryer et al. 2000; Taylor & Gordon 2003).

This review has identified five significant information gaps regarding the GLM 9 resource. A wide variety of research methods are available for tackling these information gaps, and filling these gaps effectively will probably rely on the application of a combination of complimentary research methods applied over some length of time. In particular, a priority would be the identification of the location and extent of adult populations of mussels in GLM

9, and an attempt to determine which populations are important contributors to spat harvested from GLM 9.

Likewise, it is important to understand more about the location and extent of source populations of algae and hydroids that provide the majority of the settlement substrate for mussel larvae, and are an integral part of the transport of spat onto Ninety Mile Beach, where they are accessible for harvest. Beyond understanding the source locations of components of the spat material that is harvested, there is also a need to better understand the biological and physical processes delivering the harvestable resource. It also would be useful to determine the fate of un-harvested spat material. In combination, rigorous scientific information collected for all of these areas will ensure sustainable management of this important resource from the basis of sound knowledge.

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12 APPENDICES

12.1 Appendix One - Semi-structured questionnaire for survey of local knowledge

Approved by the Auckland University of Technology Ethics Committee on 19 November 2009, AUTEC Reference number *09/263*

Ninety Mile Beach Local Ecological Knowledge Questionnaire

Dear Sir/Madam

Thank you for agreeing to take part in our research to determine the best method(s) for investigating population connectivity of the green-lipped mussel resource and associated algal species at Ninety Mile Beach and adjacent coastal areas (GLM 9). Your participation is voluntary and you can withdraw at any time without any adverse consequences.

Mussel farms in New Zealand are almost entirely reliant on wild-caught spat that wash up on Ninety Mile Beach attached to seaweeds, hydroids and other debris. But where the spat originate from, or how they are transported to Ninety Mile Beach is unknown and consequently the sustainability of this mussel resource is also unknown. Therefore a large scale study is required to identify the source of spat (broodstock mussel beds) and seaweed populations at Ninety Mile Beach and beyond, and to also understand the underlying processes that transport the spat to the beach. Before this large study can be carried out a preliminary study is required to review and evaluate the various methods that could be used, and to identify what is already known and where we lack knowledge.

Our research team is conducting this preliminary study and as part of it we will be reviewing the scientific literature to determine the gaps in our knowledge. However we also recognise that local knowledge is also an important source of information and therefore we will be interviewing coastal resource users from Ninety Mile Beach and adjacent areas in an effort to obtain some of this information. The knowledge you hold about the coastal environment surrounding Ninety Mile Beach will add to what is already known in the scientific literature and will provide another dimension to this study.

In particular we are interested in any knowledge you have on:

- Locations of mussel spat wash up
- The material mussel spat is attached to
- Locations of mussel and seaweed beds
- Whether there have been any changes in these things overtime

Outcomes of this research will be presented in a report to the Ministry of Fisheries which they may choose to release as a public document, and it may also be presented at conferences, University seminars and published in scientific journals.

Kind Regards
Drs. Andrea Alfaro, Barbara Bollard Breen, Andrew Jeffs and Jonathan Gardner.

Section 1: BACKGROUND

1. Please tell me about your fishing and/or shellfish gathering?

a) How long have you been fishing or harvesting along Ninety Mile Beach? (tick **one** box only)

less than 1 month	1-6 mths	7mths to 2 years	3-10yrs	>10yrs

b) **Using the Map provided**, please indicate where you **usually** fish or harvest around Ninety Mile Beach.

[Show maps to participant here]

c) What **percentage** (%) of fishing/shellfish gathering do you do? (tick **one** box only)

recreational	commercial	customary

The next question is directed at your main type of fishing or gathering.

c) What type of fishing do you do? (tick **as many as apply**)

Long-lining		Dredging		Mussel spat gathering	
Shellfish gathering		Trapping/potting		Harvesting seaweed	
Line fishing		Gill netting			

d) when you have been fishing or gathering have you ever noticed seaweed or other types of marine organisms attached to your gear when you haul it in?

If yes, please describe:

___

___

___

The next section focuses on mussel spat at Ninety Mile Beach

2. Since you have been visiting Ninety Mile Beach, have you noticed any mussel spat washing up on the beach? Yes No (circle one)

If yes, please describe:

____

____

____

3. Using the Map provided, please indicate where you **usually** see mussel spat washing up on Ninety Mile Beach.

[Show maps to participant here]

4. Have you noticed any changes in the distribution and abundance of spat washed up on the beach since you have been visiting Ninety Mile Beach?

Please describe these changes in detail:

____

____

____

5. Are the spat free standing or are they usually attached to something? If the latter, what materials have you seen them attached to?

Please list:

____

____

6. Have you ever seen mussel spat wash up on other beaches in New Zealand?

If yes, please list these locations:

____

____

____

7. How would you describe the weather conditions 1 day, 1 week and 2 weeks prior to seeing mussel spat wash up on Ninety Mile Beach?

1 day: ____

1 week: ____

2 weeks: ____

The next section focuses on algal beds and mussel beds around Ninety Mile Beach.

8. Since you have been visiting the Ninety Mile Beach area, have you noticed any algal beds?

Yes No (circle one)

If yes, please describe:

____

____

____

9. If yes, using the Map provided, please indicate where you **have seen** algal beds around Ninety Mile Beach.

[Show maps to participant here]

10. Since you have been visiting the Ninety Mile Beach area, have you noticed any offshore mussel beds?

Yes No (circle one)

If yes, please describe:

____

____

____

11. If yes, using the Map provided, please indicate where you **have seen** mussel beds around Ninety Mile Beach.

[Show maps to participant here]

Thank you. We have reached the end of the questionnaire. Is there anything else you would like to tell me about the Ninety Mile Beach?

Please use this space for any additional comments:

12.2 Appendix Two - Detailed findings from survey of local knowledge

Approved by the Auckland University of Technology Ethics Committee on 19 November 2009,
AUTEC Reference number *09/263*

Detailed findings from the survey of local knowledge are provided in this Appendix for each section of the survey. Five individuals were interviewed, representing a broad cross section of stakeholders including iwi, fisheries staff, commercial fishers and recreational fishers. All five subjects had lived and worked in the Ninety Mile Beach area for more than 10 years and were involved in harvesting spat, algae, or in enforcement of the management rules for the resource.

Section 1: BACKGROUND

2. Please tell me about your fishing and/or shellfish gathering?

a) How long have you been fishing or harvesting along Ninety Mile Beach? (tick **one** box only)

less than 1 month	1-6 mths	7mths to 2 years	3-10yrs	>10yrs
				100%

b) **Using the Map provided**, please indicate where you **usually** fish or harvest around Ninety Mile Beach.

all five respondents indicated the entire marine and coastal region around Ninety Mile Beach and were not willing to pinpoint exact locations

c) What **percentage** (%) of fishing/shellfish gathering do you do? (tick **one** box only)

recreational	commercial	customary
	2 respondents 100%	1 respondent 100%

2 respondents did not indicate the percentage of each type of fishing they did.

The next question is directed at your main type of fishing or gathering.

c) What type of fishing do you do? (tick **as many as apply**)

Long-lining		Dredging		Mussel spat gathering	xxx
Shellfish gathering		Trapping/potting		Harvesting seaweed	
Line fishing		Gill netting	x	other	xx

d) when you have been fishing or gathering have you ever noticed seaweed or other types of marine organisms attached to your gear when you haul it in?

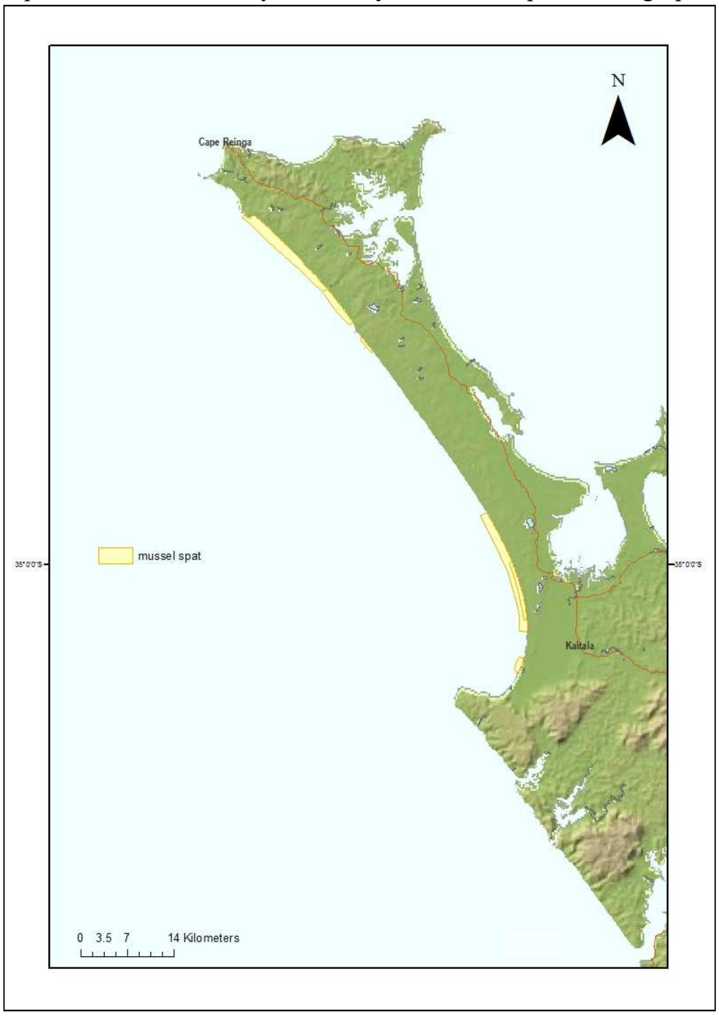
If yes, please describe:
1) seaweed found with spat on it; 2) seaweed seen on the surface floating and not covered in spat; 3) broken up agar seaweed 4) other marine organisms - sea snake

The next section focuses on mussel spat at Ninety Mile Beach

2. Since you have been visiting Ninety Mile Beach, have you noticed any mussel spat washing up on the beach? Yes No (circle one) All 5 respondents circled YES

If yes, please describe:
1) Seaweed goes over the mussel beds at Ahipara and picks up the spat, they sit together in the eddy off Ahipara, 10mm spat attaches to seaweed so you get big balls of seaweed and spat washing up all along 90 Mile Beach.
2) You need the combination of seaweed and spat for there to be spat washing up on the beach. The ease at which it comes to shore depends on the weather and a critical density of spat and seaweed. The spat appears to move north along the beach over time at between 3km to 10km per day depending on the density of the spat and seaweed. If heavier, it moves slower. Spatfall also varies with the tide, the heavier stuff falls first, then as the tide falls, the lighter stuff falls out.
3) Yes the mussel spats washes up all along Ninety Mile Beach, but there are hot spots as indicated on the maps.
4) We know there has been a spatfall when the spat gathers are driving around harvesting spat.

3. Using the Map provided, please indicate where you **usually** see mussel spat washing up on Ninety Mile Beach.



Map of the locations of mussel spat indicated by the 5 survey respondents

4. Have you noticed any changes in the distribution and abundance of spat washed up on the beach since you have been visiting Ninety Mile Beach?

Please describe these changes in detail:
1) not really

2) less spat washing up in the past 2 years
3) no there has been no decrease over time, I've been harvesting here for years
4) last couple of years there has been a decline because of the continuous easterlies from Christmas on, a prolonged Easterly turns it all off. With Northerlies you get bigger spat attached to brown algae and more broken up algae. Over time it is a variable business.
5) no

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5. Are the spat free standing or are they usually attached to something? If the latter, what materials have you seen them attached to?

Please list:
1) seaweed, hydroids
2) fine red filamentous seaweeds
3) seaweeds, sticks and grasses
4) agar seaweed - reds and only small pieces of it.
5) seaweed

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6. Have you ever seen mussel spat wash up on other beaches in New Zealand?

If yes, please list these locations:
1) no
2) no
3) no
4) nowhere else
5) no

7. How would you describe the weather conditions 1 day, 1 week and 2 weeks prior to seeing mussel spat wash up on Ninety Mile Beach?

1 day: 1) swell running, sea colour changes - murky and full of microorganisms; 2) easterly, low swell, big tides; 3) calm offshore wind, heavier spatfalls in Feb to May; 4 & 5) usually calm with easterly winds

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1 week: 1) seaweed decomposing, film on it

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2 weeks:

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comments - spat wont fall in heavy seas

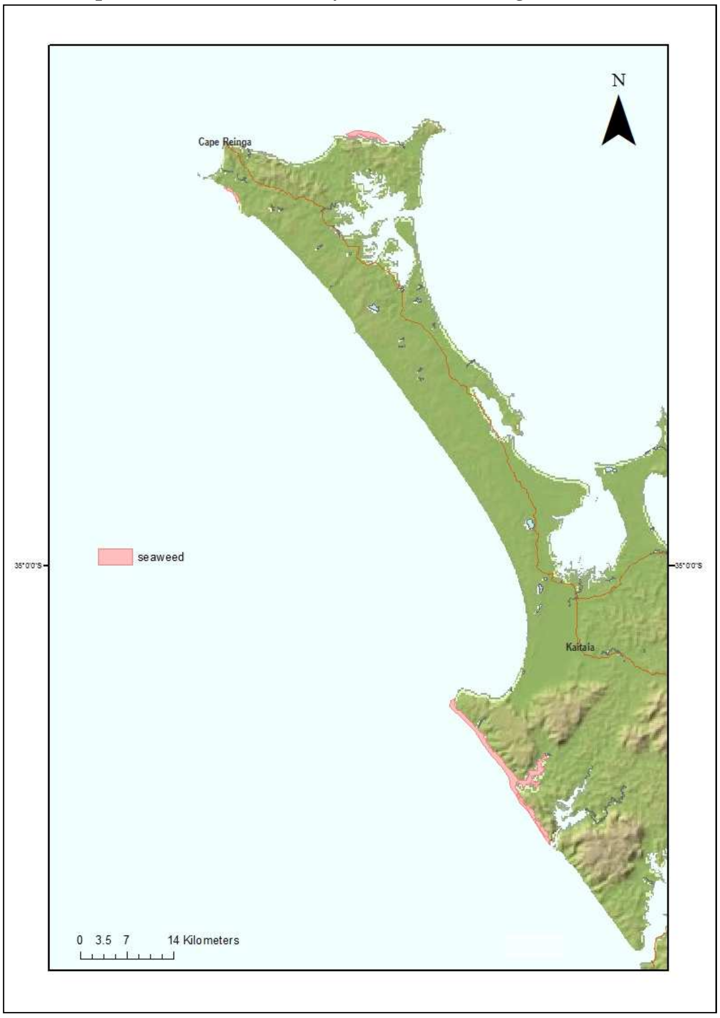
The next section focuses on algal beds and mussel beds around Ninety Mile Beach.

8. Since you have been visiting the Ninety Mile Beach area, have you noticed any algal beds?

Yes No (circle one)

If yes, please describe:
1) agar seen south of Ahipara to Hokianga, breaks off in storms and drifts around in eddy
2) south of Shipwrecks
3) free and unattached seaweed everywhere along Ninety Mile Beach, never see spat with Ecklonia species. Find the red algae off Tauroa Point.
4) and 5) not answer

9. If yes, using the Map provided, please indicate where you **have seen** algal beds around Ninety Mile Beach.



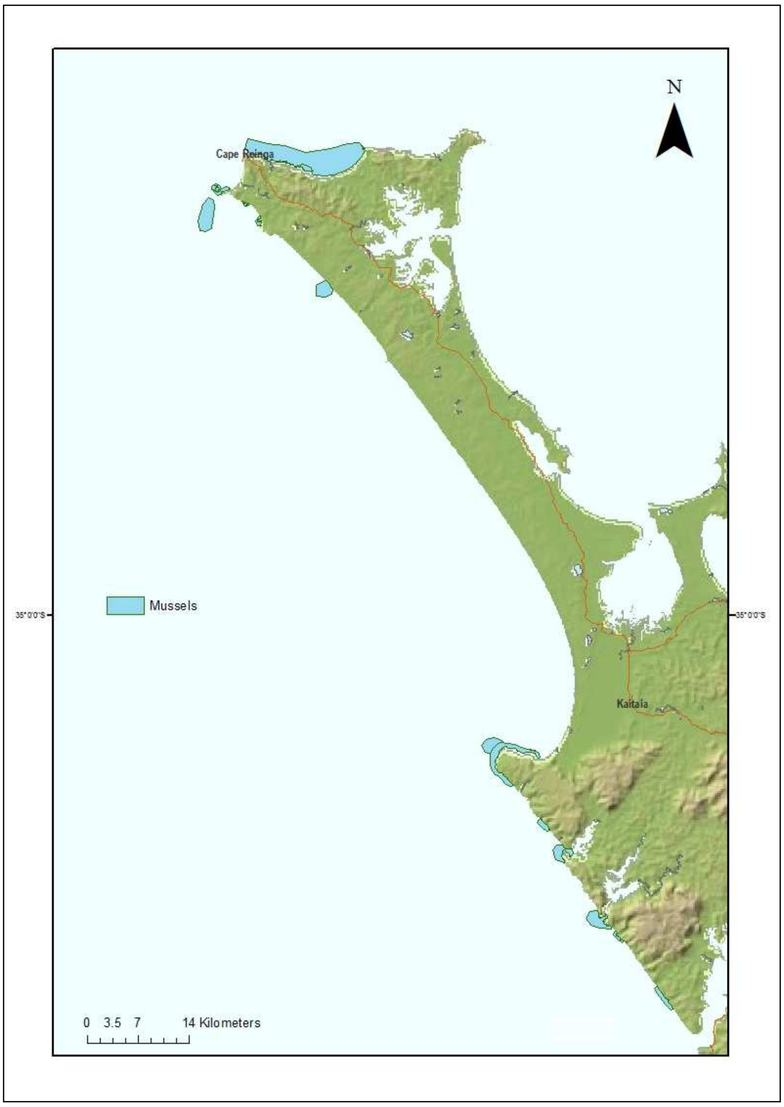
Map of the locations of seaweed indicated by the 5 survey respondents

10. Since you have been visiting the Ninety Mile Beach area, have you noticed any offshore mussel beds?

Yes No (circle one) one respondent answered yes and the other four answered no.

If yes, please describe:

11. If yes, using the Map provided, please indicate where you **have seen** mussel beds around Ninety Mile Beach.



Map of the locations of adult mussel beds indicated by the 5 survey respondents

Thank you. We have reached the end of the questionnaire. Is there anything else you would like to tell me about the Ninety Mile Beach?

1) Great concern about sustainability of the fisheries. There has been a historic issue of kiatiaki and MFish who have come in and let out Quota without consulting Iwi. There is concern that

new concessions will come in with helicopters and big boats. The respondent would like to look at cleaner ways of gathering spat on hanging frames or other un-trialled methods.

2) Need to understand the oceanographic parameters – e.g., currents in order to understand the distribution of spatfall. Great need to protect the source beds from over harvesting, run off, effluent, industry run off, boats discharging ballast and bottom trawling. Also believes the seaweed beds need to be protected. Concerned about the impact of global warming on the prevailing wind patterns and thus spatfall. Believes storm events with lightning are important to stimulate spawning of adult mussels and storm events also provides debris for the larvae to settle on. There are anecdotal records of spat being collected further south near Kaipara. Thoughts on the future of the spat collecting industry - harvesting spatfall off the beach is by far the cheapest methods of supplying aquaculture, spat nurseries still have a long way to go. The entire Greenshell mussel industry needs the wild caught spat from Ninety Mile Beach.

3) Very concerned about impacts to the adult mussel populations, particularly issues of sedimentation and pollution. Wants to ensure that when government allocates water and land resources that they demonstrate no adverse effect on the spat fishery. Concern that the surf clam fishery has impacts by changing water patterns and currents in nearshore regions - this needs to be addressed. Concerned with global warming - believes this has resulted in changing the dominant winds to easterly, the effect is instant in that it totally stops the spat fishery.