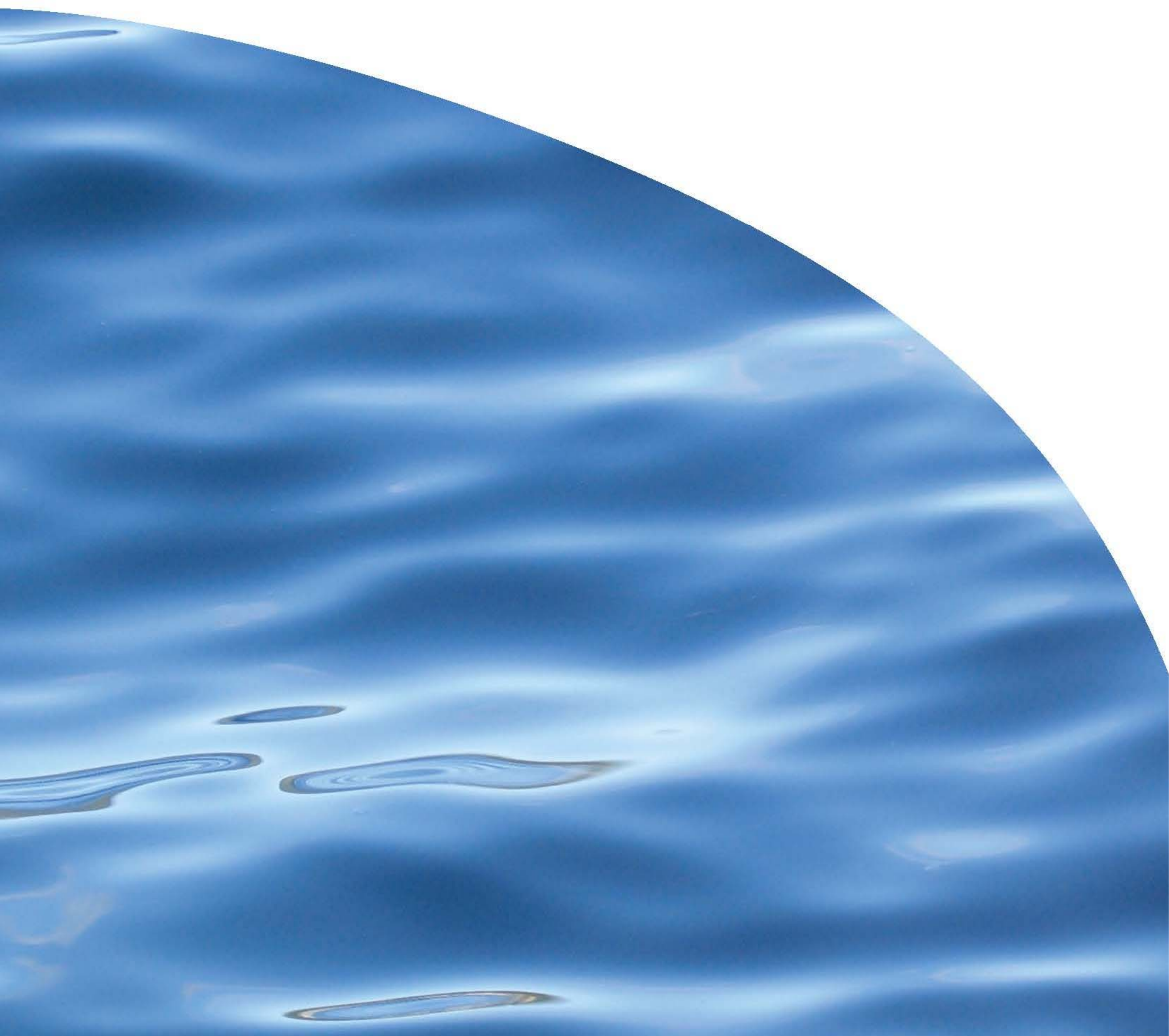
CAWTHRON INSTITUTE

REPORT NO. 2479A

# BACKGROUND INFORMATION ON THE MEDITERRANEAN FANWORM *SABELLA SPALLANZANII* TO SUPPORT REGIONAL RESPONSE DECISIONS



# BACKGROUND INFORMATION ON THE MEDITERRANEAN FANWORM *SABELLA SPALLANZANII* TO SUPPORT REGIONAL RESPONSE DECISIONS

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ISSUE DATE: 3 June 2014

RECOMMENDED CITATION: Fletcher LM 2014. Background information on the Mediterranean fanworm *Sabella spallanzanii* to support regional response decisions. Prepared for Marlborough District Council. Cawthron Report No. 2479A. 35 p.

# EXECUTIVE SUMMARY

The non-indigenous Mediterranean fanworm, *Sabella spallanzanii* (hereafter referred to as *Sabella*), was first detected in New Zealand in 2008 and has since become established in Port Lyttelton, Waitemata Harbour and Whangarei Harbour. Increasing domestic spread through the movement of infested vessels has led to *Sabella* being detected in a number of additional harbours nationally. *Sabella* is designated as an unwanted organism under the Biosecurity Act, and has been subject to targeted surveillance in eleven commercial ports and harbours around New Zealand for over a decade.

Cawthron Institute (Cawthron) was commissioned by Marlborough District Council (MDC) under the Ministry of Science and Innovation's Envirolink medium advice grant scheme to conduct a desktop assessment of key technical information relating to this species, and provide an evaluation of the invasion potential and considerations for management within the Marlborough region. At the inception of the report *Sabella* was not believed to be present in the region, however in late February 2014, a small population was discovered on a boat moored in Waikawa Bay. As such, information regarding *Sabella*'s biology, likelihood of establishment, potential for further spread, and impacts to key values is particularly timely. The key findings of this review into *Sabella*'s biology and ecology are summarised below:

- *Sabella*'s reproductive biology poses management challenges; in particular, the species' high fecundity rates (a mature female can produce > 50,000 eggs during each spawning event), 'sperm-casting' fertilisation strategy and the extended reproductive season (spawning may occur from May to late September in central New Zealand).
- Worms with a body length > 120 mm are considered to be possibly mature in New Zealand. However, there is evidence to suggest that they may attain sexual maturity when smaller than initially believed. *Sabella* from Port Phillip Bay are believed to be sexually mature when their body length is > 50 mm, while those in South Australia reach reproductive maturity at a length of 60–90 mm.
- *Sabella* worms are capable of rapid growth and are able to regenerate body structures (including the branchial crown) if damaged.
- This species has wide environmental tolerances and a lack of predators (possibly due to arsenic accumulation in body tissues).
- *Sabella* is a habitat generalist which can live in most artificial and natural habitats, including on shell debris within soft sediments.
- There is a high potential for natural dispersal from established populations due to *Sabella*'s extended larval duration (up to three weeks) and its ability to delay settlement if it encounters unsuitable environmental conditions.
- There is also a high potential for human-mediated spread due to *Sabella*'s propensity for hull fouling and ability for larvae to be transported via ballast water.

Effective management of marine pests after they have been detected in a location is often challenging and expensive. Generally, any management programmes that are initiated in response to incursions need to have a high likelihood of success because of competing funding priorities. Successful invasive species management in the marine environment is largely reliant on the species having:

- limited natural dispersal potential
- low fecundity
- specific habitat requirements
- conspicuous morphology and visible individuals.

As outlined above, it can be can be argued that *Sabella* fails to meet any of these general criteria, leading to difficulties in defining outer boundaries for surveillance and vector control. Simultaneously, the absence of effective regional and national controls on movements of potentially infected vectors means the risk of further incursions into the Marlborough region is probably high. This risk will increase over time as existing populations undergo further domestic spread.

Critical information gaps with reference to *Sabella*'s introduction to Marlborough include reliable information around potential impacts to both environmental and economic values in New Zealand. Reports that quantify negative impacts are all Australian-based and are predominantly environmental effects, as opposed to negative impacts to industry (*e.g.* aquaculture). The environmental impacts reported are localised, and in one study apparent impacts disappeared after six months of monitoring. However, *Sabella*'s introduction to Port Phillip Bay in Victoria, Australia, has considerably altered the composition of resident marine communities. It would be therefore unwise to assume that *Sabella* will not result in significant adverse effects as it spreads further within the Marlborough region. It is conceivable that *Sabella* could become a nuisance fouler on subtidal aquaculture systems, and the species' high-filtering capacity could also make it a competitor to cultured filter-feeding species such as oysters and mussels. Thus, consideration of a worst-case scenario (*i.e.* significant adverse effects on the region's aquaculture and environmental values) would be prudent when making decisions on whether, and to what extent, to respond to any future incursions in the Marlborough district.

Regional councils are now responsible for managing post-border range extensions of *Sabella*, with the Ministry for Primary Industries (MPI) supporting some responses, but not taking a leading role. Due to the requirement for specialised contractor services (*e.g.* hand removal by divers), any management efforts undertaken are likely to require significant resources. A recent *Sabella* incursion response in the Coromandel cost the region's council ~$120,000, of which ~$76,000 was split 50:50 with MPI. There are difficulties around detection of small individuals and it is likely that repeat removal efforts will be required. An on-going commitment of resources and a robust evaluation of the feasibility, costs, and benefits of all management options will therefore be necessary.

Consideration should be given to preventing or slowing the spread of *Sabella* to high value areas (*e.g.* key aquaculture regions or marine protected areas). The development of pathway management plans between regions is an important component of invasive species management, but will require a collaborative approach between neighbouring regions and central government. Although challenging, this may provide the best value for money in the event of multiple incursions or the presence of more than one target species within the region (*e.g. Styela clava*'s recent detection in Picton).

This report (Cawthron Report No 2479A) is an amended version of an earlier finalised report (released April 2014; Cawthron Report No. 2479). Changes were made to incorporate outcomes of the *Sabella* delimitation survey within Waikawa Bay carried out in late April 2014, as well as feedback from key stakeholders.

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# 1. INTRODUCTION

Introduced marine pests pose an important long-term threat to coastal ecosystems within New Zealand. In addition to biodiversity loss and the alteration of ecosystem function, the introduction of a marine pest to a region and associated response efforts can result in considerable economic costs. The last 10–15 years has seen an increased prevalence of invasions and adverse effects from marine pest species in New Zealand, particularly with reference to high-value industries such as shellfish aquaculture and fisheries. Negative impacts to key cultural and amenity values are also possible (*i.e.* impacts on food harvesting, tourism, recreational fishing).

Effective management of marine pests after they have established in a location is often challenging and expensive. Generally, any management programmes initiated to deal with such incursions need to have a high likelihood of success due to competing funding priorities. A thorough understanding of a species' invasion and spread potential, likelihood of establishment and options for control, is crucial to this process. For example, an understanding of natural dispersal potential is of particular importance as this underpins a number of common management needs. This includes identification of the spatial scales for vector control, as well as delimitation zones for surveillance. The natural dispersal ability of biofouling species can vary considerably, with vessels and other anthropogenic vectors often playing an important role in extending the spatial scale and rate of species spread. Simultaneously, knowledge of actual and potential impacts provides a critical context for understanding the importance of management, and for optimising management approaches. For example, this provides insight into the effort required to reduce invasion levels to a point where density-dependent effects are mitigated. The ability to make well-informed decisions with regard to associated costs and benefits will enable timely response actions where necessary, as well as prevent futile expenditure where eradication or management is not feasible.

The Mediterranean fanworm, *Sabella spallanzanii* is a high-profile marine pest native to the Mediterranean and the Atlantic coast of Europe. This species has established substantial non-indigenous populations in Australia, and has recently been detected in New Zealand. Large aggregations of *Sabella* have the potential to alter resident community structure and may compete with native organisms for food and space. *Sabella* is formally designated as an unwanted organism under the Biosecurity Act, and has been subject to targeted surveillance in eleven commercial ports and harbours around New Zealand for over a decade. The first detection of *Sabella* in New Zealand was in Lyttelton Harbour in March 2008. The population is now established in Lyttelton, however worm densities remain low. Further prolific and extensive populations have subsequently been detected in Waitemata (Auckland) and Whangarei Harbours (Northland). Since early 2013, additional isolated incursions have also been detected in Coromandel, Tauranga and Nelson harbours. While some of the worms found in Coromandel Harbour were believed to be mature and capable of sexual reproduction (pers. comm. A. Pande, Ministry for Primary Industries), the worms found in Tauranga were immature and therefore unlikely to have established.

Due to concerns around the further spread of *Sabella* within New Zealand, Cawthron Institute (Cawthron) was commissioned by Marlborough District Council (MDC) under the Ministry of Science and Innovation's Envirolink medium advice grant scheme to:

- Provide background technical information on the biology, vectors of spread, and ecological and economic impacts of *Sabella*.
- Assess the invasion potential and management options within the Top of the South region.
- Identify any critical information gaps with reference to species' biology, impacts and management options.

*Sabella* was not believed to be present in the Marlborough region at the time this report was started. However, a population was discovered on a moored boat in Waikawa Bay in late February 2014. Several large worms (~400 mm) were found on the vessel, suggesting the population may have been in this location for some time. A subsequent delimitation survey did not detect any further worms in the Waikawa Bay area; however, the region faces on-going risks from vectors such as vessels arriving from infested regions like Auckland. Access to information regarding *Sabella*'s biology, likelihood of establishment and potential for further spread, and impacts to key values, will assist with effective decision-making around future eradication and/or containment efforts.

In addition to regional responsibilities, MDC is a member of the Top of the South (TOS) Marine Biosecurity Partnership, which was formed in 2009 with the objective of improving marine biosecurity management. TOS encompasses the coastal areas administered by MDC, Nelson City Council and Tasman District Council. The information provided in this report will be make an important contribution to the goals of this Partnership, in particular the identification and clarification of key needs for pathway risk reduction efforts, which is presently a priority work area of the Partnership. Similarly, the information provided will assist other regional councils should there be incursions of *Sabella* not previously detected.

This report (Cawthron report no 2479A) is an amended version of an earlier finalised report (released April 2014; Cawthron report no. 2479). Changes were made to incorporate outcomes of the *Sabella* delimitation survey within Waikawa Bay carried out in late April 2014, as well as feedback from key stakeholders.

# 2. TECHNICAL INFORMATION ON *SABELLA*

## 2.1. Information sources and weighting

This summary of technical information about *Sabella* draws on New Zealand sources where possible, supported by international information where necessary. Due to this species relatively recent arrival in New Zealand, the majority of research on key biological and ecological characteristics is from overseas. Populations in the Mediterranean have been well studied since the mid-20th century (*e.g.* Wells 1951). Studies have included considerable research on the reproductive biology, biochemistry and feeding regimes of *Sabella* within this region. Where the technical studies from Australia and overseas conflict in terms of the information they provide, greater weight is generally given to the information from Australian studies. *Sabella* is assumed to have been introduced into New Zealand from an Australian source population. This means that the genetic diversity and subsequent population characteristics are likely to be closer to this region as opposed to native Mediterranean populations.

## 2.2. General description and background

The adult *Sabella* is a sessile, tube-dwelling worm species with a prominent crown of brightly coloured (orange, purple and white) bands of feeding tentacles (Figure 1). *Sabella*'s outer tube is tough and flexible and often muddy in appearance. In some instances, there can be other organisms growing on the surface of the tube. There are many native fanworms that look similar; however, with a tube length of up to 800 mm, the Mediterranean fanworm is larger than all other comparable worms in New Zealand. *Sabella* is well-recognised internationally as an invasive species and has been a very successful coloniser in its introduced range. This species has been identified as a potential threat to key environmental and economic values in New Zealand for some time. Central government has taken steps to identify and prepare for possible incursions and establishment for over a decade (MFish 2001). *Sabella* is one of nine marine pest species identified as posing significant risks to native marine environments. These species are subject to targeted surveillance within New Zealand's major trading ports and marinas as part of the MPI-lead 'Marine High Risk Site Surveillance Programme' (Inglis *et al.* 2006).

Figure 1. *Sabella* in a tidal pool at Kohimarama Beach, Auckland. Photo taken by Evan Brown (University of Auckland).

## 2.3. Distribution and invasion history

### 2.3.1. Native distribution

*Sabella* is native to the Mediterranean and the east Atlantic coast of Europe to the southern end of the English Channel (Knight-Jones & Perkins 1998). Within the Atlantic region, *Sabella* has been recorded along the Moroccan coastline, mainland Europe from Portugal to north-west France, as well as on islands within the Azores archipelago (Andrew & Ward 1997). *Sabella* is reported to be common within Mediterranean fouling communities where it also forms large aggregations on artificial substrates in eutrophic environments (Giangrande *et al.* 2005).

### 2.3.2. Worldwide distribution

This species has established invasive populations along the southern coast of Australia and in New Zealand (Read *et al.* 2011; Murray & Keable 2013). It is also a possible historic introduction to Brazil, having been recorded as early as 1856 under seven different synonyms (Clapin & Evans 1995; Knight-Jones & Perkins 1998). The first confirmed occurrence in Australia was in 1992 within Port Phillip Bay (Victoria, Australia; Carey & Watson 1992); however, it may have been present in this area since 1988 (Parry *et al.* 1996). Archived material suggests it may have also been present in Albany (Western Australia) since 1965 (Clapin & Evans 1995). Populations from three Australian locations (Western Australia, South Australia, and Port Phillip Bay) have been shown to be genetically similar, but disjoined from European populations (Andrew & Ward 1997; Patti & Gambi 2001). The separation of the three Australian populations into two different clades, and the geographic discontinuity between them, may indicate two separate invasions into Western Australia and Adelaide and to Port Phillip Bay (Patti & Gambi 2001).

### 2.3.3. Distribution in New Zealand

*Sabella* populations are well-established in Waitemata and Whangarei harbours. It is also present in Lyttelton Harbour, however based on regular surveillance that population remains at relatively low densities. Isolated incursions have been recorded within Coromandel, Nelson and Tauranga harbours and Waikawa Bay. Further detail on each area is provided below.

**Lyttelton Harbour**

The first recorded occurrence of *Sabella* in New Zealand was in Lyttelton (Port of Christchurch) in March 2008 (Read *et al.* 2011). However, based on population assessments, it is possible it first entered the country through Auckland and was subsequently translocated to Lyttelton. The species appears to be predominantly confined to within the inner port area in Lyttelton, although low numbers have been detected in the nearby vicinity (Read *et al.* 2011).

**Waitemata Harbour**

*Sabella* is very well-established in Waitemata Harbour and is found throughout the harbour area, to at least St Heliers and Torpedo bays (Riding 2014). *Sabella* has also been detected in the marina at Whangaparaoa (Gulf Harbour) and is believed to be in the nearby Weiti Estuary as the infested barges that were found in Coromandel Harbour reportedly came from there. There have also been recent reports of this species from Tamaki Straight. As such it appears *Sabella* has extended its range to the inner Hauraki Gulf.

**Whangarei Harbour**

*Sabella* was first detected when worms were found on the hulls of three commercial vessels in Whangarei Harbour in February 2012. More worms were subsequently discovered growing within the marina area despite an attempt at eradication. *Sabella* is now established in Whangarei Harbour and can be found in both marina areas and in some locations in the wider harbour.

**Coromandel Harbour**

In early April 2013, large numbers of *Sabella* worms were discovered on the hulls of two cargo barges moored in Coromandel Harbour. Both barges had recently arrived from Weiti Estuary in Auckland. The worms found on the barge hulls are believed to have been mature and capable of sexual reproduction. An incursion response was initiated to remove all the high risk mature worms, after which the vessels were moved back to Auckland. Follow up detection and delimitation surveys have found some individuals on the nearby substrate, however following removal these worms were determined to not be mature. It is hoped this has prevented *Sabella* becoming established in the region.

**Nelson Harbour**

*Sabella* was detected on the hull of a cargo vessel in Port Nelson during April 2013, following removal from the water for cleaning and refurbishment. A delimitation survey of the nearby area did not detect any additional worms. A single *Sabella* worm was subsequently found in the marina area during MPI-funded routine surveillance of the port in November 2013. This is believed to be a separate incursion event. Subsequent delimitation surveys commissioned by the Nelson City Council and MPI during November 2013 and April 2014 have detected and removed 30 individuals from within the marina area.

**Tauranga Harbour**

A single immature fanworm was found on the substrate in Pilot Bay (Tauranga; September 2013). Subsequently, a vessel on a mooring in the vicinity was found to have a single *Sabella* worm present. That vessel had been moved from Auckland several months earlier. Extensive searching of boats, moorings, marinas, wharves and substrate found a further three *Sabella* individuals at Tauranga Bridge Marina. The Bay of Plenty regional council is planning to continue to monitor for *Sabella* at high risk sites in the Tauranga Harbour (pers. comm. K. Walls, Ministry for Primary Industries).

**Waikawa Bay**

Several large *Sabella* individuals were recently found on a recreational vessel moored in Waikawa Bay (near Picton). The boat was cleaned soon after detection. A delimiting survey around the site of the infested vessel and at other sites including Waikawa Bay marina has found no further evidence of *Sabella*.

## 2.4. Biology and natural history

### *2.4.1. Body structure*

*Sabella* builds conspicuous leathery tubes that are tough, but flexible. These tubes are generally 5–20 mm wide and have been documented to reach up to 800 mm long in Whangarei Harbour (in contrast to published literature which suggests worms reach a maximum length of 400 mm). The outer tube is a pale brown colour and has a muddy or silty appearance. Often there are a number of other sessile invertebrates attached. This tube is constructed by combining mucus and faeces and is extended by the worm as it grows. The production of conspicuous amounts of mucus is a characteristic of this species (Giangrande *et al.* 2014). Individuals are able to 'glue' their base back to the substrate if they are removed (observed during ecological studies). The pronounced U-shaped bend in the tube at the base, and the ability to bury the tube to a depth of 10 cm into soft substrates (O'Brien *et al.* 2006; Ross *et al.* 2013), means that *Sabella* can use their tubes as an effective anchor (Parry *et al.* 1996). Tube strength (*i.e.* the weight needed to detach the tube) varies among members of the Sabellidae family. Species inhabiting hard substrates generally have stronger tubes than those living in soft sediments, where the tubes are often buried in sediment (and therefore protected). *Sabella* specimens have very strong tubes when compared to five other sabellid species. They have been shown to withstand ~800 g of weight before tearing (Giangrande *et al.* 2014).

*Sabella* worms have a prominent ‘fan’ that is a characteristic feature of their species. This structure (termed a branchial crown) is made up of numerous tentacles, and extends beyond the worms’ protective tube for feeding and respiration. The tentacles are often protected from predation, either chemically or structurally depending on the species (Fattorini *et al.* 2005; Kicklighter & Hay 2007). The fan can also be completely retracted inside the tube in response to different types of disturbance (Giangrande 1991; Licciano *et al.* 2012). In large adult specimens, with tubes > 300 mm, the feeding fan will account for roughly 45–60 mm of this length (NIMPIS 2014). The diameter of the fan has been known to reach up to 100–150 mm in some large specimens. The branchial crown comprises two lobes, one of which is spiraled (Figure 2A). In juvenile specimens, the branchial lobes are equal and splay into independent circles, but as the worm matures the lobes become increasingly asymmetrical. In adult specimens of *Sabella*, the right lobe is small and forms a half circle, while the left lobe develops into an extremely long and spiraled crown (Currie *et al.* 2000; Patti & Gambi 2001). The tentacles can vary in colour from a dull white banded with pale fawn, orange or brown, as well as appearing orange with brightly banded stripes of brown, red, and purple (Riding 2014) (Figure 2B).

Once removed from the tube, *Sabella* worms are most easily characterised by a wider first ventral shield (plate-like structures running the length of the body). As well, they have fleshy orange ‘lappets’ (turned down flaps of tissue just below the base of the tentacles). The thorax is divided into 8–9 segments, with an extended abdomen comprising anywhere between 50–200 segments (Furlani 1996). In addition, when viewed under a dissecting microscope, the presence of thoracic companion chaetae and abdominal chaetae arranged in spiraled bundles are both diagnostic characteristics (Murray & Keable 2013).

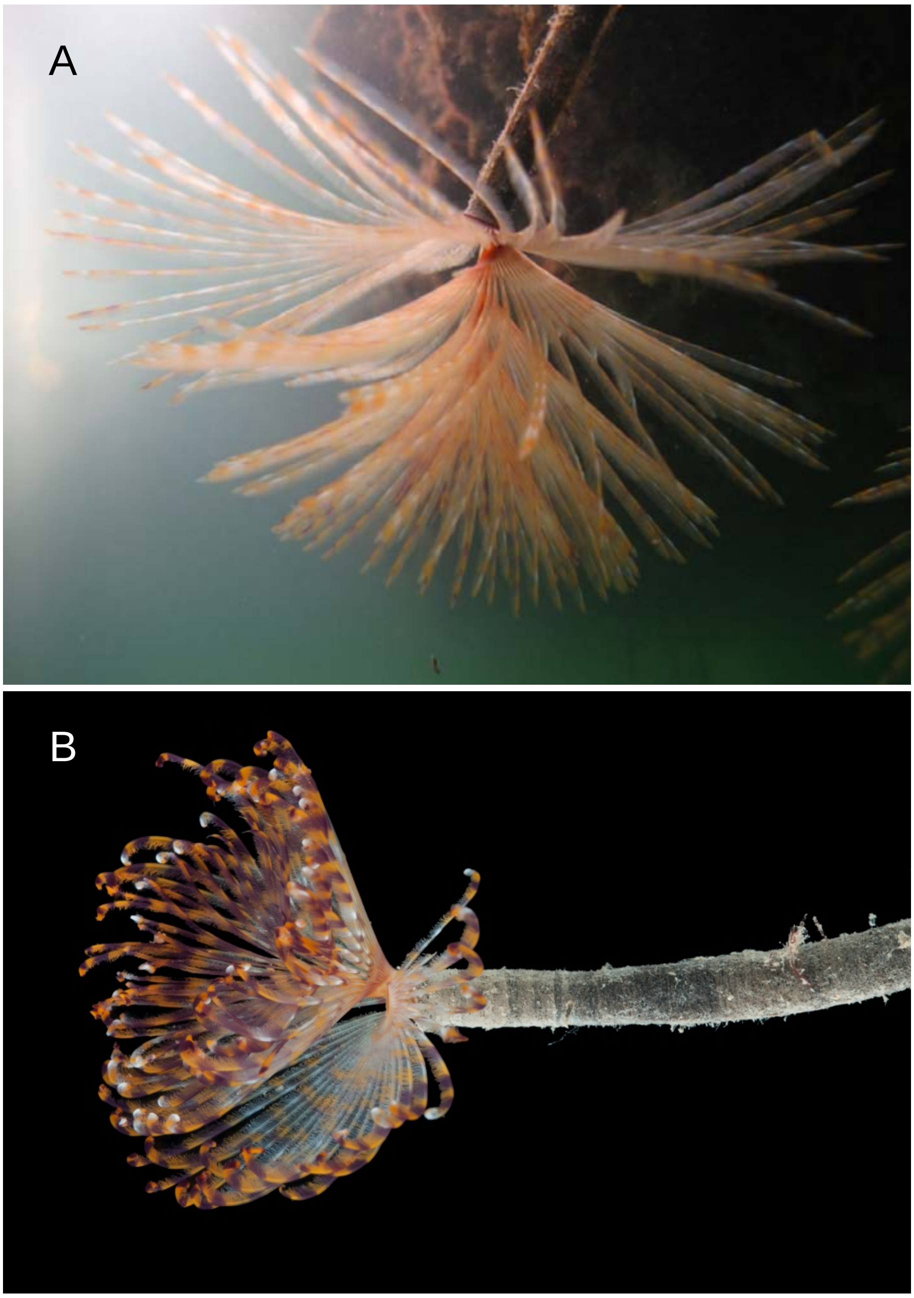


Figure 2. A) *Sabella* on vessel hull with fan extended showing spiral fan structure. Photo courtesy of Serena Wilkins (NIWA). B) *Sabella* worm showing the head of the tube and the extended branchial crown. Photo courtesy of Richard Taylor (University of Auckland).

### *2.4.2. Feeding and respiration*

*Sabella* is a suspension feeder which consumes organic matter such as phytoplankton and zooplankton. The branchial crown extends out of the tube to collect and sort material of different sizes. The fan preferentially traps particles of 3-8 µm size (Clapin 1996), which are passed by cilia from the fan to the mouth at the anterior region of the worm (Ross *et al.* 2013). Any larger particles are pushed away from the mouth and dropped into the water (Mayer 1994). *Sabella* has a high filtering capacity and is able to process up to 12 $m^3$ of seawater per day (Stabili *et al.* 2006). The feeding efficiency (volume of water filtered per metabolic demand) of a population inhabiting the bare sediment in the Southern Flats (Cockburn Sound, Australia) was found to be 13 L per $mg^{-1}$ $O_2$ consumed (Clapin 1996). Feeding efficiency has been shown to increase with temperature from 13°C, with optimum levels reached at 22°C. This feeding efficiency rate decreased sharply at 22–27°C, indicating an upper temperature limit (Clapin 1996). Under experimental conditions *Sabella* has been shown to survive with no food for 30 days (Raganato *et al.* 2001).

### *2.4.3. Reproduction and development*

Knowledge of reproductive strategies and seasonal development is of particular importance in formulating effective management strategies. *Sabella* worms are believed to employ a 'sperm-casting' strategy, as opposed to the typical broadcast spawning approach to reproduction often exhibited by marine invertebrates. Eggs and sperm are formed in the coelomic cavity of abdominal sections (this species has no discrete ovaries or testes) (Currie *et al.* 2000). Fertilisation takes place inside the worm's tube following egg release from this coelomic cavity (Giangrande *et al*. 2000; Stabili *et al*. 2009). This strategy is likely to increase fertilisation success considerably, particularly compared to external fertilisation of gametes within the water column.

The sex of adult worms and presence of mature gametes can be detected through examination of the coelomic fluid. The presence of mature eggs is indicated by turquoise or green fluid and mature sperm by a white or tan fluid. In juvenile specimens, freshly examined coelomic fluid ranges from bright orange to brown (Currie *et al.* 2000; Giangrande *et al.* 2000). A thorough review of gamete development for an Australian population is provided in Currie *et al.* (2000).

Female worms spawn by extending the thorax and upper abdomen from the tube and releasing long mucus strings that contain the fertilised eggs (~1 m length) (Currie *et al.* 2000). Estimates of mature egg densities in large *Sabella* specimens (~400 mm body length) suggest that > 50,000 eggs are produced and released during spawning (Currie *et al.* 2000). The lecithotrophic (non-feeding) larvae remain in the water column for up to three weeks following external fertilisation (Giangrande *et al.* 2000). The larvae are gregarious, and recently settled specimens are often found in clusters.

Metamorphosis into a feeding juvenile stage was found to occur ~10 days after settlement. However, this was under experimental conditions and the authors noted that both pelagic duration and time to metamorphosis may have been influenced by this (Giangrande *et al.* 2000). Research to date indicates that *Sabella* does have the potential for a long pelagic period, and can delay its settlement and metamorphosis to overcome adverse and unsuitable external conditions.

Information on worm size at sexual maturity differs based on the geographic regions examined. Minimum size (body length) indicating sexual maturity was about 150 mm (excluding the crown) in a native population from the Gulf of Taranto (Mediterranean Sea; Giangrande *et al.* 2000). However, *Sabella* from introduced Australian populations appear to reach sexual maturity at a smaller size. For example, an examination of 80 *Sabella* from Port Phillip Bay (Victoria) indicated that worms with bodies > 50 mm were sexually mature (Currie *et al.* 2000). Similarly, a recent study in South Australia reportedly found gametes in the coelomic cavity of a worm that was only 39 mm long (Lee 2013). However, there were 12 worms with no gametes in the range of 42–87 mm, and the majority of juvenile worms in the study were < 90 mm in length. As such, the author concluded that this South Australia population reached reproductive maturity when body length was 60–90 mm (Lee 2013). Only one specimen collected from a Botany Bay (New South Wales) population was found to be sexually mature, and this was the largest worm in the study with a body length of 112 mm (Murray & Keable 2013). Tube to body length correlations carried out on the South Australian population show that tubes > 158 mm long are predicted to house reproductively mature worms of > 90 mm in length (Lee 2013). In New Zealand, worms with a body length > 120 mm are considered to be possibly mature.

The conflicting size at maturity information may be due to differences in defining what constitutes a 'mature' worm. In the Mediterranean study, eggs were classified as mature at ~250 µm (Giangrande *et al.* 2000). In contrast, the Port Phillip Bay study defined eggs as mature if their diameter was > 160 µm (Currie *et al.* 2000), which may have led to the lower body length estimates for mature worms within this region. Adding to the confusion, the only other study to investigate the timing of reproductive events used different criteria to classify the maturity of eggs. Lee (2013) defined eggs as 'developing' (< 50 µm), 'early mature' (50–100 µm), or 'late mature' (> 100 µm). Interestingly, the largest egg recorded during this work was only 170 µm in diameter. In addition, inter-annual differences in the rate of egg development are also apparent. In Port Phillip Bay, immature eggs developed into mature stages (> 160 µm) within four months over late 1995 to 1996. However, in the following year (1997), the majority of immature eggs took seven months to mature (Currie *et al.* 2000). In the same manner, egg development was reported to take nine months within the Mediterranean population (Giangrande *et al.* 2000), but only two months within the South Australian population (Lee 2013).

The reproductive cycles and timing of spawning in marine invertebrates is often determined by local environmental conditions, particularly water temperature or photoperiod. Male and female spawning is recorded during autumn / winter and largely synchronous in *Sabella.* This timing coincides with decreasing seawater temperatures and concludes when temperatures fall to the annual minimum (Currie *et al.* 2000; Giangrande *et al.* 2000). Spawning occurs when seawater temperatures decrease from approximately 14°C to 11°C in both the Mediterranean region and Port Phillip Bay (Currie *et al.* 2000; Giangrande *et al.* 2000). In Victorian waters this occurs from March to September, with a maximum spawning period during May and June. Sea surface temperatures in central New Zealand are generally within this range from May to late September (Fletcher *et al.* 2013). This provides a potential 5-month reproductive season for *Sabella* in this region. Early gamete development begins when spawning stops and as seawater temperatures begin to rise again. Subsequent increases in water temperature coincide with the main periods of gamete production and maturation (Currie *et al.* 2000).

A recent study carried out in Wirrina Cove (South Australia), found quite noticeable differences in the timing of reproduction between populations at this location and those in Port Phillip Bay (Victoria). Female specimens showed a significant drop in early and late mature eggs between November and December, remaining low until March. The mature sperm count in male specimens was lowest in December and January, and remained low until March (Lee 2013). This decrease in mature gametes suggests a major spawning event in late November or early December, which continued through to early autumn. This observation is 4–5 months earlier than what was documented for the nearby Port Phillip Bay population (Currie *et al.* 2000). This finding is unexpected, and may have been influenced by specific methods used to determine the onset of spawning. Reports of changes in the timing of spawning may be supported by data from long-term monitoring of reproduction and recruitment in a Mediterranean *Sabella* population. Researchers noted an advance of at least three months for the spawning period during late 2008, when compared to data from previous years (Giangrande *et al.* 2010). The effects of climate change were suggested as a reason for this change, as temperature changes occurring in this region over recent decades have led to progressively warmer summers, while winters have remained cold (Giangrande *et al.* 2010).

#### 2.4.4. Growth, generation time, and longevity

Growth rate data for New Zealand populations is limited, but indicates *Sabella* individuals are capable of rapid growth over the warmer summer months. The first worm found in Tauranga Harbour had a tube length of 100mm and was believed to be at least 6 months old at the time. Rapid growth has been reported for the population in Whangarei Harbour, with worms able to grow 50-100 mm in eight weeks. Growth rates of 30 mm in two months were reported for a population in Port Phillip Bay (Currie *et al.* 2000). Reports from *Sabella*'s native range indicate a more modest growth rate, with worms growing approximately 8–10 mm per month in two Mediterranean populations (Giangrande & Petraroli 1994; Stabili *et al.* 2010). Individuals exhibit remarkable regenerative abilities if an amputation or wound occurs, including the ability to regenerate the branchial crown (Licciano *et al.* 2012). Individuals are believed to live for at least two years, but are known to live for longer than five years in the native region (Giangrande & Petraroli 1994).

### *2.4.5. Habitat and environmental tolerances*

*Sabella* populations generally inhabit subtidal areas at depths of up to 30 m, although they can be found in the intertidal zone following unusually low tidal events (Figure 3). This species shows a propensity for colonising harbours and embayments that are sheltered from direct wave action. In shallow waters, worms are often sparsely distributed. They can be found growing on a range of solid surfaces, including artificial structures (concrete, wood, steel), as well as directly on other benthic organisms such as mussels and oysters (Currie *et al.* 2000). Higher densities observed on wharf and pier pilings may suggest a preference for vertical surfaces. In Port Phillip Bay, *Sabella* was rarely found close to the water surface and densities generally increase with depth (Currie *et al.* 1998). However, in the Nelson marina almost all worms found were on the underside of floating pontoons (within 1 m of the water surface). Worms collected from soft sediments are almost always anchored to dead oyster and scallop shells (Currie *et al.* 1998), although worms have been found growing in the soft sediments of the Marsden Cove marina without a hard substrate to anchor to (pers. comm. K. Walls, Ministry for Primary Industries). Where suitable substrates are limited, *Sabella* are gregarious and will often form dense clumps of numerous individuals (Figure 3).

Figure 3. Dense clumps of *Sabella* exposed during an extreme low tide at Meola Reef in Waitemata Harbour. Photo courtesy of Richard Taylor (University of Auckland).

*Sabella* can survive in temperatures ranging from 2–29°C. Minimum temperature tolerances of 2°C are based on anecdotal reports of overnight survival at 2–4°C

(NIMPIS 2014), as well as observed survival for 12 hours at 4°C under laboratory conditions (Clapin 1996). Because winter sea surface temperatures in the Mediterranean only drop to 11°C (Giangrande & Petraroli 1994), this temperature is often used in laboratory experiments for species sourced from this region (Giangrande *et al.* 2000). Reported maximum temperature tolerances of 29°C appear to be based on temperature fluctuations within *Sabella*'s native range. During a study in the Gulf of Taranto (Italian coast) the water temperature range was 11–29°C (Giangrande & Petraroli 1994). As such, this upper temperature limit was used in laboratory experiments for specimens collected from the same area (Giangrande *et al.* 2000). *Sabella* was found at a maximum temperature of 27.6°C during surveys in the northern Ionian Sea (Mediterranean Sea) (Stabili *et al.* 2006). Some worms were observed producing mucus and detaching their branchial crowns (a stress indicator) when held at 27°C under experimental conditions (Clapin 1996). However, other specimens of the species have survived 12 hours in laboratory conditions at 30°C (Clapin 1996). Ambient water temperatures do not get to these levels within the species' Australian range; Cockburn Sound (Western Australia) has an annual range of 15–23°C (Clapin 1996), while temperatures in Queenscliff (Victoria) are documented at 11.3–22.8°C (Currie *et al.* 2000). Sea surface water temperatures in New Zealand are similar to southern Australia. They range from 10°C in the south to 23°C in the north during summer (February), while winter (August) temperatures range from 6–18°C (Chiswell 1994). Differences in the level of establishment between the Auckland and Lyttelton populations may be driven by cooler water temperatures experienced in the Lyttelton region.

*Sabella* is also able to tolerate a salinity gradient of between 26 and 39 PSU[1]. This species cannot survive long in fresh water, with death reported after two hours exposure in one study (Gunthorpe *et al.* 2001). Worms have survived translocation to brackish conditions in Italy (27 PSU), surviving for the seven months of observations. Interestingly, during this period some female worms reached maturity, although this was at a smaller body size than populations under normal salinity levels (34 PSU) (Raganato *et al.* 2001). Maximum salinity tolerances (39 PSU) are based on monitoring of established populations in both Mediterranean and Australian waters (Giangrande & Petraroli 1994; Currie *et al.* 2000; Stabili *et al.* 2006).

### 2.4.6. Ecology and population dynamics

*Sabella* can be found singularly, in small groups, or in extensive beds at densities of anywhere between 300 and 1,000 individuals/m$^2$ (Parry *et al.* 1996; pers. comm. A. Pande, Ministry for Primary Industries). Densities appear to be higher on hard substrates, particularly artificial surfaces such as wharf piles and boat hulls (Figure 4). That being so, large numbers of worms are still found within soft sediment environments. Densities of up to 13 individuals/m$^2$ have been recorded on soft

[1] Practical salinity units

sediments over large areas (~50 $m^2$), and up to 200 to 300 individuals in concentrated patches or clumps < 1 $m^2$ (Parry *et al.* 1996).

In some locations it appears to be a 'boom-or-bust' species, with considerable fluctuations in local densities. *Sabella* was initially present in high numbers (mean density > 50 individuals / $m^2$) on pier pylons at all commercial wharves in the Port of Geelong (Victoria Australia; Currie *et al.* 1998). However, densities have declined to relatively low levels in recent years when compared to the period in the late 1980s to mid-1990s when the species became established and the population expanded (Ross *et al.* 2007). A similar pattern has occurred in the population in Twofold Bay (New South Wales). Again, densities steadily increased in late 1996 until 2008 (when first detected), then a sharp decline to pre-2005 numbers followed (Murray & Keable 2013). In the Auckland context the population is still expanding into new areas of the Waitemata Harbour and inner Hauraki Gulf with no evidence of a decline to date.

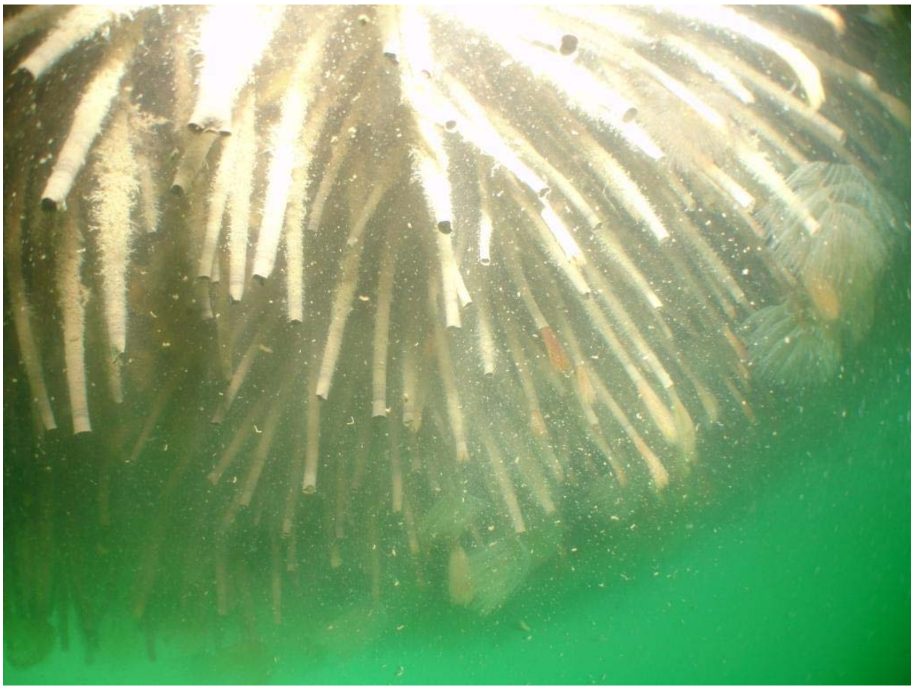

Figure 4. High densities of *Sabella* on a barge hull within the Coromandel region. Note that most worms have their fans retracted. Photo courtesy of Anjali Pande (MPI) and New Zealand Diving and Salvage Ltd.

### 2.4.7. Predators

There are no reports of *Sabella* predation within New Zealand. This species can biotransform arsenic into relatively toxic dimethylarsinic acid (DMA). This may be an adaptive mechanism against predation in more vulnerable tissues (Notti *et al.* 2007) and is supported by analysis of arsenic concentrations in various body tissues.

Concentrations of 40–60 µg/g were found in body parts, while concentrations of > 1,000 µg/g were reported within the branchial crowns (Fattorini & Regoli 2004). In Australia, there are no known predators of *Sabella* in the wild however it is used to feed leatherjackets in aquaria (NIMPIS 2014). Similarly, in Italy, *Sabella* is used as bait to catch large Sparidae fish (such as sea bream). There is some anecdotal evidence of water rats consuming *Sabella* in Port Phillip Bay; however, such predation would only be in near-shore areas close to their habitat (Currie *et al.* 1998). *Sabella* worms have a high tolerance to being wounded (Clapin & Evans 1995; Furlani 1996) and as mentioned earlier, can regenerate from fragments (Licciano *et al.* 2012). Individuals can also detach their branchial crown spontaneously in response to adverse conditions. This response may be an additional anti-predatory strategy to prevent the entire worm being captured (Licciano *et al.* 2012). *Sabella*'s lack of predators and defense mechanisms may well account for its proliferation in new environments. However, other biological parameters, including availability of food, are also likely to be important.

## 2.5. Human use

While *Sabella* is considered problematic when introduced to non-native environments, some unique properties of this species have the potential to be utilised in a number of applied scenarios. *Sabella* could be used as a bioremediator species in a range of situations. Bioremediation in marine systems is a new and sustainable tool that can be applied in waters subjected to high levels of organic pollutants, for example from fish farms or urban sewage discharges (Licciano *et al.* 2005). Recent field and laboratory studies conducted on *Sabella* highlighted its ability to accumulate and concentrate bacteria from the surrounding environment (Licciano *et al.* 2005; Stabili *et al.* 2006; Licciano *et al.* 2007). This ability may be relevant to the negative effects of vibriosis[2] in commercial aquaculture operations. *Sabella* has also successfully reduced the bacterial abundance in waste from a recirculating aquaculture system in Italy. Individuals in the study were able to filter, accumulate and remove all the considered bacterial groups from the waste, including human potential pathogens and vibrios (Stabili *et al.* 2010). The filtering activity of *Sabella* promotes the transfer of this organic matter from the water column to the sediment as faeces and pseudofaeces. Because this species utilises its own pseudofaeces in the tube-building process (Pierri *et al.* 2006), this organic matter is definitively removed from the system. This trait is not present in other potential bioremediator species such as mussels. *Sabella* could also be considered as a bioindicator in water quality monitoring. It may provide a suitable tool for detecting and monitoring microbial contamination in urban environments, even when pollutants are present in the water column at very low concentrations.

[2] One of the most prevalent fish diseases, and caused by bacteria in the genus *Vibrio*.

## 2.6. Natural and human-mediated pathways of spread

It is important to understand the natural dispersal potential of invasive species as this underpins a number of common management needs. This includes identification of the spatial scales for vector control, as well as delimitation zones for surveillance (*e.g.* Forrest *et al.* 2009). As many biofouling species have a limited natural dispersal ability, vessels and other human-mediated vectors can play an important role in greatly extending the spatial scale and rate of species spread. An understanding of human-mediated spread helps to define locations at risk, as well as key vectors that should be targeted as part of management efforts.

### *2.6.1. Natural dispersal*

As adult *Sabella* are sessile organisms, the primary method of natural dispersal for this species is the transportation of larvae by water currents. Larvae reared in the laboratory have been shown to remain able to settle for approximately 14 days, or over 20 days under stressful conditions (Giangrande *et al.* 2000). This extended pelagic duration is the longest reported among sabellid worms (Giangrande *et al.* 2000), and means that natural dispersal over substantial distances is possible depending on local hydrological conditions. Long-distance advection is less likely when the many factors that limit true dispersal are considered (*e.g.* predation in the water column). Larvae reared in the laboratory will also not be exposed to natural settlement cues (*e.g.* physical and chemical habitat cues, light conditions encountered) which may extend the free-swimming period. In addition, the presence of conspecific individuals (other larvae, juveniles or established adults) may encourage further settlement of larvae within an area, thereby leading to retention close to the natal site (Rius *et al.* 2010). In Whangarei Harbour, there has been the suggestion that larvae are recruiting close (*i.e.* within meters) to the parent population (pers. comm. K. Walls, Ministry for Primary Industries). In addition to factors limiting dispersal distance, a wide range of post-settlement processes will also affect the successful establishment and persistence of populations.

Larval spread modelling techniques have recently been applied to track theoretical *Sabella* propagules released from two heavily infested barges within the Coromandel Harbour (Knight 2013). The model was based on a two-week spawning period and assumed worm densities of 1000 worms/m$^2$ and 800 worms/m$^2$ on the two barges. The proportion of worms able to spawn was assumed to be 40% of the total population and an estimated 50,000 propagules per spawner for two spawning events each were modelled. Results showed the highest concentrations of propagules are likely to be found within the harbour after the two week period. However, *Sabella* propagules were able to reach embayments and islands to the north and south (~10–15 km from release site), although they were at much lower concentrations than that observed close to the barges. Larvae produced during each annual spawning period in Port Phillip Bay are reported to be able to successfully disperse up to 20 km from parent populations, prior to settlement onto suitable substrates and metamorphosis into juveniles (Parry *et al.* 1996). From a regional perspective, larval dispersal potential of up to 20 km is considerable. Unfortunately, as *Sabella* is a habitat generalist and is able to colonise a variety of soft and hard substrates, it is unlikely to encounter unsuitable habitats that act as barriers to spread.

### *2.6.2. Human-mediated spread*

*Sabella* is able to be transported rapidly around New Zealand as biofouling on a range of structures. Intra- and inter-regional vessel movements, as well as aquaculture activities such as the transfer of equipment and shellfish seed-stock among growing regions, are likely to be the most important mechanisms for human-mediated spread. Due to the growing number of reported incursions of this species nationally, it is likely to become increasingly difficult to manage infection sources within a region. This will be of particular relevance when new incursions are not responded to early on, or if established populations are left unchecked. As such, the importance of human-mediated spread of this species cannot be underestimated.

It is likely that *Sabella* was first introduced to Australia through shipping because of its discovery around commercial shipping wharves. There has been considerable domestic spread over the following decades. Surveys within the Kangaroo Island Natural Resource Management Region (South Australia) have observed *Sabella* as hull-fouling on recreational vessels that were traced to Wirrina Cove as the main source (Kinloch *et al.* 2010). *Sabella* was also accidently spread further within Port Phillip Bay via the translocation of shellfish stock (Gunthorpe *et al.* 2001). *Sabella* was introduced into New Zealand after Australia, and the most likely method was a heavily-infested barge that arrived from Australia to Waitemata Harbour (Auckland). Within New Zealand, *Sabella* has almost certainly been introduced to the Coromandel region through inter-regional vessel movements, arriving as hull fouling on two barges recently relocated from Weiti Estuary, within the inner Hauraki Gulf. A similar scenario is likely for the Nelson incursion; based on the spatial extent of the *Sabella* found in the marina, introduction via one or more vessels berthed at the marina is probable.

Translocation between regions via ballast water from domestic shipping is also possible. *Sabella*'s pelagic larval phase of ~14 days before settlement, or 20+ days under stressful conditions (Giangrande *et al.* 2000), means larvae could conceivably survive short-term journeys in ballast tanks.

## 2.7. Impacts associated with introductions

Reliable information about impacts of *Sabella* infestations is critical to understanding the benefits of management. However, as is the case for most marine pests, the level of *Sabella*'s invasiveness and its associated adverse effects appear to vary considerably between locations and across various times of the year. This species can occur in high densities and efficiently filters food from the water column, so has the potential to affect natural shellfish beds and shellfish farming, and could modify natural ecosystems through the possible exclusion of native species. In very high densities it is likely to impact commercially important species including mussels, oysters and scallops.

### 2.7.1. Impacts on the environment

Environmental impacts of *Sabella* can differ depending on the type of substrate they colonise. The presence of a dense *Sabella* canopy can affect larval abundance and recruitment patterns of a range of other sessile invertebrates on hard substrates (Holloway & Keough 2002a). Resident fanworms have been found to inhibit settlement and recruitment of other species at larger scales (individual wharf pilings), however effects at a smaller scale (individual settlement plates) were more varied, with a number of positive effects reported (Holloway & Keough 2002a). Suggested mechanisms for the large-scale effects include hydrodynamic effects, with continuous worm cover providing a barrier to water movement and a reduction in water exchange between the outside and inside of the canopy (Merz 1984). Larval predation by resident fanworms has also been suggested, although clear evidence of this occurring is limited. The information available suggests large sabellids consume small particles (< 20 µm), less than the size range containing most invertebrate larvae (100-2,000 µm) (Fitzsimons 1965; Merz 1984). The presence of *Sabella* has also been shown to influence community composition in the early stages of community development (up to 10 weeks) (Holloway & Keough 2002b). After six months, however, there were few differences reported between *Sabella* canopy-covered and cleared areas, and assemblages beneath canopies and those outside canopies did not differ (Holloway & Keough 2002b).

Three Port Phillip Bay-based studies looking at the impacts of *Sabella* in soft sediments have found the spatial distribution and density of *Sabella* appears to heavily influence the impacts recorded (O'Brien *et al.* 2006; Ross *et al.* 2007; 2013). Effects are likely to be negligible where *Sabella* are randomly distributed and at low densities, however localised dense clumps have been shown to impact the benthic infauna present. Sediment underlying clumps of *Sabella* was found to have significantly lower abundances of cumaceans, ostracods and harpacticoid copepods; small (< 1 mm), mobile crustacean taxa that live on the sediment surface or burrow into the sediment (O'Brien *et al.* 2006). A study carried out soon after, found no effect of *Sabella* on the resident macrofauna, with the exception of lumbrinerid polychaetes and gammarid amphipods, however these taxa only represented a small proportion of those present (Ross *et al.* 2007). The most recent study found no difference in the total abundance of macrofauna between *Sabella* and control plots. However, the composition of assemblages did change significantly in the presence of *Sabella*, with a significant increase in the abundance of echinoderms (largely attributable to brittle stars) in the presence of *Sabella* at all three sites investigated (Ross *et al.* 2013). *Sabella* has also been observed to grow over seagrass beds in this area (NIMPIS 2014).

*Sabella* has the potential to affect the abundance of macrofauna in the surrounding soft sediments using mechanisms caused by:

- changes in the benthic habitat due to the physical presence of the tube
- the worm's biological activities, particularly suspension feeding and biodeposition (Ross *et al.* 2007).

Changes in water flow around *Sabella* clumps may affect resident assemblages directly by influencing water velocities, or indirectly through changes in sediment stability, oxygen levels or concentration of organic matter in the sediment (O'Brien *et al.* 2006 and references therein).

Impacts to nutrient availability are also possible. The efficient removal of suspended organic particulates has the potential to change nutrient cycling and the microbial community. Organic nitrogen (N) taken up by the worm in particulate matter is metabolised to ammonium ($NH_4$), with waste then resuspended as pseudofaeces and often incorporated into tube-building by the worm. This prevents nutrients from reaching the sediment where it would normally be converted by denitrifying bacteria (Ross *et al.* 2013). As such, there has been considerable concern about the effect of *Sabella* on nitrogen cycling in Port Phillip Bay (Harris *et al.* 1996). A recent study found a significant decrease in the concentration of chlorophyll-*a* and a significant increase in the main degradation product of chlorophyll-*a* (phaeophytin) in the water when *Sabella* is present. In addition, a major increase in oxygen ($O_2$) consumption and ammonium production in the presence of *Sabella* was reported at all sites (Ross *et al.* 2013).

*Sabella* populations also provide additional habitat for a range of epifauna including amphipods, barnacles, and serpulid polychaetes. A range of species typically associated with fixed or hard surfaces rather than soft sediments have been documented within *Sabella* assemblages (Ross *et al.* 2013). The combined filter-feeding capacity of these organisms has been shown to be much greater than those of communities associated with seagrass beds and bare sediments. Epifauna on the tubes has been estimated to represent up to 60 % of the enhanced filtering capacity of *Sabella* clumps on bare sediments (Lemmens *et al.* 1996).

### 2.7.2. Impacts on industry

*Sabella* has not caused significant detrimental effects to marine industries in New Zealand with its present distribution. But it would be unwise to assume this species could not cause negative widespread effects, particularly if it becomes established in a key aquaculture region such as the Marlborough Sounds. This species is able to colonise a wide range of habitats, including directly onto shellfish (see Figure 5). It is therefore conceivable that *Sabella* could become a nuisance fouler on subtidal aquaculture systems such as commercial mussel lines or fish culture cages. The high biomass of problematic fouling organisms' increases the time and costs of harvesting, transporting and factory processing of cultured species. In addition, *Sabella*'s high filtering capacity may make it a competitor to cultured filter-feeding species such as oysters and mussels.

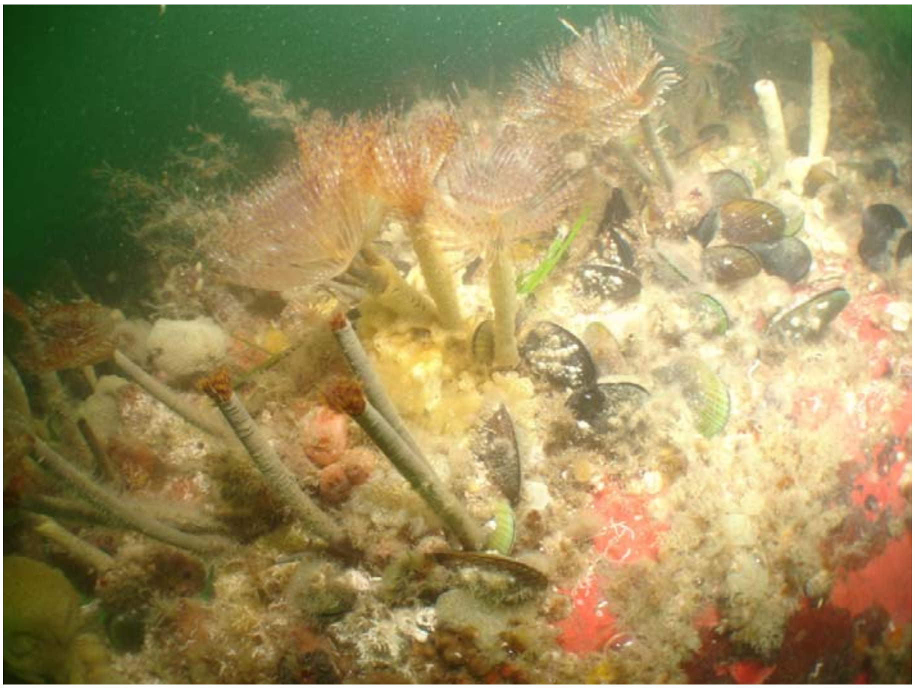

Figure 5. *Sabella* on a vessel hull, with fans extended and partially retracted. Photo courtesy of Anjali Pande (MPI) and New Zealand Diving and Salvage Ltd.

*Sabella*'s presence has caused isolated impacts to shipping and recreational boating in New Zealand. Operators arriving on vessels with *Sabella* worms present may be required to remove their vessel for cleaning, which can be a costly undertaking. This was necessary in the Whangarei and Coromandel incursions and in each situation the cooperation of vessel owners facilitated this process considerably. *Sabella* also has the potential to impact operators of commercial vessels because of decreased efficiency through hull fouling, with subsequent impacts on fuel consumption.

Information about the impacts of *Sabella* to industries overseas is also scarce. The scallop fishing industry in Port Phillip Bay reported it increasingly time-consuming to sort catches from dredges clogged with *Sabella* following the introduction of this species to the region (Currie *et al.* 2000). This is no longer a current problem however, as the industry has been closed since 1996 due to concerns around dredging effects on benthic communities. In a recent survey of anglers and divers interacting with the environment of Port Phillip Bay, one angler who had been fishing in the area since the mid 1950's described the introduction of *Sabella* as one of the 'major ecological changes to the Bay' (Jung *et al.* 2011). Impacts of *Sabella* on blue mussel (*Mytilus galloprovincialis*) production in Western Australia have been negligible. It has been reported as 'little more than a slight nuisance', based on interviews with commercial operators (Clapin & Evans 1995).

# 3. CONSIDERATIONS FOR MANAGEMENT

Control and eradication of pest species in the marine environment is often technically and financially difficult (McEnnulty *et al.* 2001; Meyerson & Reaser 2002). Very few efforts to eradicate a marine species have ever been successful, with key exceptions being instances where arguably novel circumstances (*e.g.* the ability to close off an environment for treatment) have contributed to these successful outcomes (*e.g.* Culver & Kuris 2000; Bax *et al.* 2001; McEnnulty *et al.* 2001; Wotton *et al.* 2004; Hopkins *et al.* 2011). If *Sabella* is again detected in the Marlborough region, decisions regarding the feasibility of eradication or control will be necessary. To assist with this decision-making, the history of *Sabella* control efforts in New Zealand, management techniques available, and considerations of the species' invasion potential in the Top of the South region are outlined below.

## 3.1. Efforts to manage *Sabella* in New Zealand

This first *Sabella* specimen was detected in Lyttelton Harbour (Port of Christchurch) during routine port surveillance sampling on 3 March 2008 (Read *et al.* 2011). This individual was 115 mm long (excluding the crown) and had no gametes present within the reproductive structures. Seven more worms were found during subsequent surveys of the port area during June 2008, and 98 worms were collected over several days during an intensive removal operation by commercial divers in August 2008 (Read *et al.* 2011). Some of the female worms collected during this operation were assessed as having the potential to reproduce, based on overseas research (Currie *et al.* 2000; Giangrande *et al.* 2000). Periodic monitoring undertaken over 2009, continued to detect large *Sabella* specimens, but the population numbers were low (Read *et al.* 2011). The 2008 eradication programme had seemed to be progressing well until two events that led to questions around the futility of these activities. In May 2009, for the first time a single *Sabella* worm was found outside the inner port area and in late 2009, a number of smaller worms (< 20 mm) were detected. This indicated reproduction had been successful and a second generation of individuals was now present (Read *et al.* 2011).

On the 19 August 2009, during bi-annual MPI-lead surveillance conducted by the National Institute of Water and Atmospheric Research (NIWA), a large (133 mm) female worm was found in Waitemata Harbour (Auckland) (Read *et al.* 2011). Further surveillance and culling efforts by commercial divers during October 2009 recovered more than 700 worms from the port area and the hull of a large barge moored near the entrance of the harbour. On-going surveillance during January and February 2010 detected adult and young *Sabella* individuals at increasing distances from the initial location of detection (Read *et al.* 2011). Based on this increasing rate of spread and the unlikelihood of achieving complete eradication, the decision was made in June 2010 to discontinue these programmes at both Lyttelton and Waitemata harbours

(MAFBNZ 2010). However it was decided to continue targeted surveillance for *Sabella* incursions in these and additional locations around New Zealand.

The next location where *Sabella* was detected in New Zealand was in Whangarei Harbour in February 2012. Worms were found on the hulls of two fishing vessels berthed at Port Nikau and subsequently on another commercial vessel in Marsden Cove marina. All three vessels had come from the Waitemata Harbour, where they had been berthed for an extended period after being slipped and painted. Subsequently, *Sabella* was found on wharf piles at Port Nikau and the Portland Cement Terminal, as well as on pontoons and the sea floor at the Marsden Cove marina. Any worms found were removed, however the detection of further worms at other sites in early 2014 means *Sabella* is now believed to be established in Whangarei Harbour.

The next *Sabella* incursion was in early April 2013, when a large population was discovered on two cargo barges moored in Coromandel Harbour (Waikato). The density of the worms on the barges was estimated to be ~1,000 individuals/$m^{-2}$ (pers. comm. A. Pande, Ministry for Primary Industries). The barges were cleaned of the heaviest fouling (a joint response between Waikato Regional Council and MPI) and then towed back to Auckland. Subsequent monitoring detected *Sabella* on another vessel, near the initial incursion site, but this was slipped and cleaned. A subsequent delimitation survey found 21 worms in the harbour (on a vessel and natural substrate) which were removed (pers. comm. A. Pande, Ministry for Primary Industries). A follow-up survey in early 2014 did not detect any more worms.

Isolated incursions were also detected in Nelson and Tauranga harbours during 2013. A cargo vessel in Nelson for cleaning and refurbishment was found to have a heavy infestation of *Sabella* on the vessel hull. This vessel had arrived from Auckland in late March, and was subsequently moored in the port area for three weeks (TOS Marine Biosecurity Partnership 2013). The worms present were determined to be sexually immature and there appeared to be a single age class of worms on the vessel. Nelson City Council and MPI initiated a response to the incursion, including a survey of the area where the vessel was moored. No further *Sabella* were found at this time. A single *Sabella* worm was detected in the Nelson marina area during routine surveillance of the port in November 2013. This is believed to be a separate incursion event. Two subsequent delimitation surveys have detected low numbers of *Sabella* within Nelson marina. The size of the worms found, the fact that there is no evidence they have spawned, and the confined location of the population suggests this is a recent incursion. MPI and Nelson City Council are currently working to eliminate the population.

In Tauranga Harbour, a single sexually immature worm was initially located near the Pilot Bay boat ramp in September 2013. This individual is believed to have been dislodged from the hull of a visiting vessel. Following an extensive survey of the area, a second worm was subsequently discovered on the hull of a moored boat. This worm was determined to also be immature. The Bay of Plenty Regional Council made contact with the owner of the boat, who was concerned and agreed to have the vessel hauled out and cleaned. Due to the low number of worms found and their sexual immaturity, *Sabella* is also not believed to have established in Tauranga Harbour.

## 3.2. Management techniques available

The proliferation of invasive species and the associated impacts on environmental and economic values has led to an increased demand for tools to mitigate the effects of pest species. Control options generally involve treatments for the reduction or removal of biomass and have had varying levels of success. Management options for minimising the likelihood of human-mediated spread as well as controlling established populations are summarised below.

### *3.2.1. Measures to minimise human-mediated spread*

Domestic pathway management is an important consideration, in particular identifying human-mediated vectors of spread that can potentially transport *Sabella* much further than possible through natural dispersal alone. Management of high-risk vectors, such as recreational and commercial vessel movements, may involve:

- the application of anti-fouling paints, in the case of vessel hulls
- increased levels of surveillance, regulation and vessel maintenance to prevent fouling accumulation in ‘niche areas’ (*e.g.* sea chests) that are often not anti-fouled (Coutts & Dodgshun 2007).

Anti-fouling treatments need to be regular and effective (*i.e.* utilising a toxic paint coating) to minimise further spread of this species via hull fouling. With reference to the Whangarei *Sabella* incursion, worms were generally found on areas of the vessel hulls where anti-fouling paint had not been applied or where it was inadequately applied (*i.e.* rubbing strips and the bottom of keels). This highlights the importance of effective anti-fouling measures. A number of marinas in the Northland region are declining marina berth applications for any vessel that hasn’t had anti-fouling paint applied within the past 12 months, to prevent the spread of *Sabella*. Vessels are required to provide information about their recent location, the age of their anti-fouling paint or the date the boat was last removed from the water and cleaned (YNZ 2013).

Activities associated with the aquaculture industry can lead to the inadvertent transport of fouling species across regional scales. Although *Sabella* is not yet established on a marine farm in New Zealand, recent incursions within key aquaculture regions (*i.e.* the Coromandel and Marlborough Sounds) as well as the ability to colonise bivalve shells directly means this is a possibility. If *Sabella* became established on marine farms in these areas, management of associated activities would be needed. This may include regulations around vessel movements and aquaculture transfers, as well as sterilisation of contaminated aquaculture equipment or seed-stock (*e.g.* Forrest *et al.* 2007). As bivalves are regularly transported among sites for grow-out, routine industry practices regarding the translocation of both stock (*e.g.* mussel declumping and washing) and equipment are currently in place to reduce the risk of spread at regional scales (Wasson *et al.* 2001; Forrest *et al.* 2007). However, as is the case with most fouling control methods, such treatments may not be 100% effective (*e.g.* Forrest & Blakemore 2006).

### *3.2.2. Measures to control established populations*

Localised *Sabella* incursions may be suppressed by the physical removal of first colonisers, particularly if this is before they have grown to maturity and are able to reproduce (McEnnulty *et al.* 2001). Identification of newly-settled *Sabella* recruits to species level is generally not possible prior to at least four weeks post settlement (Floerl *et al.* 2010). In order to avoid missing newly-settled individuals it will be necessary to repeat surveys or completely remove all species. A combined hand picking and vacuuming treatment was trialed during the recent incursion response for *Sabella* on the hulls of barges within Coromandel Harbour. Divers manually removed worms from the barge hull and deposited them directly into a vacuum hose connected to specialised filtering equipment. Although initially promising, this technique was reported to be very slow because the filtering equipment proved to be unreliable and work was frequently interrupted to resolve problems related to shell debris clogging the pump and issues with filter bags (Hodges & Simmons 2013). With further refinement this method may still be useful for future incursion responses.

There is also scope to further develop in-water plastic encapsulation (‘wrapping’) of structures that are heavily fouled. This technique was first applied in the management of another marine pest, the sea squirt *Didemnum vexillum*. It has since become a widely-used treatment method for vessels and marine structures in New Zealand. Combined treatments with relatively eco-friendly chemicals such as bleach and acetic acid can also be effective; however, it is worth noting that the use of chemicals generally requires approval from the relevant regional council and the Environment Protection Authority. Wrapping techniques and encapsulation of populations have been applied successfully for *Sabella* treatments in New Zealand. The Northland Regional Council recently conducted trials of a pontoon specially developed to enclose a vessel of ~16 m length, with the enclosed sea water subsequently treated with chlorine. Initial results indicate that the treatment caused rapid die-off of the *Sabella* present. Similarly, a large recreational vessel with small *Sabella* present on the hull was recently wrapped in Nelson Harbour, after which 200 L of acetic acid was added to the enclosed sea water. The wrap was left on for nine days, and with the combination of acid and asphyxiation through reduced dissolved oxygen, was sufficient to kill the worms present. In a similar manner to plastic encapsulation, smothering techniques using dredge spoil or geotextile fabrics are also an option for control of soft sediment populations (*e.g.* Coutts & Forrest 2005; 2007).

Other relatively simple treatments may be suitable under certain circumstances. The application of physical stressors such as air drying, ultraviolet light, steam, hot water, freshwater immersion, electricity and pressure washing has been used successfully with other high-profile marine pest species (*e.g.* Carver *et al.* 2003; Forrest & Blakemore 2006; LeBlanc *et al.* 2007; Denny 2008; Paetzold & Davidson 2010; Arens *et al.* 2011). Treatment of infected structures may be particularly important in concentrated aquaculture regions, such as the Marlborough Sounds, where species' spread can be facilitated by the large number of artificial structures in close proximity.

## 3.3. Invasion potential in the Top of the South region

The recent discovery of *Sabella* on a boat moored in Waikawa Bay has serious implications for the Top of the South region. Eighteen worms, including several relatively large individuals (~400 mm), were found on the boat following removal and cleaning. This suggests that the population may have been present in this location for some time. The vessel is believed to have been moored in Waikawa Bay for approximately two years prior to the worms' detection, however this has not been confirmed. MDC and MPI jointly responded to the incursion, with an extensive delimitation survey conducted just prior to publication of this report. This survey did not detect any *Sabella* either in the immediate vicinity of the vessel, in areas with boats and moorings in Waikawa Bay or in the Waikawa marina. Accordingly, besides the removal of the worms from the boat hull, no population control has been needed.

It is not currently known if *Sabella* has spread further than Waikawa Bay, however *Sabella*'s larval duration of ~14 days (and over 20 days if adverse conditions are encountered) means natural dispersal of larvae over considerable distances is possible. As discussed above (Section 2.6.1), a number of factors will impact the successful dispersal of larvae as well as the subsequent establishment of populations. Observations from overseas populations suggest natural spread of < 20 km per year (Parry *et al.* 1996). Although no populations were found during the delimitation survey, the possibility of further human-mediated spread cannot be completely discounted. Waikawa Bay is a significant recreational vessel hub, with many boats travelling from here to more remote parts of the Marlborough Sounds and to other regions of New Zealand. As 6-monthly surveillance funded by MPI is limited to the main ports and marinas, populations outside of Waikawa Bay may have already become established, but without a regional surveillance programme, are yet to be detected.

*Sabella* is a habitat generalist and based on observations from previous incursions in New Zealand it could become established in a range of locations within the Top of the South region. *Sabella* is unlikely to be limited by any environmental constraints within the region, with temperature and salinity profiles both well within this species' tolerance.

## 3.4. Understanding the costs and benefits of management

The Ministry for Primary Industries regards *Sabella* as an unwanted organism that is 'post-border' (MAFBNZ 2011). As such, regional councils are responsible for managing any post-border range extensions of *Sabella*, with MPI supporting responses but not taking a leading role. Even with complete knowledge of a species' biological characteristics, the outcome of introductions is extremely challenging to predict with any confidence, making it difficult to weigh costs and benefits of management. However, a robust evaluation is crucial, especially with limited funding available and competing priorities for invasive species management (Molnar *et al.* 2008).

The efficacy of any control or mitigation strategies initiated will depend on the on-going long-term commitment of resources. Eradication or control has been shown to be easier, cheaper and more effective very soon after detection, particularly if the target species is confined to a restricted area (*e.g.* Hopkins *et al.* 2011). This approach has been successfully applied in the incursion responses for Coromandel, Tauranga and Nelson harbours and Waikawa Bay, which were undertaken within weeks of first detection and prior to the assumed winter spawning season. Surveillance and removal efforts will need to be frequently repeated in the initial stages of any management programme. Detection is often made difficult by extensive fouling on the pontoons and piles, which makes it likely that small individuals will be missed. Specialised contractor services are required for activities such as hand removal by divers so diver-based management efforts are likely to require significant resources. A recent *Sabella* incursion response in the Coromandel cost ~$120,000 (Hodges & Simmons 2013). This is likely to be on the high-end of costs however, at Coromandel there were no haul out facilities available so the more expensive option of in-water cleaning was required (pers. comm. D. Hodges, Waikato Regional Council). Other methods such as encapsulation, wrapping and chemical treatment may prove more cost-effective in future, especially where vessels and structures are heavily infested.

# 4. CONCLUSION

Successful invasive species management in the marine environment is generally reliant on the species having:

- a limited natural dispersal potential
- low fecundity
- specific habitat requirements
- conspicuous morphology and easily visible individuals.

It can be can be argued that *Sabella* fails to meet any of the general criteria above, leading to difficulties in defining outer boundaries for surveillance and vector control. Although relatively conspicuous when fully grown, younger individuals are often difficult to detect, particularly when part of established fouling communities. Efficacy of detection before worms reach sexual maturity is thus a key component of this criterion. Simultaneously, even though containment of the Waikawa Bay population appears to have been successful, the absence of effective regional and national controls on movements of potentially-infected vectors means the risk of further incursions into the Marlborough region is probably high. This is likely to increase over time as nationwide spread from existing populations increases. MPI is currently addressing domestic spread of this and other marine pests around the country through development of a national marine pathways plan.

A critical information gap, which makes management decisions difficult, is our understanding of potential impacts to both environmental and economic values. Reports of negative impacts are all Australian-based and are predominantly environmental effects as opposed to negative impacts to marine industries. The introduction of *Sabella* to Port Phillip Bay (Victoria, Australia) has considerably altered the community composition of the bay. It is therefore possible that *Sabella* could have similar adverse effects if it spreads further within the Marlborough region and conceivable that it could become a nuisance fouler on subtidal aquaculture systems. The high-filtering capacity of this species could also make it a competitor to cultured filter-feeders such as oysters and mussels. Consideration of a worst-case scenario, *i.e.* significant adverse effects on the regions aquaculture and environmental values, would be prudent when making decisions on whether, and to what extent, to respond to any future incursions in the Marlborough district.

In addition, reliable information about the reproductive strategies of the *Sabella* populations in New Zealand is lacking. An increased understanding of the duration of the reproductive season and critical temperature thresholds for spawning will enable more effective risk management for this species. New incursions are currently deemed to be sexually immature if worms are < 120 mm long and eggs have a diameter of 200–250 µm. Reliable information of local population dynamics is crucial because decisions regarding the feasibility of containment efforts are often based on whether the species are believed to have spawned or not. Recent research on a South Australian population suggested worms become sexually mature when they are much smaller (60–90 mm long) and that the reproductive season begins considerably earlier (4–5 months) than a nearby Port Phillip Bay population (Lee 2013). This highlights the limitations inherent in inferring invasiveness from other situations (*e.g.* places, times, and related species), as well as the need for site-specific research on key biological traits. At present, research into *Sabella*'s biology and population dynamics in New Zealand is limited. Current project include research on settlement and physiological tolerances of *Sabella* (MSc project, Auckland University), as well as on-going research by NIWA into the Lyttelton population. This may increase with further spread of this species into additional regions and the possibility of negative impacts to key environmental or economic values.

Consideration should also be given to preventing or slowing the spread of *Sabella* to high-value areas (*e.g.* key aquaculture regions or marine protected areas). A key component of this will be the development of pathway management plans, incorporating strategies such as increased regulations around regular hull anti-fouling in relation to the movement of vessels between regions. The development of pathway management plans between regions is an important component of invasive species management in general, but will require a collaborative approach between neighbouring regions and central government. Although challenging, this may provide the best value for money in the event of multiple incursions or the presence of more than one target species within the region (*e.g. Styela clava*'s recent detection in Picton). It should be noted that although pathway management plans will likely reduce the risks of incursions, they will not be removed. Response efforts will still be required for incursions that have not been prevented through pathways management, particularly for marine pests known to cause impacts to regional or national values.

# 5. ACKNOWLEDGEMENTS

I am grateful to Barrie Forrest and Grant Hopkins (Cawthron Institute), Anjali Pande, Tim Riding and Kathy Walls (Ministry for Primary Industries), Serena Wilkens (NIWA), Dave Hodges (Waikato Regional Council) and Richard Taylor (University of Auckland) for helpful discussions and contributions to this report.

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