Control of *Undaria pinnatifida* in Breaksea Sound, Fiordland

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Undaria pinnatifida on a wave exposed coastline in Otago

Executive Summary

First discovered in New Zealand in 1987, and now widespread, the invasive kelp *Undaria pinnatifida* is one of only two seaweeds listed in the 100 most invasive species in the world. Native to north east Asia, *Undaria* is a laminarian kelp that can rapidly colonise a number of natural and artificial substrates creating a thick monospecific canopy from intertidal to subtidal zones. With a microscopic life stage, which can remain dormant for several years, it is particularly difficult to manage. The potential for *Undaria* to detrimentally alter ecosystem structure and function, and displace native biota has prompted incursion responses in several locations, although to date, these responses have been largely unsuccessful.

Undaria was first discovered in Sunday Cove Breaksea Sound, Fiordland, in April of 2010 prompting a multi-year, multi-agency eradication response. The response which consisted primarily of the manual removal of *Undaria* sporophytes during monthly dive surveys was successful in reducing the densities of *Undaria* around Sunday Cove. In April 2017 however, divers found reproductively mature individuals outside of the Sunday Cove search area and dense stands are now present in and around Beach Harbour, the Harbour Islands, John Islands and First and Second Coves.

Although previous eradication attempts for *Undaria* have relied primarily on hand removal, there are a number of methods that have been used in responses to other invasive marine species that may provide some guidance for future *Undaria* responses. Aside from species specific tools, key components to successful control/eradication efforts appear to include committed funding, resources and effort, an adaptive management approach, early detection/rapid response, and vector management.

It is clear that eradication at this time is unlikely given the extent of the incursion and constraints on resources and tools available. Instead, we recommend focusing attention on preventing the spread of *Undaria* and reducing its biomass in Breaksea Sound using an adaptive management framework applied over the next five years. Key steps include:

(1) **Biomass removal**: manually removing as much *Undaria* as possible, as soon as possible, from high density areas (i.e. Harbour Islands, John Islands, Beach Harbour, First & Second Coves) using a dedicated control dive team (Aug-Oct 2019);

(2) **Mapping the extent/distribution of *Undaria***: determining where *Undaria* was, and remains post biomass removal, using a second team of divers, so the feasibility of continued control efforts can be assessed (Nov-Dec 2019);

(3) Assessing the feasibility of continued control efforts: using information from (1) and (2) to decide how best to proceed with control (Early 2020);

(4) Modelling *Undaria* dispersal using a 3D hydrodynamic model: contingent on (3), modelling spore and fragment dispersal to inform continued control efforts (Summer 2020);

(5) Continued control and monitoring: contingent on (3), continuing with targeted biomass removals (Aug-Oct) and monitoring (Nov-Dec) for an additional four years. Following this, an evidence based decision, on the feasibility of continued control should be made in early 2025.

For control efforts to be efficient, focused and well managed, it is imperative that response action is supported and assessed using independent data. In this manner response actions can be modified to suit changing conditions and what is being observed in the field. By focusing on halting the spread of *Undaria* in Breaksea Sound and reducing its biomass through targeted control supported by research in the short term, the longer term goal of eradication could well be possible, especially if new methods/tools become available.

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Introduction

The Asian kelp, *Undaria pinnatifida* (Harvey) Suringar 1873 (common name Wakame; hereafter *Undaria*) is a laminarian kelp native to Japan, China, Korea, and Russia (Hunt et al. 2009). Since 1981 it has extended its range to 14 countries including France (Floc'h et al. 1991), Ireland (Kraan 2017), USA (Zabin et al. 2009), Australia (Sanderson 1990), and New Zealand (Hay & Luckens 1987). *Undaria* is one of only two seaweeds (the other being the "killer algae" *Caulerpa taxifolia*) listed in the IUCN Invasive Species Specialist Group's list of the 100 most invasive species in the world (Lowe et al. 2000, www.iucngisd.org). Described as opportunistic, *Undaria* can rapidly colonise a wide range of substrates, creating a thick monospecific canopy from the intertidal zone down to 20-25 metres in depth (Russell et al. 2008, James 2016, Epstein & Smale 2017). The potential for *Undaria* to detrimentally alter ecosystem structure and function, and displace native biota has prompted incursion responses in several locations invaded by *Undaria*.

Need for this report

In April 2010 during an annual compliance and surveillance exercise, a single specimen of *Undaria* was found attached to a mooring rope in Sunday Cove, Breaksea Sound, Fiordland. Though pervasive in New Zealand at the time, this was the first detection of *Undaria* in the Fiordland (Te Moana o Atawhenua) Marine Area (FMA). A joint agency response was initiated including Environment Southland (ES), Biosecurity New Zealand (BNZ/MPI, previously MAF), and the Department of Conservation (DOC), with the Fiordland Marine Guardians (FMG) as key supportive stakeholders. The approach initially recommended, was monthly surveillance and removal until *Undaria* was not detected for three years. As *Undaria* was still being found nine months into the response, the agencies agreed to continue monthly surveys until *Undaria* was not detected for 18 months at which point a three year monitoring period would be adopted.

The response began in July 2010 with monthly dive surveys aiming to eliminate *Undaria* from Sunday Cove primarily through manual removal of *Undaria* sporophytes. Additional eradication measures included the application of chlorine under tarpaulins to treat high risk habitat and the translocation of 35 000 kina (*Evechinus chloroticus*) as a bio-control in 2011 (Atalah et al. 2013). Permanent transects were established around Sunday Cove, where possible, to enable repeat surveys, and removed sporophytes were treated with chlorine and discarded on land. As of May 2017, 1933 *Undaria* individuals of which 11 were reproductively mature had been removed from the Sunday Cove search area. Densities of sporophytes decreased markedly in Sunday Cove from the time removals began, although six individuals were discovered between Nov 2015 – Jan 2016 downstream of targeted removals (Fig 1).

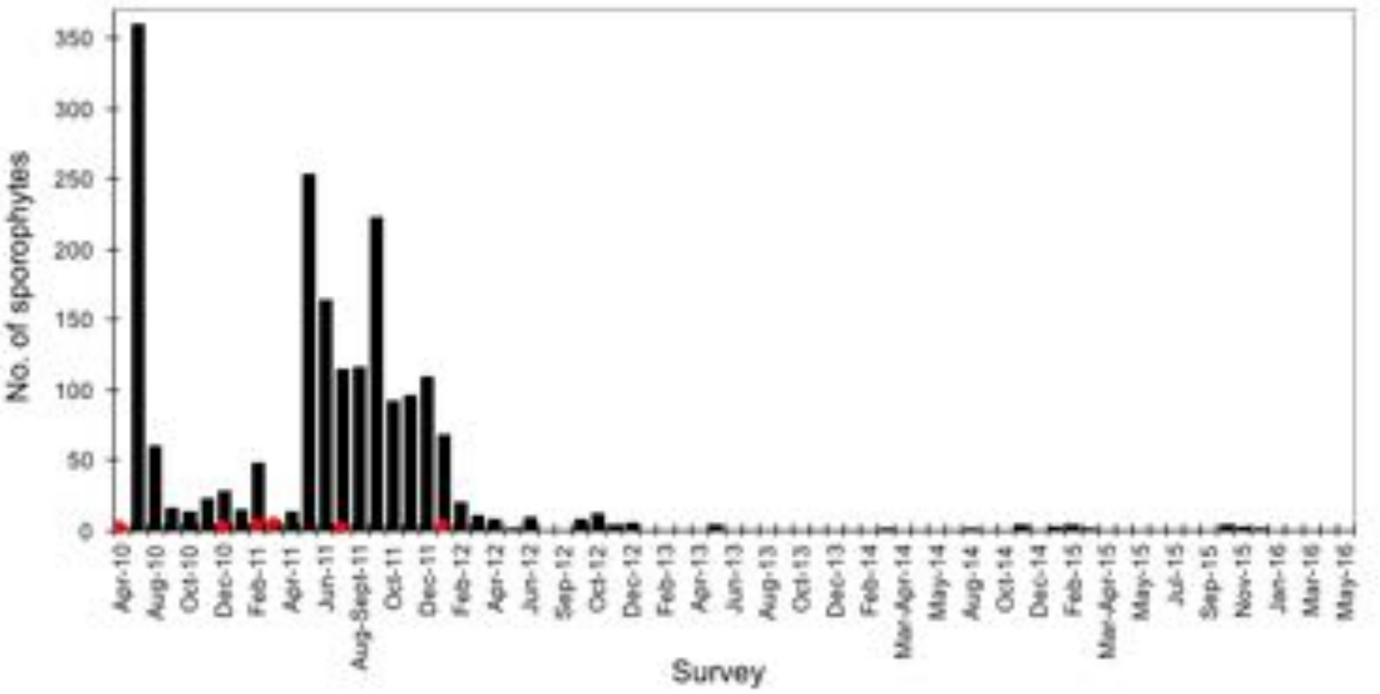

Fig 1. Number of *Undaria* sporophytes removed from Sunday Cove April 2010- May 2016. Red dots indicate surveys where mature individuals were found.

On 13 April 2017, divers on a joint agency scheduled biosecurity surveillance trip found 16 *Undaria* specimens, outside the Sunday Cove search area (Fig 2). They were found on a mooring line four metres deep in Beach Harbour, approximately two kilometres from Sunday Cove in a direction opposite to predominant current or tidal flows (Fig 2). Six of these individuals had reproductive sporophylls and were badly eroded suggesting that they were likely to have already released spores. A month later, in May 2017, divers surveying Sunday Cove found more mature and eroded sporophytes throughout Beach Harbour and the John Islands area. A delimiting survey was subsequently conducted from the 5-9 of June 2017 to assess the extent of the incursion. *Undaria* was found on the southern side of Breaksea Sound from the edge of Sunday Cove to the top of the John Islands with dense stands of mature individuals in and around Beach Harbour. *Undaria* was most abundant on the outer edges of the Harbour Islands, John Islands and the inner Beach Harbour area at depths between 0.5 and 6 metres although deeper dives were not carried out during the delimiting surveys. *Undaria* was not detected on the moorings in Beach harbour or the vessels moored in the area. It was found in all life stages: old mature stipes and large/small immature sporophytes. In December 2017, another team of divers determined that *Undaria* had re-invaded the previously controlled area around Sunday Cove and had spread further than first thought. The same month, a Controlled Area Notice was issued for Breaksea Sound by ES to restrict mooring, anchoring and equipment use within the incursion area, with the hope that it would reduce the risk of *Undaria* being spread to other parts of Fiordland. Since discovery of the new incursion, monthly surveillance trips were suspended for six months (May – Dec 2017) while management options were considered. Trips since December 2017 (e.g. Jan, March 2019) have focused on removing *Undaria* from the top of the Acheron Passage through to Sunday Cove. Since the delimiting survey in June 2017 *Undaria* has subsequently been discovered on the northern side of Breaksea Sound near Half, First, and Second Coves (Fig 2).

Environment Southland sought advice on the feasibility of controlling mature *Undaria* populations in Breaksea Sound, Fiordland, with the overall goal of minimising the ecological impacts and spread of *Undaria* in Fiordland. For this, a literature review which included 300+ articles/reports on the biology and management of invasive marine species in New Zealand and internationally was conducted.

The specific aims of this report are to:

- Compile information on responses to marine invasive species in New Zealand and internationally
- Compile information available on past and present research programmes on *Undaria* in New Zealand and internationally
- Provide advice on a possible approach to control *Undaria* in Breaksea Sound

Fig 2. Current extent of *Undaria pinnatifida* incursion in Breaksea Sound (Source: Environment Southland)

Part 1 Responding to Marine Invasions

Where a decision is made to actively respond to a new invasion, managers have three options:

(i) Eradication – the complete and permanent removal of every individual so that recolonisation is dependent on a separate incursion event (Simberloff 2013).

(ii) Control - attempts to mitigate or reduce the presence of the invasive species short of complete removal (Anderson 2007)

(iii) Containment - actions aimed at creating barriers to minimise the risk of the invasive species dispersing beyond the invaded area.

Regardless of which option is selected responding to invasive species in the marine environment is typically more difficult and less feasible than it is in terrestrial systems because of a lack of appropriate tools or methods, and difficulties inherent with working in the ocean (Hewitt et al. 2005). Invasive seaweeds in particular are difficult to eradicate because they typically grow fast, reproduce early, are able to reproduce from vegetative fragments, and have microscopic gametophytes that can persist for long periods of time as seed banks (Smith 2016). Ultimately, the choice of which invasion response to adopt must reflect the overall goal of managers as well as the feasibility of achieving it.

Eradication and control programmes are unlikely to succeed if they do not have adequate funding, equipment or expertise (Panetta 2014) and there are many examples in the literature of eradication attempts that have failed because of a lack funding or committed effort (e.g. *Caulerpa taxifolia* in the Mediterranean, (Meinesz et al. 2001); North Pacific seastars in Victoria, (Thresher 1999); *Undaria* in Southern New Zealand (Stuart 2004). Success is also more likely when the invading population is small and geographically restricted, when vectors can be controlled, when the response action is taken early, and effective methods/tools exist (Williams & Grosholz 2008).

1.1 Tools for Eradication or Control

Methods for responding to invasive marine species can be divided into three main classes (1) physical/mechanical (2) chemical, and (3) biological. Habitat management (4) is also a potential response method although examples of its use are rare. Given the life history of many invasive species, several methods used in combination and adapted over time is likely to be required for success.

1.1.1 Physical/Mechanical

(a) Hand removal

By far, the most common response method is removal by hand – used for a number of species with varying levels of success (Table 1, Fig 3). For biphasic species that have a microscopic life phase physical removal of visible mature life stages may not prevent dormant spores or gametophytes from reseeding an area (e.g. the seaweed *Kappaphycus sp.* in Hawaii, Conklin & Smith 2005). In these instances, for manual removal to be effective, there may need to be a long term commitment to removal (Hewitt et al. 2005). For species that reproduce via spores or fragmentation, there must also be clear protocols for collection and disposal so that spores and fragments are not accidentally released during removals. The costs of hand removal are context specific, dependent on a number of factors including: site accessibility, the extent of the infestation, and the life history of the invading species.

(b) Encapsulation

For a number of species, shrouding or encapsulating/wrapping structures such as wharf pilings, jetties and the seabed to smother invasive species has been attempted. Encapsulation is meant to trigger anoxia as organisms within the trapped layer respire. Anoxia combined with shading, starvation, and sulphide toxicity then kills organisms trapped in the barrier (Atalah et al. 2016). The method is non-selective however and may require long term deployment. Encapsulation is relatively inexpensive and if combined with a chemical treatment has proven to be fairly robust (Anderson 2005). Several materials have been used including polythene sheeting and dredge spoil for the invasive ascidian *Didemnum vexillum* in the Marlborough Sounds (Coutts & Forrest 2007) and biodegradable jute mats for the macrophyte *Lagarosiphon major* in freshwater lakes in Ireland (Caffrey et al. 2010) and *Caulerpa taxifolia* in New South Wales (Glasby et al. 2005). In the latter example, jute matting was found to be difficult to deploy because it was positively buoyant and needed to be weighted down. Furthermore, while most of the vegetation under the mats was eventually killed, *Caulerpa* was found growing between mat joints and within tears (Glasby et al. 2005).

(c) Underwater vacuums

Diver operated suction devices have been trialled for several invasive marine species including *Caulerpa taxifolia* (Australia (Creese et al. 2004); Mediterranean (Meinsz et al. 2001)), and *Sargassum muticum* in the United Kingdom (Critchley et al. 1986). In the case of *Caulerpa* in Australia, the suction device was effective for small patches at shallow sites with sandy bottoms and good visibility. Unfortunately, the environment was rarely characterised as such. The 'super sucker' a modified gold dredge fitted with a 4- horsepower diesel engine that runs on biodiesel, has been used successfully to permanently clear large expanses of invasive seaweed, mainly *Graciliaria salicornia* off reefs in Hawaii. The super sucker consists of a 10cm diameter hose that sucks up algae with 200-300 gallons of water per minute. Divers are required to feed algae into the hose after peeling it from the reef. The captured material is fed onto a screening bed on a barge where sorters can sift through it and the vacuum can remove up to 360kg of algae an hour (Schrope 2008, Fig 3).

In New Zealand, in 2002, NZ Diving and Salvage trialled an underwater vacuum for the removal of the invasive sea squirt, *Didemnum vexillum* from a barge moored in Shakespeare Bay, Picton and the surrounding seabed. The vacuum, which was to be operated underwater by a diver, consisted of a cutter head powered by a hydraulic motor to shred and gather the sea squirt coupled with a bronze propeller. Ultimately, the cutter head and hose umbilical assembly proved too awkward for use underwater and there were issues with hose blockages and pump failures. Divers switched to gathering *D. vexillum* by hand and feeding the fragments into the cutter head. The trial resulted in 80% of the gross mass of *D. vexillum* being removed (NZ Diving & Salvage Ltd 2002).

(d) Floating barriers

Flexible floating barriers i.e. booms, like those used to contain oil spills, have been used to contain seaweeds such as *Sargassum* in Quintana Roo, Mexico (Mexico News Daily 2018). Some barriers consist of surface barriers alone, while others include bottom skirts made of mesh that restrict movement of plant material and debris. There are a number of models currently available including ones specifically designed for long term deployment in exposed areas subject to current, wind and tides (e.g. mavideniz.com, elastec.com).

(e) Heat

In general, heat treatments in open ocean environments are logistically difficult and expensive - particularly if the area requiring treatment is large. Heat treatments, depending on the method of delivery, can also be non-specific – killing more than the target organism. For these reasons, heat has rarely been employed as a method for responding to invasive marine organisms in a field setting (the one notable exception being the response to *Undaria* in the Chatham Islands, see section 2.3.1). Heat has however been used in more constrained settings e.g. as a means of sterilising marine farming equipment or stock (Forrest & Blakemore 2006), treating water sports equipment (Anderson et al. 2015, Shannon et al. 2018), for treating water from aquaria or containment facilities prior to its release into the marine environment (Williams & Schroeder 2004), and for treating cooling systems of power stations subject to invasion by mussels and oysters (Rajagopal et al. 2005)

1.1.2 Chemical Controls

Although there does not appear to be any commercially available marine herbicides or algicides developed specifically for invasive marine species as they have been for invasive freshwater species, generic biocides including acetic acid, chlorine bleach, sodium bisulphate, copper, and bromine have been used in experiments and trialled in the field for species including *Caulerpa taxifolia*, the tunicate *Ciona intestinalis*, the sea squirt *Didemnum vexillum*, and the crown of thorns starfish *Acanthaster planci* (Table 1, Fig 3). Household items that have been trialled with some success include freshwater, and salt (sodium chloride) to induce osmotic shock and death (Table 1).

The use of chemical controls however is limited by a number of factors including dilution in the marine environment, difficulties associated with application of the chemical such as diver exposure, and the contact time required for the effect. Furthermore, as many of the chemicals proposed or used in the field are general biocides, they pose a risk to the wider environment including non-target species and human health. Biocides, not already approved for use in New Zealand need to be approved by the Environmental Protection Agency in accordance with the Hazardous Substances and New Organisms Act 1996, and any use of a biocide in the coastal marine environment needs to be with resource consent or permitted under the necessary Coastal Marine Plan or Regional/District plan under the Resource Management Act 1991.

1.1.3 Biological Controls

(a) Bio-controls

Biological controls, that use host-specific natural enemies are relatively common in terrestrial systems to control invasive species but are less so in the marine environment. There are three types of biocontrol (1) classical biocontrol, where a non-native predator from an introduced pests' native range is introduced to control the introduced pest (2) neoclassical biocontrol, where a non-native predator is introduced to control a native pest (3) augmentative biocontrol, where native predators are enhanced to improve their control of native or introduced pests. Compared to chemical controls, biocontrols are often viewed as being ecologically safe despite there having been several well documented biocontrol disasters in terrestrial systems (e.g. Cane toads introduced to Australia to control the native grey-backed cane beetle). Typically, biocontrols are not intended to eradicate the pest species completely but keep them supressed at acceptable levels.

The biggest challenge with the use of biocontrols is host specificity, that is, ensuring that the biocontrol species will inflict maximum damage on the target species without negatively affecting non-target species (Secord 2003). This challenge is exacerbated by difficulties associated with assessing ecological effects of biocontrols, particularly indirect non-target effects. Where classical or neoclassical biocontrol is used and the predator released is non-native, it can be difficult or impossible to reverse the effects of release should it be found to be detrimental. The introduced population can respond to the new environment, adapt, and evolve. Thus any biocontrol programme that introduces a new exotic species to the environment requires balancing the uncertainties of that introduction against the long term damage done by the invasive species.

There appear to be no examples of classical or neoclassical biocontrols used in the marine environment, though several have been proposed, including the introduction of the ctenophore *Beroe ovata* to control the invasive ctenophore *Mnemiopsis leidyi* in the Caspian Sea (RFERL 2004), and sacoglossan sea slugs e.g. *Elysia viridis,* to control the green macroalga *Codium fragile* in Scotland (Trowbridge 2002). Many of the proposed biocontrols are invertebrates namely, molluscs and sea urchins, although various herbivorous fish have also been considered (e.g. Davis et al. 2005).

Though there are no examples of classical or neoclassical biocontrol in the marine environment, there are several examples of augmentative biocontrols - likely because this comes with fewer risks – used to control invasive macroalgae. The short spined sea urchin *Tripneustes gratilla* is a generalist herbivore native to Hawaii. It feeds on at least five species of invasive macroalgae common to the islands (*Kappaphycus* clade A & B, *Eucheuma* clade E, *Acanthophora spicifera*, and *Gracilaria salicornia*), that can form dense mats on reefs, smothering corals. Local managers and researchers concerned about the spread of the macroalgaes in Kāne'ohe Bay, tested a number of control methods and found that urchin biocontrol following manual removal led to an 85% decline in invasive macroalgal cover between 2011-2013. Urchins were hatchery raised, with a new cohort produced every 30-60 days. Stocking density was designed to be ~ 4 ind m^{-2}, although after outplanting urchin densities were estimated to be much lower (0.9 and 0.74) (Neilson et al. 2018, Fig 3). The project cost $817 000 USD and approximately 22000 hours of work, spread between field and hatchery operations to treat 24,600km^2 ($33 m^{-2}) of affected reef.

(b) Genetic controls

Since the 1960s interest in genetic controls has developed from Sterile Insect Techniques which utilise mutations in the Y chromosomes of insect pest species (Hamilton 1967) to gene drive technology in which the genetic sequences of target species are manipulated with desirable traits/synthetic DNA (transgene) sequences to suppress wild populations (Alphey 2014, Webber et al. 2015, Harvey-Samuel et al. 2017, Leitschuh et al. 2018). CRISPR technology has already been developed to engineer mosquitos that can transmit a sterilising mutation, to suppress mosquito populations (Kyrou et al. 2018) and the technology is now being investigated as an alternative to toxicants to control rodents (Leitschuh et al. 2018). While there has been little investigation of these tools for the management of invasive marine species and seaweeds in particular to date, rapid advances in these techniques, and technology, do make this a possibility for the future.

1.1.4 Habitat Management

Theoretically, sites with a thriving native vegetative community will offer only limited colonisation opportunities for invasive species. Seeding with fast growing natives may slow the spread of exotic species. The practicality of this approach has not been demonstrated.

Fig 3. Tools for eradication/control of invasive marine species: (A) the super sucker suction device for invasive seaweeds, Hawai'i (Credit: Hawai'i DLNR), (B) manual removal of lionfish, Florida (Credit: scubadiving.com), (C) urchin bio-controls for invasive seaweeds, Hawai'i (Credit: Hawai'i DLNR) (D) injection of Crown of Thorns starfish with toxins, Great Barrier Reef Marine Park Authority (Credit: livingoceansfoundation.org).

Table 1. Examples of tools used in eradication programmes for invasive marine species (Note table does not include treatments tested in laboratory settings)

Method	**Species Name**	**Common Name**	**Location**	**Success?**	**Reference**
Physical					
Hand removal	*Magallana gigas/Crassostrea gigas*	Pacific Oyster	Oosterschelde, Netherlands	No	Nehring 2011
	Crepidula fornicate	American limpet	England	No	Hancock 1969
	Littorina littorea	Common periwinkle	British Columbia, Canada	Yes	Harley et al 2013
	Styela clava	Asian tunicate	Washington, USA	No	Clarke & Therriault 2007 GISD 2015
	Trididmnum solidum	Tunicate	Bonaire, Netherlands	No	Ferns & Curnow 1998
	Codium fragile	Sponge seaweed	Victoria, Australia	No	Smith et al. 2004
	Gracilaria salicornia	Canot-canot	Hawaii, USA	No	Smith 2016
	Sargassum muticum	Wire weed	California, USA	No	Critchley et al. 1986
			Isle of Wight, UK	No	Miller et al. 2004
	Ascophyllum nodosum	Knotted wrack	San Francisco, USA	Yes	Meinesz et al 2001
	Caulerpa taxifolia	Caulerpa	Croatia	No	
Encapsulation	*Didemnum vexillum*	Carpet sea squirt	North Is, NZ	No	Coutts & Forrest 2007
	Teredo navalis	Shipworm	USA	No	Hoppe 2002
	Caulerpa taxifolia	Caulerpa	NSW, Australia	No	Glasby et al. 2005
Dredge	*Magallana gigas/Crassostrea gigas*	Pacific Oyster	Oosterschelde, the Netherlands	No	Nehring 2011
	Crepidula fornicata	American limpet	Normandy, France	No	Blanchard 2009
	Perna perna	Brown mussel	Tasman Bay, NZ	Yes	Hopkins et al. 2011
Underwater Vacuum	*Caulerpa taxifolia*	Caulerpa	Croatia, Spain	No	Meinesz et al. 2001
Trapping	*Carcinus maenas*	European Green Crab Asian Crab	California, USA	No	De Rivera et al. 2007 DFO 2011

	Charybdis japonica		Newfoundland, Canada Auckland, NZ	No	Golder Associates 2008
Water blasting	*Didemnum vexillum*	Carpet sea squirt	North Is, NZ	Yes	Coutts & Forrest 2007
Culling	*Sabella spallanzanii*	Mediterranean fanworm	Lyttelton, NZ	No	Read et al. 2011
	Pterois volitans	Lionfish	Florida, USA	No	Albins & Hixon 2013
Dynamite	*Teredo navalis*	Shipworm	Canada	Yes	Hoppe 2002
Chemical					
Acetic Acid	*Ciona intestinalis*	Tunicate	Prince Edward Island, Canada	No	Locke et al. 2009
	Styela clava	Asian tunicate	Prince Edward Island, Canada	No	Clarke & Therriault 2007, Ramsay et al. 2008
Chlorine	*Mytilopsis sallei*	Black striped mussel	Darwin, Australia	Yes	Willan et al. 2000
	Caulerpa taxifolia	Caulerpa	California, USA	Yes	Anderson LW 2005
Copper	*Mytilopsis sallei*	Black striped mussel	Darwin, Australia	Yes	Willan et al. 2000
Potassium	*Dreissena polymorpha*	Zebra mussel	Millbrook Quarry	Yes	Fernald & Watson 2013
Bleach	*Didemnum vexillum*	Carpet sea squirt	North Is, NZ	No	Coutts & Forrest 2007
Formalin injection	*Acanthaster planci*	Crown of thorns seastar	Mariana Islands	Yes	Marsh & Tsuda 1973
Rotenone	*Tilapia mariae*	Tilapia	Queensland, Australia	No	Bradford et al. 2011
Salt/Sodium Chloride	*Caulerpa taxifolia*	Caulerpa	NSW, Australia	No	Glasby et al. 2005
Biological					
Interference with spawning	*Acanthaster planci*	Crown of thorns seastar	Australia	Ongoing	Hoey et al. 2016
Predatory cichlid	*Tilapia mariae*	Tilapia	Florida, USA	No	Bradford et al. 2011, Annett et al. 1999
Urchins	*Sargassum muticum*	Wire weed	California, USA	No	Smith 2016

Case Study 1: The Hydrilla Eradication Programme – An Integrated Pest Management Response (Kratville 2013)

Hydrilla verticillata (hereafter *Hydrilla*) is an invasive submerged aquatic perennial native to Australia, Africa and the Indian Subcontinent but is common now in freshwater bodies globally (Fig 4). Initially imported into the United States for aquariums it rapidly spread throughout the south-east US after plants were released into waterways in Florida. *Hydrilla* outcompetes native species by forming dense mats on the water's surface, limiting light to other species. It grows rapidly, monopolising carbon dioxide and increasing the alkalinity of the water. *Hydrilla* produces turions and tubers, reproductive structures that can remain dormant and viable for several years, surviving ice cover, desiccation, and digestion by waterfowl. Mats formed by *Hydrilla* have a number of economic impacts including the obstruction of dams, canals, boating and hydroelectric intakes in addition to ecological impacts such as effects on water chemistry, habitat structure and trophic dynamics.

Hydrilla
Hydrilla verticillata
Photo by Vic Ramey
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Fig 4. *Hydrilla verticillata*

Hydrilla was first discovered in California in 1976 in a man-made lake in Yuba County. A year later, the California Legislature mandated that the California Department of Food and Agriculture create a detection and eradication programme. The CDFA *Hydrilla* Eradication Program is a cooperative effort, with the CDFA receiving financial support, manpower, regulatory support and technical assistance from a number of groups, agencies and public departments including the US Army Corps of Engineers, California Department of Boating and Waterways, and the US Department of Agriculture. Since 1976 *Hydrilla* has been introduced 29 times in 18 counties in California. The

CDFA has successfully eradicated *Hydrilla* from 20 of these sites, with the other sites currently receiving treatment.

The *Hydrilla* Eradication Program uses an integrated pest management approach which includes surveillance (surveys of infested waterways and high risk areas), containment (quarantine zones), eradication, and monitoring (of sites post treatment). Eradication methods include manual removal, dredging, biological controls and aquatic herbicides, namely fluridone. A standard protocol is followed for each eradication. CDFA staff intensively treat and survey infested sites for a minimum of three growing seasons from the last *Hydrilla* detection. The following three seasons after that, the site is surveyed without treatment. Thus, eradication is only considered to be successful a minimum of six years following the last *Hydrilla* detection. The time lag is intended to ensure that dormant tubers do not continue to seed plants following plant removals. The *Hydrilla* Eradication Program costs approximately $2.5 million (USD) annually and has been successful in restricting and eradicating *Hydrilla* in a number of waterways in California. The programme is one of the largest scale, successfully sustained eradication programmes globally, relying on multiple methods for eradication coupled with extensive monitoring.

Case Study 2: Caulerpa Taxifolia

The “killer algae”, *Caulerpa taxifolia* (hereafter *Caulerpa*) like *Undaria,* is listed in the Invasive Species Specialist Group’s 100 world’s worst invasive species. It is a green macroalga native to the tropical Atlantic, Indian and Pacific Oceans (Fig 5). Used extensively in aquaria, the cold-tolerant clone invaded the Mediterranean in 1984 and southern California in 2000. *Caulerpa* can colonise a wide variety of substrates including rock, mud and seagrass beds and it has a wide thermal tolerance (7-32.5°C). It has the ability to smother native algae, seagrasses and sessile invertebrate communities, by outcompeting them or releasing toxic caluerpenyne compounds. As an all-male clone, *Caulerpa* reproduces by fragmentation and its spread has been attributed to improper waste disposal from the aquarium trade.

As described in Anderson 2005, *Caulerpa* was discovered in California in June 2000, at Agua Hedionda Lagoon, a small estuary 50km north of San Diego. Divers surveying native eelgrass beds, discovered the invasive species and reported it to the California Department of Food and Agriculture who were able to confirm the identity of the species within 24-72 hours of its discovery. A week later, the decision to eradicate *Caulerpa* was made by a group comprised of state and federal agencies, and local stakeholders. This group came to be known as the Southern California Caulerpa Action Team (SCCAT). SCCAT acted as an advisory consortium and its goal was the eradication of *Caulerpa*. Two weeks after its discovery, discussions centred around the probability of successful eradication and the feasibility of various methods for containment and eradication. Pilot studies were conducted on chemical controls using registered aquatic herbicides, including household bleach, (sodium hypochlorite) (e.g. Williams & Schroeder 2004). Eventually, SCCAT determined that the best method for eradication involved using polyvinyl chloride (pvc) sheeting placed over pvc framing with bleach injected into the sheeting. Bleach was ultimately replaced with chlorine tablets, which was easier for divers to handle. Treatment began 17 days after *Caulerpa* was discovered in the lagoon, with the dive team who made the discovery being deployed for the work. When another incursion was found at Huntington Harbour, a few weeks after the Agua Hedionda discovery, the same processes were followed. Funding for the response was obtained under urgency as emergency funding for 'clean-up and abatement' through the San Diego Regional Water Quality Board and a power plant located on the lagoon. The invasion was essentially treated like an oil spill and the designation of the response as 'clean-up and abatement' removed potential legal constraints. Subsequent funding came from NOAA-Fisheries, California Department of Fish and Game and the California Coastal Conservancy which awarded $1.3m USD for eradication and monitoring in 2004-2005. *Caulerpa* was eventually eradicated in 2005, with no individuals sighted for two years. The total budget for the eradication came to $7.6m USD.

Compared to the urgent targeted response to *Caulerpa* in southern California, the lack of a response to the Mediterranean invasion has meant that *Caulerpa* has continued to spread steadily since its introduction in 1984. Although small patches have been manually removed by divers (Cottalorda et al. 1996), the species has spread along the coastlines of six countries: Spain, France, Monaco, Italy, Croatia, and Tunisia (Meinesz et al. 2001), and is unlikely to be eradicated.

Fig 5. *Caulerpa taxifolia*

Part 2 *Undaria pinnatifida*

2.1 Natural History

2.1.1 Lifecycle

Undaria pinnatifida is an annual laminarian kelp, that most closely resembles the native laminarian kelp *Ecklonia radiata* (Fig 6). It is distinguishable from *E. radiata* and other native kelps by the convoluted sporophyll at the base of its stipe when mature, and a midrib visible through the blade (Fig 6). It is heteromorphic, with macroscopic sporophyte and microscopic gametophyte phases (Saito 1975, Fig 7). In its native range, *Undaria* is a winter annual with sporophytes growing through the winter and spring and senescing in summer and autumn (Morita et al. 2003). The rapidly growing sporophyte which may develop 15-20 days after spore settlement, matures early (50-70 days after settlement) and lives between 6-9 months (Saito 1975), growing up to three metres in height. Prior to senescence in summer, sporophytes release millions of asexual spores that germinate into dioecious gametophytes. Male gametophytes release motile sperm which fertilise eggs produced by female gametophytes. The resulting zygote develops into a sporophyte, when temperatures are suitable (Schaffelke et al. 2005). Thus, a single sporophyte can seed an entirely new generation. In its native range these gametophytes remain dormant over the late summer-autumn when temperatures exceed those optimal for fertilisation. In some locations however where temperatures remain cool, such as in southern New Zealand, the annual lifecycle is less clearly defined and gametophytes can fertilise through the year producing sporophytes year round (Hay & Villouta 1993, Schiel & Thompson 2012, James et al. 2015). If environmental conditions are unfavourable, gametophytes can remain dormant for multiple years (2.5+) creating a seed bank over multiple generations (Hewitt et al. 2005).

Fig 6. Mature *Undaria pinnatifida* sporophytes

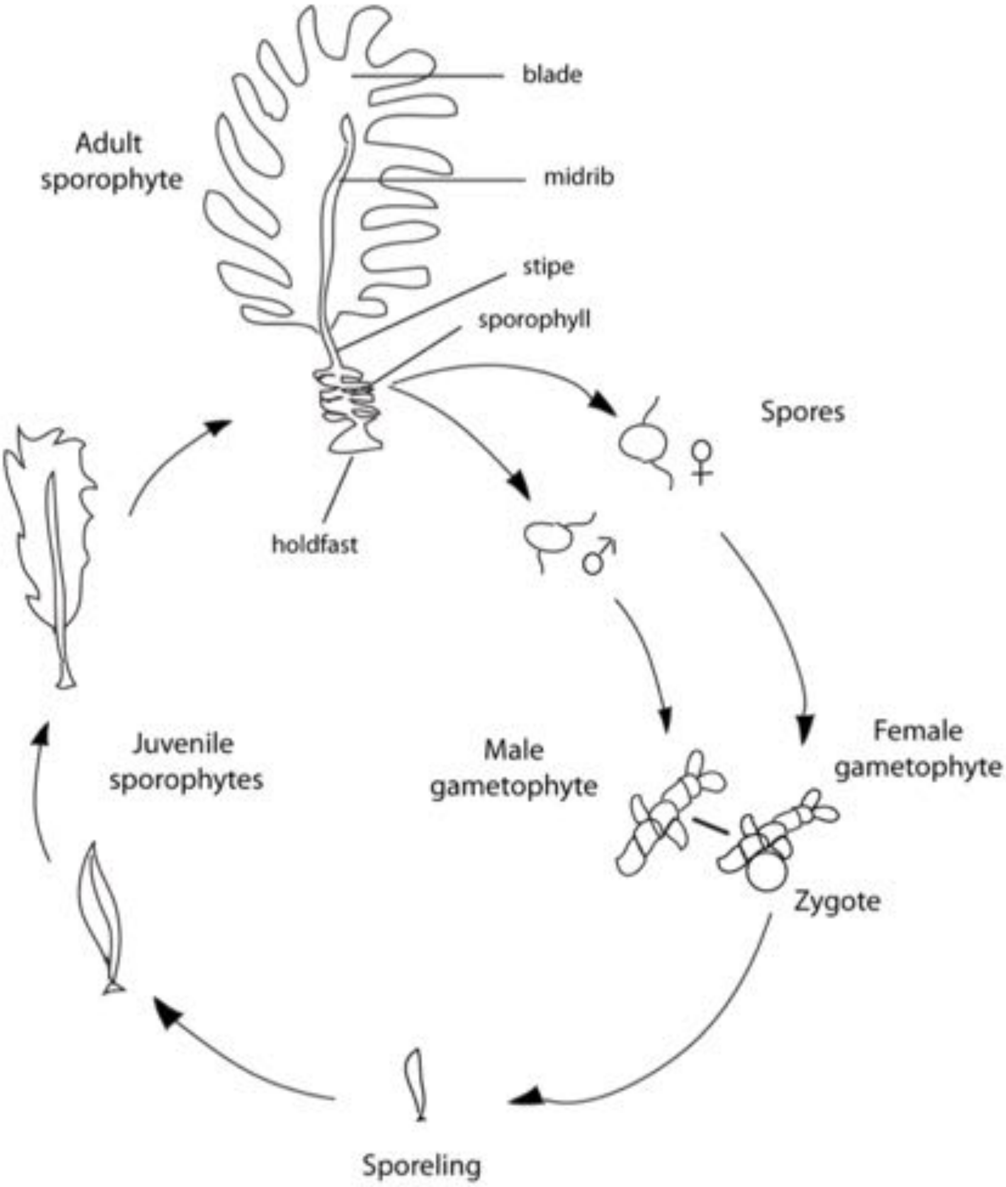

Fig 7. Life cycle of *Undaria pinnatifida* illustrating its diphasic life history with macroscopic sporophytes and microscopic stages (spores, gametophytes, and sporelings) (Jimenez 2015).

2.1.2 Invasive traits

Undaria has a number of traits typical of invasive species and that promote an ability to successfully colonise new environments. These include a rapid growth rate, early maturation, high fecundity, a hardy microscopic gametophyte phase, morphological plasticity, and a large temperature tolerance (James 2016). Occupying a broad ecological niche, growth and distribution is defined by a number of abiotic factors including temperature, salinity, photoperiod, light, nutrients and wave exposure (South et al. 2017). Though typically found in intertidal or shallow subtidal environments, the species has been found at depths up to 25 metres provided there is adequate light (Miller & Engle 2009). Where light is limited, sporophyte growth and density may be reduced (James & Shears 2016). *Undaria* has a wide temperature tolerance and although the optimal temperature range for sporophyte growth is 5-20°C the species can colonise locations with maximum temperatures between 13.5-29.5°C and minimum temperatures between 0.1-15.5°C (Bollen et al. 2016). Where water temperatures exceed 20°C annual populations are supported, but in areas where temperatures remain below 20°C, sporophytes may be evident year round (Bollen 2017). *Undaria* is typically found in fully saline conditions with salinities less than 27 psu generally limiting its range (Bollen et al. 2016), although it has also been observed in low salinity areas (Russell et al. 2008). Similarly, *Undaria* is more commonly found in sheltered-moderately sheltered bays and reef areas although it can establish reproductive populations in areas subject to significant wave action (Russell et al. 2008). There is some evidence that the morphological plasticity observed in *Undaria* is due in part, to the local wave environment (Nanba et al. 2011).

2.1.3 Dispersal

Undaria is easily transported and dispersed via human vectors. Human mediated transport occurs through hull fouling, contaminated ballast water, and transfers of aquaculture species (e.g., Japanese oysters) and equipment (Bax et al. 2003). Visible sporophytes, zoospores, and gametophytes can be transported, though the movement of mature sporophytes is perhaps of greatest concern because of its potential to release millions of spores. Natural dispersal is comparatively more limited. Spores are believed to disperse up to 100m from parent sporophytes due to low motility (Epstein & Smale 2007) while drifting sporophytes are thought to achieve longer dispersal distances, from hundreds of metres to kilometres (Forrest et al. 2000, Russell et al. 2008, Sliwa et al. 2006). Drifting sporophytes are also believed to remain viable considerably longer than zoospores (Epstein & Smale 2007). Local hydrodynamics and weather events are likely to play a significant role in dispersal and natural range expansion (James 2016). For example, it took 10 years for *Undaria* to spread from Dunedin harbour to the open coast (Russell et al. 2008) and in Moeraki, it took almost five years for *Undaria* to spread less than a kilometre from a breakwater to coastal reefs (Schiel & Thompson 2012). In Tasmania comparatively *Undaria* spread 10 kilometres per year (Shepherd 2013).

Undaria has a remarkable ability to colonise a range of natural and artificial substrates including cobble and boulder areas, boat hulls, docks, wharves, mooring lines, and tyres (Fig 8), with coralline turfs playing a possible role in facilitating recruitment (Thompson 2004). Only soft mud or sand appears to be undesirable substrates for colonisation (Stuart 2004). When *Undaria* invades new sites along exposed coastlines, shallow intertidal areas are typically colonised first but the species quickly moves down the vertical gradient into subtidal areas, particularly areas with limited native canopy forming species (Russell et al. 2008).

Table 2. Summary table of *Undaria pinnatifida* Life History Traits

Feature	**Trait Detail**
Lifecycle	Diphasic
Maximum size (length)	1-3m
Maximum age (sporophyte)	1 year (annual)
Mating strategy	Sporic
Dispersal	Motile zoospores/drifting sporophytes
Zoospore longevity	Up to 222 days
Gametophyte longevity	≥ 2.5 years
Time to sexual maturity	50-70 days
Size at sexual maturity	As small as 33 cm
Depth range	Intertidal – Subtidal (20-25 m)
Colonising substrate	Natural, artificial, disturbed environments
Salinity tolerance	Typically > 27 ppt
Temperature tolerance	0.1-23°C

Fig 8. *Undaria* as an epiphyte: overgrowing a native sea tulip (top) and a native seaweed *Carpophyllum* (bottom)

2.1.4 Ecological Impacts

Despite being present in New Zealand for more than 30 years, the ecological impacts of *Undaria* in native communities are not well understood. There has been little research on the ecological impacts of *Undaria* outside of its native range and part of the problem is a lack of baseline data on native communities prior to invasion. Research that does exist appears to be contradictory – with *Undaria* described as having limited or no impact on native communities in some instances (Forrest & Taylor 2002, Schiel & Thompson 2012) and described as a high risk invasive with negative effects in others (Nyberg & Wallentinus 2005). Not all of these studies will be relevant or informative however, to predicting how *Undaria* might affect the Fiordland marine environment. A number of studies that concluded that *Undaria* has limited or no impact on native communities in Southern New Zealand for example (e.g., South et al. 2016) took place in intertidal communities which differ markedly from the subtidal communities within which *Undaria* is found in Fiordland. The reality is *Undaria* has a remarkable ability to grow in a broad range of environments and colonise substrates (including sessile/mobile invertebrates) that native macroalgae cannot. It has the potential therefore, to substantially alter rocky subtidal and intertidal communities around New Zealand (Russell et al. 2008).

Undaria has been classified as an opportunistic rather than aggressive dominant competitor colonising areas that have been disturbed via dieback, fishing pressure, grazing or storm events (Valentine & Johnson 2003, Valentine & Johnson 2004). In stressed environments, *Undaria* has the potential to displace native seaweed species. Following the 2017-18 heatwave in southern New Zealand for example, *Undaria* recruited in high densities to areas around Lyttelton Harbour in which bull kelps (*Durvillaea spp.*) experienced dieback (Thomsen et al. 2019). Given that the magnitude and duration of heatwaves are predicted to increase, and other climate change stressors (ocean warming, acidification) are also likely to have an effect on the marine environment, *Undaria* may gain an advantage over native macroalgae which are less able to adapt and become more pervasive (Ladah et al. 1999, James et al. 2015).

Functionally, *Undaria* plays an ecosystem role that can be strikingly different from native macroalgaes. For some species *Undaria* can be a preferable or palatable food source (Irigoyen et al. 2011). However, *Undaria* is an annual, which in contrast to the majority of native species which are perennial, means that it can be an inconsistent source of food (and habitat) for associated fauna (Jimenez 2015, Leahy 2018). The replacement of more structurally complex native seaweeds with *Undaria* can also result in a reduction in the abundance and diversity of epifauna at an ecosystem level which has the potential to affect the flux of materials to higher trophic levels (Jimenez et al. 2017).

A comprehensive review of existing research on the ecological impacts of *Undaria* is beyond the scope of this review and readers are directed to reviews by James (2016) and South et al. (2017). What is clear from the literature however is that more research on the ecological effects of *Undaria* is required – particularly with respect to the Fiordland marine environment and this research ought to take into account site specific variability, changing ocean conditions and a range of ecological processes.

2.2 Invasion History in New Zealand

Undaria was first discovered in New Zealand, in Wellington Harbour in 1987 with the introduction presumed to be the result of hull fouling or contaminated ballast (Hay & Luckens 1987). *Undaria* has since spread to almost every major port in New Zealand from Rangaunu Harbour in Northland to Boat Harbour in the Snares Islands, with the notable exceptions being western ports in the South Island. Given *Undaria's* limited dispersal, the speed at which *Undaria* invaded a significant proportion of the New Zealand coastline, and the haphazard manner in which it spread, it seems likely that dispersal has been aided by shipping (Hay 1990, Forrest et al. 2000). Furthermore, the presence of at least 10 haplotypes in New Zealand suggest that there have multiple invasion events since the 1980s (Uwai et al. 2006).

In the 10 years following its discovery in Wellington, the control or eradication of *Undaria* did not appear to be a management priority, in part perhaps because of a general lack of interest in marine biosecurity at the time (Forrest 2007) and a belief that *Undaria* would remain largely confined to artificial structures given what was observed in ports early in its invasion (Russell et al. 2008). It was only when *Undaria* was discovered in Big Glory Bay (Stewart Island) in March 1997, that attention became focused on controlling or eradicating the species. The trigger being the potential for *Undaria* to spread to areas with outstanding biodiversity and conservation values such as the sub-Antarctic Islands and Fiordland (Forrest & Hopkins 2013). In 1999, the government directed the Ministry of Fisheries to develop a national strategy for the long term management of *Undaria*. This began with stakeholder consultation and a report on options for management. This report, recommended that attention be focused on keeping *Undaria* out of high value areas such as the sub-Antarctic Islands and Fiordland which were not only areas of high conservation value but also areas in which vector management was possible. Unfortunately, the discovery of *Undaria* in the Snares Islands in 2006 and then Breaksea Sound in 2010, highlights the ability of this invasive species to reach new locations and establish in a range of habitats.

Undaria is currently classified as a pest in several regional pest management plans including Taranaki, Gisborne, Southland, Northland, Hawkes Bay, and Tasman/Nelson. These plans are prepared under the Biosecurity Act 1993 and set out priorities for biosecurity management.

2.3 Responses to *Undaria* Invasions

Given its life history, the probability of reintroduction by shipping, and the resources typically required to effectively control and manage an invasive marine species, few attempts have been made to control or eradicate *Undaria.* By the time it is detected, eradication is often deemed impossible (Hay & Luckens 1987) and in some countries e.g. France and Spain, the focus seems to have shifted from eradication, to containment and utilisation of *Undaria* as a resource (Kraan 2017, FAO 2019). In New Zealand, eradication action has been taken in Southland (Big Glory Bay, Bluff, Fiordland) and the Chatham Islands, while international attempts include Australia (Victoria and Tasmania), and the United States (California) (Appendix 1). While many of these eradication attempts resulted in significant reductions in *Undaria* biomass and density they ultimately failed. Only two have resulted in complete eradication: (1) Chatham Islands, and (2) Western Port Bay, Victoria.

2.3.1 Chatham Islands (Wotton et al. 2004)

On March 17 2000, a 40m steel trawler, the *Seafresh 1* foundered at Hanson Bay in the Chatham Islands. It eventually sank in 20 metres of water, in sandy habitat approximately 2.2 kilometres from the nearest rocky reef. When it was inspected on March 23, two *Undaria* sporophytes were discovered, attached to the hull. A Ministry of Fisheries assessment concluded that *Undaria* posed a sufficient threat to the environment, economy, and social values of the Chatham Islands and that a response was warranted. To facilitate the proposed removal and ensure that the vessel owners were compelled to act, the Chief Technical Officer of marine biosecurity classified *Undaria* as an "unwanted organism" under the Biosecurity Act 1993. After experiencing difficulties with salvage, the Ministry of Fisheries opted to use heat treatments coupled with monthly monitoring to eradicate *Undaria* from the ship's hull. Research undertaken by DOC determined that gametophytes are killed when exposed to temperatures of 60°C for more than 5 seconds (Webb & Allen 2001). The heat treatment consisted of two methods: (a) a plywood box attached to the ship's hull heated with elements and (b) flame torches. These were designed to target the microscopic gametophytes. The wooden box contained heating elements contained within foam seals. One side of the box was open so it could be placed onto the ship's hull. The heating elements were powered by a generator on a support vessel which heated the water inside the box to 70°C within 15 minutes. The heat treatment was applied for 10 minutes. The box was applied 311 times to the hull over the course of a month (28 May – 29 June 2001) and only areas close to where the sporophytes had been located were treated.

The torch was an adapted Petrogen oxy-gasoline cutting torch which was used in areas inaccessible to the hot water box. Monthly monitoring continued until March 2003 with the final follow up inspection taking place in December 2003. Overall, eradication cost $423 500 NZD over a 15-month period and the cost was largely borne by the ship's insurers.

To date, this has been the only documented eradication that has successfully removed *Undaria* in New Zealand. Its success is ascribed to a number factors including: early detection, rapid response, relative isolation, long term committed funding and effort, and an adaptive management approach in which managers targeted both mature sporophytes and gametophyte stages.

2.3.2 Western Port Bay, Victoria Australia (Primo et al. 2010)

Undaria was first detected in Victoria in 1996, on a shallow basalt reef near Point Wilson in southwest Port Phillip Bay. On December 21 2000, 7-8 immature sporophytes were found growing on abalone shells in Western Port Bay, approximately 40 km south east of Port Phillip Bay. The shells were within a 3 x 3 m area, in 3 metres of water adjacent to a landing on Flinders Pier. The sporophytes were immediately removed and the find was reported to the Department of Natural Resources and Environment.

The Marine and Freshwater Resources Institute initiated a response managed by the Department of Natural Resources and Environment and guided by the *Interim Victorian protocol for managing marine exotic organism incursions*. Eradication appeared possible because it seemed that the *Undaria* had been introduced as gametophytes on shucked abalone shells. On December 28 2000 a surface inspection of the Flinders Pier pylons and adjacent seabed was undertaken and divers removed four immature sporophytes from the abalone shell piles as previously identified. Shells on the surface layer of the pile were also removed. On 12 January 2001 and 22 May 2001 follow up surveys were completed, with divers swimming the length of Flinders Pier and transects through mooring areas north and south of the pier. Abalone shell piles were video recorded and intertidal walks 250 m north and south of the pier were also conducted. No further individuals were found during surveys on 12 January 2001 or 22 May 2001.

As was the case in the Chatham Islands, the response in Western Port Bay was fast and coordinated. Success was also likely due to the *Undaria* being immature and restricted to a small area where the substrate could be removed.

2.4 Tools for Eradication or Control of *Undaria*

2.4.1 Physical/Mechanical

(a) Manual Removal

The most common method used in previous *Undaria* control/eradication responses has been hand removals by divers/snorkelers (NZ, AUS, USA). While fast, relatively cheap and effective when *Undaria* is at low densities, it can be very labour intensive when densities are high. Spore dispersal also remains a risk when plants are mature, and removals must factor in secure collection, transport and disposal. In most instances, divers aim to remove *Undaria* at the holdfast to prevent re-growth, but this can be difficult if individuals have grown in cracks or from below boulders. There is some evidence to suggest however that cutting the thallus below the meristem is sufficient for removal and the remaining holdfast lacking a meristem senesces (Dietrich & Lonhart 2010).

(b) Encapsulation

Encapsulation of wharf piles and parts of the seabed in plastic was attempted for the control of *Undaria* in Bluff harbour between 2007-2009. There were issues however, with dislodgement of plastic wraps by strong water currents. Approximately 20% of piles had damaged wraps that were not replaced while 50% of the remaining 450 piles required monthly repair and maintenance (Sinner et al. 2009). In addition, *Undaria* was found growing on some of the wrapping. Efforts were discontinued in 2009 when the partial control was deemed ineffective.

(c) Heat

In addition to the heat box and modified torches used to eradicate *Undaria* in the Chatham Islands (see section 2.3.1), a steam sterilisation tool was also developed by DOC for treatment of *Undaria*. Instead of heating seawater adjacent to the treatment area however, it delivered freshwater or steam heated by an industrial steam cleaner at the surface. The hot water/steam is then delivered via a hose to a silicone cone (diameter 30cm) which is held against the substrate for treatment. Although the system led to high mortality of *Undaria* there were issues with the cone maintaining a tight seal on complex substrates, compromising its effectiveness. As the system also requires diver operators, there were also issues associated with depth and decompression limits attained by divers operating the system.

2.4.2 Biological Controls

In August of 2011, 30 000-35 000 kina (New Zealand sea urchin, *Evechinus chloroticus*) a generalist herbivore were trialled as a biocontrol for *Undaria* in Sunday Cove. The kina were collected by divers from sites in the outer reaches of Breaksea sound and transplanted to Sunday Cove within hours of their collection. In the year following translocation, *Undaria* abundance remained low, with one mature sporophyte and 142 juveniles detected in 2012 and only three juveniles detected in 2013. The kina directly grazed on *Undaria* and also reduced the cover of native seaweeds making detection of *Undaria* easier for divers manually removing individuals. A study looking at non-target effects and kina dispersal following the translocation was conducted simultaneous to the release (Atalah et al. 2013). Researchers found that there were significant reductions in kina density at treatment sites. Average densities of 52 individuals per m^2 had reduced to 5 individuals per m^2 after 9 months, after which time they stabilised. After the translocation there were also significant reductions in the native macroalgaes, *Ecklonia radiata* and *Carpophyllum flexuosum* in treatment sites, and the mean number of taxa observed through time. The control sites remained dominated by kelp forest assemblages while treatment sites resembled sea urchin barrens. The study highlighted the possible non-target effects resulting from the use of a generalist biocontrol.

While not specifically a biocontrol trial, similar effects of grazing on *Undaria* by the sea urchin *Heliocidaris erythrogramma* were observed in Tasmania. In an experiment, where densities of urchins and *Undaria* were manipulated, researchers found that urchins have the ability to destructively graze *Undaria* eliminating most of the sporophytes. That said, areas where urchins had grazed did not necessarily enhance recovery by native canopy forming species, and *Undaria* was shown to successfully recruit in sea urchin barrens (Valentine & Johnson 2005).

2.4.3 Chemical Controls

Several chemical treatments have been trialled in a laboratory setting for *Undaria* with mixed success. Gametophytes suffered 100 percent mortality after immersion in freshwater for two days, while plantlets suffered the same level of mortality after immersion for 10 minutes (Forrest & Blakemore 2006). Similarly, gametophytes and plantlets treated with acetic acid of concentrations less than 1% for one minute, induced mortality (Rezek 2001, Forrest et al. 2007). A commercial antifoulant (Sea-Nine 211) achieved mortality at concentrations greater than 1.6mg/L and commercial herbicides (atrazine, diuron, casuron, coptrol) also induced mortality depending on how they were applied (injection, sponges soaked with the treatment, bags surrounding the thallus) (Sanderson 1996). In the field, chlorine applied under tarpaulins has been used around Sunday Cove to treat areas adjacent to where mature sporophytes have been found to good effect. Sodium hypochlorite granules were also used to sterilise floating structures in Big Glory Bay while brominated oxidising agents used in Bluff harbour were found to be ineffective (Stuart 2004).

2.4.4 Habitat Management

In the case of *Undaria* a key factor in its success as an invasive is its ability to settle and develop on almost any hard substrate in the marine environment including artificial substrates from which it can spread unimpeded. Many of these substrates are less likely to be colonised by native kelps, thus management of these environments with native kelps may not be possible. However, there is evidence that where native canopies are intact *Undaria* invasion may be inhibited with sporophytes being less abundant, smaller, and with a lower biomass (Leij et al. 2017).

Table 3. Methods used to control/eradicate *Undaria pinnatifida*

Method	**Effect**	**Feasibility**	**Concerns**	**Example**	**Success/Failure**	**Reference**
Physical						
Hand removal of sporophytes	Reduces sporophyte population density and inhibits range expansion	Only practical at small spatial scales and requires on-going removals	Disturbance of benthos, dispersal of spores by divers	Sunday Cove, Fiordland, Big Glory Bay Bluff Harbour	Reduced sporophyte abundance but eradication not achieved	Hunt et al. 2009
				Tasmania		Hewitt et al. 2005
				Port Phillip Bay Victoria		Crockett et al. 2017
				Venice, Italy		Curiel et al. 2001
				California, USA		Kaplanis et al. 2016, Lonhart & Bunzel 2009
				Argentina		Dellatorre et al. 2014
Encapsulation	Contains and kills *Undaria* by shading and anoxia	Only practical at small spatial scales. Difficult to implement in areas with high water movement/wave action	Non-target effects	Bluff harbour	Reduced sporophyte abundance but eradication not achieved	Coutts & Forrest 2007, Sinner et al. 2009

Method	**Effect**	**Feasibility**	**Concerns**	**Example**	**Success/Failure**	**Reference**
Heat	Destroys gametophyte stage	Only practical at small spatial scales and limited application in complex environments	Non-target effects	*Seafresh 1* Chatham Islands	Success	Wotton et al. 2004, Hunt et al. 2009
		Potential method to sterilise ballast water		Experimental	NA	Stuart 2004
Chemical						
Sodium hypochlorite (bleach)	Oxidising agent	Difficult to maintain required concentration.	Negative effect on nearby fauna and water quality	Big Glory Bay	Did not kill all *Undaria*	Stuart 2004
Chlorine	Oxidising agent that kills gametophytes	Concentrations maintained by placing chlorine under tarpaulins in targeted areas	Negative effect on nearby fauna and water quality	Sunday Cove, Fiordland	Success	Brunton, pers comm 2019
Brominated micro-biocide	Oxidising agent that kills gametophytes	Not practical in open water where it is difficult to maintain necessary concentrations Independent toxicology studies found that to kill *Undaria* gametophytes, concentrations had to be	Negative effect on nearby fauna and water quality	Bluff harbour	Considered ineffective	Stuart 2004

		20 ppm (40x the manufacturer's recommended dose)				
Method	**Effect**	**Feasibility**	**Concerns**	**Example**	**Success/Failure**	**Reference**
Biological						
Sea urchin translocation (*Evechinus chloroticus*)	Reduces sporophyte densities but also clears macroalgae so *Undaria* is visible to divers searching	Not practical for large areas as urchin density requires maintenance. Method is a control measure rather than eradication measure	Non-target effects. Urchins just as likely to graze on native species. If surveillance is not maintained *Undaria* can colonise barrens.	Sunday Cove, Fiordland	Reduction in kelp densities and shifts to urchin barrens	Atalah et al. 2013
Habitat Management						
Kelp bed rehabilitation	Potential means of increasing rate of native algal recovery	Practicality needs to be demonstrated	Minimal environmental concerns	NA	NA	NA
Impact Mitigation						
Modify aquaculture practices e.g. restrict transfer	Means of preventing new incursions and dispersal of *Undaria*	Feasible but there will be high labour costs to aquaculture industry	Minimal environmental concerns	Big Glory Bay (transfers into BGB restricted from other marine farming regions)	NA	Hunt et al. 2009

of aquaculture equipment						
Vessel Monitoring	Means of preventing new incursions and dispersal of *Undaria*	Feasible but requires consistent effort and compliance by boat owners	Minimal environmental concerns	Stewart Island, Bluff Harbour, Fiordland	NA	Hunt et al. 2009
Vessel antifouling	Means of preventing transport via biofouling	Feasible but responsibility for regular maintenance typically remains with vessel owners. May require support via encapsulation based sterilisation, chemical/heat treatments for internal recesses	Minimal environmental concerns	NA	NA	South et al. 2017

2.5 Vector Management

Regardless of the control/eradication method chosen, without adequate vector management and monitoring there is nothing to prevent the invasive species from re-invading a controlled area using the same human mediated pathway. Regular monitoring can also prevent incursions from known pest species occurring in the first place – saving considerable time and effort in control and eradication once the species becomes established.

2.5.1 Management of Biofouling

As has been demonstrated with *Undaria*, vessel biofouling is a major vector for the introduction of invasive marine species. In accordance with the Biosecurity Act 1993, vessels arriving in New Zealand must do so with a clean hull, that is free of biofouling. Vessels arriving in New Zealand must provide evidence of biofouling management before they arrive. Without verifiable evidence of compliance, MPI may require a hull inspection on arrival, require cleaning offshore, or restrict entry of the vessel into NZ.

Vessels entering within one nautical mile of the landward boundary of the Fiordland Marine Area (FMA), are governed by the rules in in the Fiordland Marine Pathway Plan. Vessels entering the FMA are required to hold a Clean Vessel Pass, the standard required being that hull and niche areas have no more than a slime layer and goose barnacles. This is subject to inspection by authorised divers. Likewise, all marine gear and equipment on the vessel must be visibly clean and free of fouling and sediment, and on board residual water has to be treated or visibly clean and free of sediment. The owner or person in charge of the vessel is required to keep records of actions taken to meet clean hull, gear, and residual water standards and make these available to inspectors on request. Given the presence of *Undaria* in multiple ports and harbours including those in close proximity to Fiordland (Bluff, Stewart Island), it is imperative that biofouling is carefully managed to prevent additional incursions.

For vessels infected by biofouling, the most effective way to treat them is to remove them from the water (e.g. dry dock) and scrape the hull clean. In situ methods of hull cleaning, can actually aid in the dispersal of the invasive species, if fragments or spores released during the cleaning process survive and colonise the surrounding environment, although new in situ methods are being developed for complete in situ encapsulation e.g. the IMProtector (www.biofouling.com). The regular application of antifouling paints can also prevent reoccurrence of biofouling.

2.5.2 Management of Ballast Water

Ballast water, used to stabilize vessels relative to the amount of cargo on-board, can contain a variety of organisms at various life stages (Bax et al. 2003). The uptake and release of ballast water therefore has the potential to transport marine organisms from one location to the other. Internationally, the International Maritime Organization adopted guidelines for preventing the introduction of unwanted aquatic organisms and pathogens from ballast water (resolution MEPC.50(31)). These guidelines require vessels to conduct mid-ocean ballast water exchange and restrain from discharging unexchanged water in coastal areas. The International Convention for the Control and Management of Ships' Ballast Water and Sediments (Ballast Water Convention), which entered into force on September 8 2017, also requires all ships to implement a ballast water management plan and carry a ballast water record book by 2024. New vessels must meet the new treatment standards, while existing vessels have until 2024 to comply and are currently only required to exchange ballast water mid-ocean.

In New Zealand, Biosecurity New Zealand has an Import Health Standard, as minimum requirements for ballast water originating from outside of NZ territorial waters and intended for discharge within NZ territorial waters. Essentially, no ballast water may be discharged into NZ waters unless it has been exchanged with mid-ocean seawater en route to NZ, is fresh water, or it has been treated using a shipboard treatment system (IHS 1.6). Non-compliance with the standard can result in actions being required to mitigate the risk of discharging the ballast and/or being charged with an offence under the Biosecurity Act 1993. Even if there is 100 percent compliance with international guidelines and national rules, the effectiveness of mid-ocean ballast water exchange to prevent transport of pest species in ballast tanks is questionable. Studies suggest that some organisms remain in the ballast tank even after the water exchange (Taylor et al. 2007, Piola et al. 2009).

There are a number of methods to treat ballast water (e.g. imo.org), including filtration, acoustic treatments, electric pulse or plasma systems, magnetic field treatment, biocides, UV sterilisation, deoxygenation, and heat treatments. Methods have not been developed specific to *Undaria*, although between 1996 and 1998, the Ballast Water programme at the Cawthron Institute, investigated sterilisation of ballast water against potentially harmful species, including *Undaria* zoospores. Unfortunately, funding was cut before a method for on-board sterilisation could be fully developed (Stuart 2004).

Traditional detection based on morphological assessments can be time consuming and expensive, requiring taxonomic expertise that is often unavailable. Recent advances in molecular techniques may however provide a more effective means of rapidly detecting invasive species in ballast water (Zaiko et al. 2015). Molecular tools for targeted surveillance include polymerase chain reaction (PCR) and quantitative PCR methods, and fluorescence in situ hybridization (FISH). They work by detecting short segments of an organism's genome in a sample – thus they are able to improve species level identifications as they do not rely on morphological identification. These methods do have a number of limitations however, including the need for reference sequences and an inability to translate positive DNA signals to actual organism counts. A positive molecular signal may also provide no information on whether the detected organism is alive and thus of biosecurity risk. Advances in environmental DNA and RNA (eDNA, eRNA) high throughput sequencing (HTS) metabarcoding may soon address this issue however (Mahon et al. 2013, Pochon et al. 2017). And despite potential limitations, molecular detection methods are increasingly used in a number of surveillance programs (see review in Darling & Frederick 2018).

2.5.3 Management of Marine Farming/Aquaculture Transfers

Marine farming/aquaculture is another significant vector for the transport of invasive species, particularly where species are cultured outside of their native range and the potential for escape is high (e.g. Atlantic salmon farmed on the Pacific coasts of North America, Barry & VanderZwaag 2007). Aquaculture has been directly implicated in the introductions of *Undaria* to Big Glory Bay (Stewart Island) and the coast of France (Floc'h et al. 1991, Floc'h et al. 1996, Stuart 2004). Recognising the risks posed by the transfer of marine farming equipment in the spread of invasive species, several methods have been trialled for their treatment including freshwater immersion, acetic acid, brine, hydrated lime, sodium hypochlorite, alkaline ammonia, and manual removal in addition to quarantine zones and restrictions on the movement of equipment and vessels from infected regions (e.g. Carman et al. 2016).

In the case of *Undaria*, transfer of the species through marine farming activities is especially relevant because the species is established in the major marine farming regions of New Zealand e.g. the Marlborough Sounds, Firth of Thames, and Golden Bay (Forrest 2007). Seed stock, marine equipment (e.g. ropes, frames, floating structures etc.), and vessels are possible vectors. For *Undaria* gametophytes however, 100% mortality has been achieved via high pressure spraying (2000 psi for 2s and 3000 psi for 1-2s), freshwater immersion (2 days at 10°C), air drying (2-3 days at 10°C), hot water immersion (35°C for 10min, 45°C for 45s, 55°C for 5s), and acetic acid (0.1-2% for 1 minute) (Forrest & Blakemore 2006, Forrest et al. 2007).

Part 3 *Undaria* in Fiordland

3.1 Significance of Fiordland

Fiordland is internationally recognised as an area of high conservation value, designated by the United Nations as a World Heritage Area (WHA) in 1986. While the waters of the fiords are not included in the WHA designation, the marine environment is as exceptional as the land above with high biodiversity and unique species assemblages including long-lived black corals and sea pens at shallow depths, and ancient brachiopods seen nowhere else in the world (NIWA 2013). In 2005, the importance of the Fiordland marine environment was formally recognised with the creation of the Fiordland (Te Moana o Atawhenua) Marine Area, eight marine reserves, and protected areas of special significance termed ‘china shops.’ Additional to its exceptional conservation and ecological values, Fiordland is reported as adding $228 million to the New Zealand economy every year by receiving approximately 33 000 overnight visitors and 560 000 day visitors (DOC 2006). It additionally, supports a number of valuable fisheries including rock lobster, pāua, kina and blue cod. Preventing the introduction and spread of invasive marine species, therefore is paramount to the preservation of this unique marine environment. *Undaria* has the potential to significantly alter the marine ecosystem in Fiordland, reducing biodiversity and disrupting ecosystem processes. The shallow distribution of black corals for example means that *Undaria* could directly settle and grow on the coral. If *Undaria* in Breaksea Sound is not successfully controlled or eradicated or, the risk of it spreading throughout the Fiordland Marine Area remains high. While examples of successful *Undaria* eradications are limited to the Chatham Islands and Western Port Bay, Australia, lessons could perhaps be learned from international responses to other marine invasive species (e.g. Case Studies 1 & 2).

3.2 A 5 Step Control Programme

Given the extent of the *Undaria* incursion discovered in 2017, and constraints on resources and tools available, eradication does not appear to be achievable - at least in the short term. The length of coastline that would require attention is 20 times the length of the Sunday Cove search area (~28.8km vs ~1.4km). The previous model of eradication therefore using a team of 6 divers manually removing *Undaria* every month to six weeks is not likely to be sustainable both from funding and effort perspectives.

The emphasis instead, should be on control: preventing the spread of *Undaria* and reducing its biomass using an adaptive management framework applied over the next five years (Fig 9).

The key steps to a robust control programme include:

1. Biomass removal
2. Mapping the extent/distribution of *Undaria*
3. Assessing the feasibility of continued control efforts
4. Modelling *Undaria* dispersal using a 3D hydrodynamic model
5. Continued control and monitoring

While the response merits urgency, action needs to be carefully planned and managed so as to best utilise the resources, capacity and time available. Response action needs to be supported and assessed by independent data and there must be opportunities to adapt control methodology as more is learned about the incursion and *Undaria* in Fiordland. **Steps (3) -(5) therefore, are contingent on Steps (1) & (2).** If it becomes clear at Step (3) for example that it is no longer feasible to control *Undaria* in Breaksea Sound, then decision makers will need to decide what action to take (Fig 9).

By focusing on halting the spread of *Undaria* in Breaksea Sound through targeted control efforts supported by research in the short term, the longer-term goal of eradication could well be possible provided new methods/tools become available.

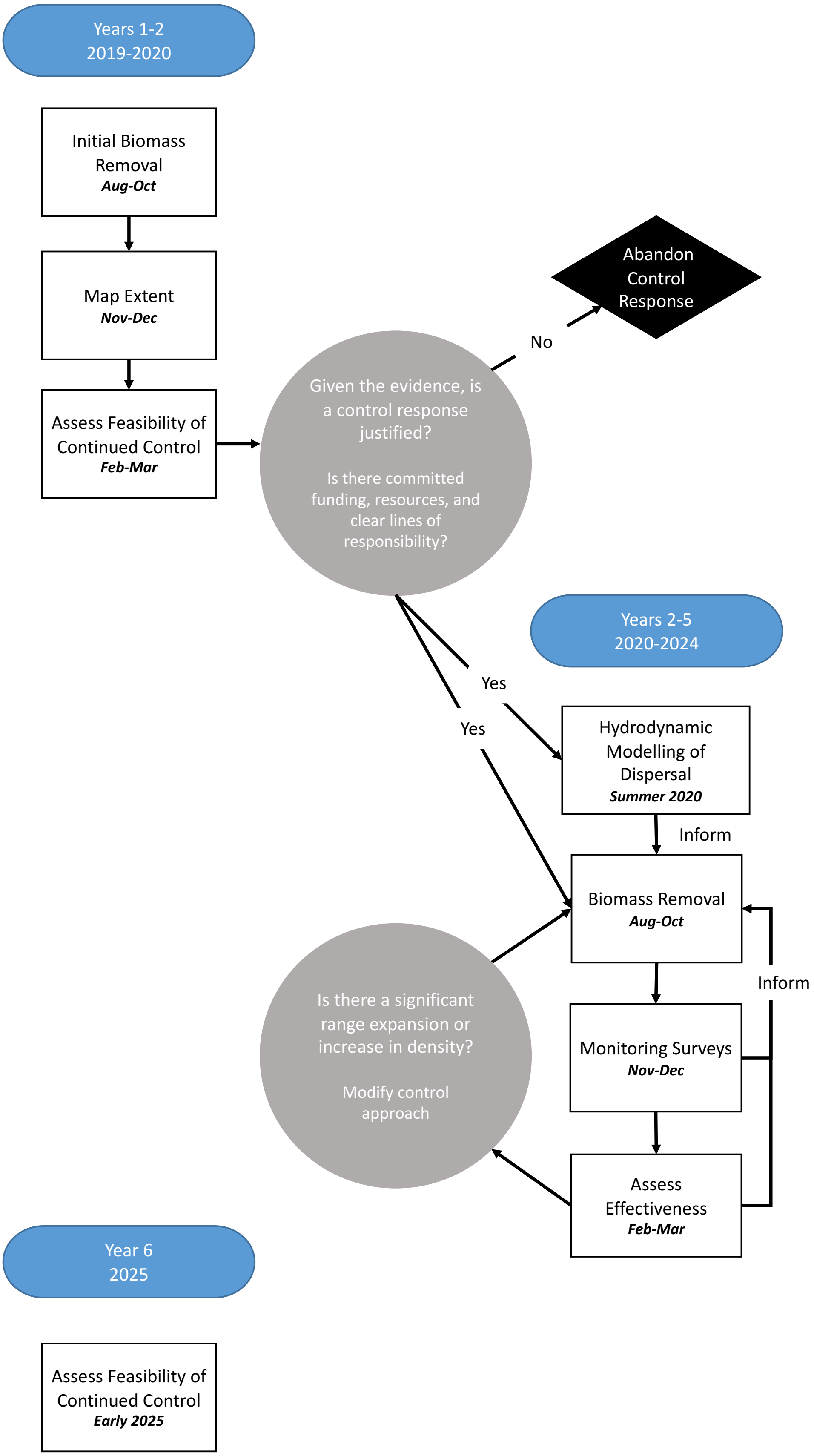

Fig 9. Adaptive framework for a *Undaria* control programme in Breaksea Sound

3.2.1 Step 1. Biomass Removal (August-October 2019)

Central to the control of *Undaria* in Breaksea Sound is biomass removal: removing as much biomass as possible, as soon as possible. The earlier this action can be taken, the less likely it is that *Undaria* will spread into new locations in Breaksea Sound and the surrounding fiords. Following this initial removal, information from Steps 2 and 3 will inform future control responses and decisions about how best to proceed.

Key considerations for an initial targeted biomass removal include:

Time of year for removals

Between April 2010 and May 2016 monthly surveillance trips removed 1933 individuals. The bulk of these removals (57%) were in winter, followed by spring (19%), autumn (13%) and summer (10%)[1]. Of the 11 reproductively mature individuals collected during this time period, 91% were found between December and April (Fig 10). *Undaria* is (typically) a winter annual that grows through the winter-spring and senesces in summer. Prior to senescence in summer, individuals release zoospores with one individual sporophyte able to release millions of asexual spores (Primo et al. 2010). If removals are delayed the likelihood of dispersal increases, as densities of mature sporophytes also increase. It is important therefore for control action to begin in 2019.

Recommendation

- **Target removals for August-October 2019**. During this time the majority of sporophytes should be visible but immature (as highlighted by previous collections). Plants would also be smaller than they would be at the end of the growing season so there would be less biomass to remove. If surveys occur later, the risk of spore dispersal is higher and divers are more likely to only encounter plant remnants or bare stipes.

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[1] Note percentages are weighted by number of surveys per season. Winter n = 17, spring n = 18, autumn n = 21, summer n = 17. Note the winter average is heavily influenced by the July 2010 removals which occurred two months after the initial discovery of *Undaria* in Sunday Cove. With 2010 removed, the winter average becomes 29%. With 2010 removed, the months with highest *Undaria* finds are May (18%), September (16%), and June (12%), followed by July, August, October and December (8%).

- Effort should be focused on the August-October window and the number of surveillance trips made throughout the rest of the year should be reduced particularly when *Undaria* has senesced and is no longer visible.

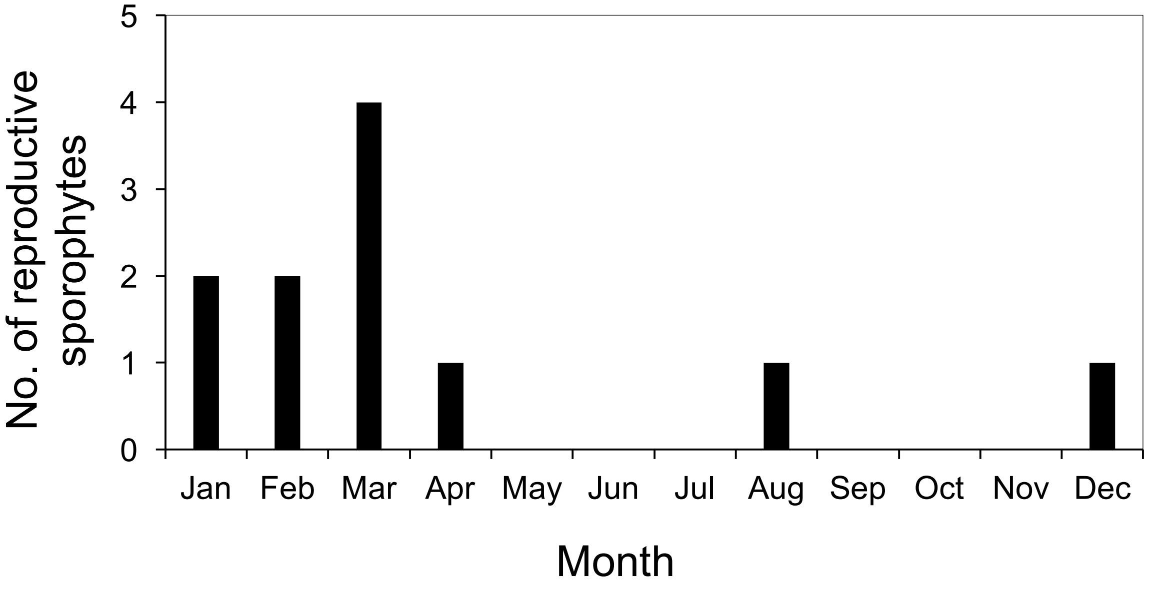

Fig 10. Number of reproductive *Undaria* sporophytes collected from Breaksea Sound and their month of removal April 2010-May 2016

Personnel

Previous *Undaria* removal trips typically utilised six divers at a time, at a cost of approximately $20 000 for four days of work (Table 4). Divers are required to have a WorkSafe Certificate of Competence (CoC) for occupational diving and have flexibility to travel/work in a remote location. Divers are usually paid approximately $300 per day (including travel days), and may be based anywhere in New Zealand (thus travel costs are also covered and are an additional expense).

Table 4: Cost Breakdown of monthly joint agency surveillance/elimination trips. Note, if contract divers are used they are paid $1500-1600 for the week but if divers from the agencies are used, their pay is covered by their salaries.

Item/Activity	Cost	Cost
Heli Flights (2 x flights)	5 310	

Vessel (5 days)		7 000
Food (5 days)	550	550
Dive/trip leader/logistics	2 600	2 600
Flights if needed	1-2000	1-2000
Divers (5)	8 000	8 000
Misc (O_2 rental, compressor parts, dive spares, fuel for dinghy etc.)	300	300
Total	**18 760**	**20 450**

While the need for CoC qualified divers with flexible work schedules may limit the pool of personnel available for monthly control trips, if control trips are specifically targeted for August-October and planned well in advance, then this provides certainty for dive contractors and it may be possible to recruit a larger pool of divers. We recommend that a biomass removal/control dive team be set up expressly for this purpose to undertake these removals year after year (dependent on Step 3) and that this team works somewhat independently of those involved in research and monitoring. In addition, the focus for this team at this time should be on the control of *Undaria* rather than broader surveillance activities. Where possible divers from Otago/Southland should be recruited as this would reduce costs associated with travel.

Recommendation

- Plan control trips in advance for the August-October period providing certainty for dive contractors and allowing for the recruitment of a greater number of divers.

Depth

Where light is limited, sporophyte growth and density may be reduced but with clear water conditions it is possible that sporophytes may grow deeper. *Undaria* has been recorded at 20 metres around Otago (Stuart 2004, Russell et al 2008), and in the Snares Islands dense stands have been found between 15-18 metres with individuals up to 25 metres. Within Breaksea Sound, the deepest an individual has been found is 17.4m (Survey December 2010) although since 2017 *Undaria* has been found primarily between 0.5 – 6 metres. *Undaria* cover and density across depth gradients should be investigated as part of Step 2 or as additional supporting research.

Recommendation

- **Target depths between 0.5-6 metres**. While it is possible that there may be individuals deeper than six metres, the 0.5-6m depth range contains the bulk of the *Undaria* biomass thus should be the primary focus. If Step 2 identifies significant densities beyond six metres, control efforts/methods will need to be reassessed and/or modified.

Where to focus effort

Since the discovery of *Undaria* in Beach Harbour in April 2017, *Undaria* has been confirmed as present on the north side of Breaksea Sound adjacent to Half Cove, First Cove, and Second Cove, and the southern side of Breaksea Sound passed Saturday Cove into the Acheron Passage, and opposite the John Islands (Fig 2). High densities (> 50 individuals per 50m) have been found around the Harbour Islands, John Islands, and inner Beach Harbour as well as around First and Second Coves. It is these areas that should be the priority for targeted control in 2019, as they have the potential to release millions of spores. Beach Harbour also has moorings subject to regular use by vessels.

Once high density areas have been cleared, the priority shifts to areas with low densities (< 10 individuals per 50 m) or where individual sporophytes have been collected before i.e. Sunday Cove to the Acheron Passage. Ideally, this would also occur in 2019, at the same time as the initial biomass removal.

In November-December 2019, once the removals have been completed it is imperative that the full extent of the *Undaria* incursion is mapped (Step 2) and this should include areas outside of those where *Undaria* has been removed/areas that have been confirmed as having no *Undaria* in the past e.g. Gilbert Islands. This process will be informed by GIS data from the previous eradication attempts and the Aug-Oct 2019 biomass removal. Thus with a first round of removals complete and a map of its extent/distribution decisions can be made in early 2020 as how best to proceed.

Recommendation

- **The first priority for control efforts in 2019 are high biomass areas** e.g. Harbour Islands, John Islands, Beach Harbour, First and Second Coves.
- Low density areas should be cleared as a secondary priority while areas outside of the known incursion should be surveyed and mapped as part of Step 2 to define the extent of the problem.

Trip Length

The Sunday Cove eradication encompassed an area of coastline approximately 1.44 km in length. This area was typically searched by six divers for four days at three depths. There are high density areas in 19.7 km of the total 28.8 km incursion area so clearing this length of coastline with six divers would take 54 days. With twice (or three times) the number of divers working twice the length of time this area could be cleared in two to three trips in the August-October period. (Two is more likely as *Undaria* will not occupy the entire 19.7 km stretch). While increasing the length of trips will increase the cost of individual trips, if the number trips outside of the August-October period are reduced (i.e. particularly during the senescent period when *Undaria* are not visible) the annual costs are unlikely to increase and expenditures will be more effectively targeted.

Recommendation

- **Double the length of trips** (while keeping in line with safe diving practices and being mindful of weather) to increase effort at critical times of the year.

Disposal

Within Breaksea Sound there are areas accessible by small boat, where *Undaria* could be landed and disposed of on land e.g. the south west side of Sunday Cove, or within First Cove. Disposal on land within Breaksea is likely to be the easiest and most cost effective method of disposing high densities of *Undaria*. Other options including sterilising plants (e.g. with chlorine/bleach) and disposing within the fiord, transporting out of Breaksea Sound via helicopter or on board vessels, which would increase costs, and potential dispersal risk.

Recommendation

- **Dispose of collected *Undaria* on land** within Breaksea Sound using small boats

Methods for removal

At the present time, manual removal appears to be the only viable option for biomass removal given the urgency of the response required, and the funding currently available. More efficient means of removal i.e. a dredge (see 1.1.1(c)) should be investigated as part of supporting research. In the meantime, increasing the number of divers and the length of trips should result in a significant reduction in *Undaria* biomass in Breaksea Sound.

As an example of what is possible in a high density area, in November 2018, a trial harvest by divers from the University of Otago at Huriawa Peninsula in East Otago, resulted in the removal of approximately 2.5t of *Undaria*. *Undaria* was removed by 5-6 divers (alternating between snorkelling and SCUBA diving) using dive knives that allowed them to remove *Undaria* from under the holdfast, for a total time of 6 hours over 2 days. The biomass removed was collected in modified catch bags in the water, taken to a support vessel and disposed of on land.

Of particular concern during physical removal of *Undaria* is the potential for spores to be released. Spores are between 5-6 μm in diameter (Perez et al. 1981), thus standard catch bags will not contain them. By targeting removal efforts at a time when plants are unlikely to be mature however, the risk of releasing spores during collection is reduced. Even if limited spore release was to occur (e.g. a plant with a reproductive sporophyll was found in August 2011), we would consider the benefits of removing as much immature biomass as possible, in terms of reducing future spore release outweigh the risk of potential limited spore release.

On previous surveillance trips in Breaksea Sound, when biomass was low, divers placed specimens collected underwater in ziplock bags and brought these to the surface. In areas of high density, ziplock bags will not be effective nor efficient as they are cumbersome to use. For the initial biomass removals therefore, when sporophytes should be largely immature, we would suggest using standard catch bags or larger mesh bags that could be hauled on board. Once the bulk of *Undaria* has been removed, then methods for collecting *Undaria* during subsequent removals can be re-evaluated.

Recommendation

- **Remove as much biomass as possible using modified dive knives and standard or modified catch bags to collect *Undaria*.**
- Consider development of alternative tools or methods for removal of *Undaria* that limits potential spore release and increases efficiency.

Treatment of Gear/Equipment

Any dive gear and equipment brought into Breaksea Sound for control work should be clean and dry before arrival to prevent contamination from other sites in New Zealand. In addition, it is imperative that dive gear and any equipment used in biomass removals are thoroughly disinfected before use in new sites. Hot water (e.g., 60°C), and a solution of detergent (2%, active ingredient < 3% potassium hydroxide (KOH), or dilute bleach (2%) should be utilised (Gunthorpe et al. 2001). Care should also be taken with vessels and containers used to transport *Undaria* to ensure that fragments and plants that potentially have spores do not contaminate new locations i.e. when catch bags are hauled onto vessels, they should be placed immediately within containers to prevent catch bag contents from being spilled onto the boat deck and flushed back into the water.

Recommendation

- **Disinfect dive gear and equipment used in areas with *Undaria*** prior to its use at new sites using hot water, detergent, or dilute bleach.

Data Collection

For Steps 2-5 that follow, it is important **that accurate and consistent data records are kept**. To be able to map the extent of the incursion (Step 2) for example, it is vital that data includes:

(a) GPS tracks/points of areas searched
(b) GPS tracks/points of areas where *Undaria* has been found and cleared
(c) A record of the depths at which *Undaria* has been removed

To assess the feasibility of continued control efforts (Step 3) it would also be important to record:

(d) The reproductive status of individuals
(e) Weights/numbers of individuals removed
(f) Length of time divers are in the water
(g) Biomass removed per dive

Clear record keeping and data analysis will be important in assessing the success of the control programme and in directing future efforts, thus, every effort should be made by the control team to keep clear records during removals in August-October 2019.

3.2.2 Step 2. Map the extent/distribution of *Undaria* in Breaksea Sound (Nov-Dec 2019).

Step 1 is aimed at substantially reducing the biomass of *Undaria* in Breaksea Sound so that densities remain low and the potential for dispersal to new areas within and outside of Breaksea Sound is reduced. In Step 2, the aim is to accurately map where *Undaria* was, and remains, in Breaksea Sound. Steps 1 + 2 together will inform decision making on the feasibility of continuing control efforts (Step 3).

Recommended Approach:

Time of surveys

Mapping should begin soon after the biomass removals have been completed between August-October, ideally November/December 2019. At this time, sporophytes still present in Breaksea Sound should be clearly visible to searching divers. By starting in November, mapping should also be completed in time to inform decision on whether control efforts are to continue in early 2020.

Areas to survey

Areas of Breaksea Sound that require mapping include (1) sites in which biomass removals occurred in August-October 2019 and (2) areas in the wider Breaksea Sound. While information on the extent of *Undaria* in biomass removal sites should be available from Step 1, it will be important to determine what remains (if anything) in targeted areas. The wider Breaksea Sound survey should include areas where *Undaria* has yet be discovered including the Gilbert Islands, Breaksea Island, Entry Island and inside of the Johns Islands. While the primarily focus should remain on the 0.5-6m depth range, it is important to determine if the depth distribution of *Undaria* in Breaksea Sound, particularly in new locations. Thus these surveys should also include deeper dives (up to at least 15m) where possible.

Data required

Accurate and detailed maps of the incursion require information on *Undaria* presence/absence and:

(a) depth
(b) colonising substrate type
(c) density
(d) geographical location

Personnel & Length of Trip

A team of divers (4-6) working for at least 7-10 days would be required to adequately map the extent. It is recommended that divers mapping the extent be different from those used in biomass removals so as to maintain objectivity and remove potential biases based on previous removal efforts.

Disinfecting Gear

To minimise the possibility of transferring spores between locations in Breaksea Sound disinfecting dive gear between sites will be important. In addition, it would be wise to survey areas outside of the biomass removal areas that are less likely to have *Undaria* first, before surveying areas where *Undaria* is known to occur.

3.2.3 Step 3. Assess the feasibility of continued control efforts (Early 2020)

Using the information from the biomass removals from Step 1 (time, cost, biomass removed, logistics) and information on the extent of the *Undaria* incursion in Step 2, in early 2020 a decision should be made as to whether to proceed with control efforts and how best to do so in terms of funding, effort, designation of tasks and reporting. It is recommended that a workshop be held, that includes relevant government agencies, University of Otago, Ngāi Tahu, and the Fiordland Marine

Guardians. There should be a clear presentation of what has been learned by those responsible for Steps 1 & 2 over the previous 6-8 months, thus enabling an informed decision to be made.

3.2.4 Step 4. Modelling *Undaria* dispersal using a 3D hydrodynamic model (Beginning Summer 2020)

If a decision is made to continue with control efforts, 3D hydrodynamic modelling of dispersal potential is the logical next step. Without a clear idea of *Undaria* dispersal potential in Breaksea Sound i.e. the possible path spores and sporophyte fragments may take based on hydrodynamic conditions and the position of *Undaria* in Breaksea Sound, control efforts will likely miss key areas – ultimately limiting the success of removals and efforts to slow the spread. The decision whether to proceed with modelling however, as part of a control programme is one that should ultimately be made during Step 3 in early 2020.

A number of software tools have been developed to provide a framework for this type of modelling for example the ABM lab developed by DHI (Mortensen 2003). The DHI ABM lab integrates agent based modelling with classical water quality and hydrodynamic modelling (MIKE 2019). By combining the capability of the DHI ABM lab with Acoustic Doppler Current Profiler (ADCPs) deployments and GIS data on *Undaria* in Breaksea Sound from Steps 1 and 2, it would be possible to build a comprehensive 3D *Undaria* dispersal model.

This model could then be used to map the likely pathways of *Undaria* spores and fragments within Breaksea Sound and locations for settlement. This information will then feed directly into biomass removals and monitoring in subsequent years. The presence/absence of *Undaria* in locations relative to model predictions will for example provide an assessment of the effectiveness of removal efforts and whether incursion boundaries have expanded.

Development of a model that utilises the DHI ABM platform was estimated in 2018 as costing approximately $240 000 (GST exclusive) and if started in the summer of 2020 preliminary results should be available by the summer of 2021, thus in time to inform the control response in Aug-October of that year. One of the advantages of a modelling approach is that the quality of the model outputs would continue to improve as additional data becomes available and the model is refined.

Table 5 provides an overview of the broad scale tasks required to develop a modelling tool to simulate the spread of *Undaria* in Breaksea Sound based on the DHI ABM lab platform.

Table 5. Tasks required to develop an *Undaria* modelling tool

Task Description
Stage 1: Preliminary model setup and initial simulations
Review available data from Breaksea Sound. Rainfall, inflows, currents, stratification, winds, existing *Undaria* monitoring/eradication data
Deploy ADCPs on moorings for 3 monthly periods within Breaksea Sound to characterise local water movement and direction
Setup MIKE3 Model using broad scale forcing and calibrate against existing data
Provide input to planning of field data collection to refine the MIKE3 Model
Total (Stage 1)
Stage 2: Refine model and provide input to longer term planning
Refine model based on site specific data and inclusion of *Undaria* life cycle behaviour, estimates of potential management options and habitat mapping

3.2.5 Step 5. Continued biomass removals (Aug-Oct) and Monitoring (Nov-Dec) (2020-2024)

Following a decision to proceed with control efforts in early 2020, we recommend a further four years of targeted biomass removals (Aug-Oct) and monitoring dive surveys (Nov-Dec). The hydrodynamic model should inform this step. Specifically, it should identify areas that should be targeted for removals (i.e. locations from which spore/fragment dispersal would be particularly problematic) and monitoring (i.e. locations which are predicted as having high chances of spore/fragment settlement). As was recommended in Steps 1 & 2 above, we recommend that control and monitoring teams work somewhat independently to maintain objectivity in assessments of success but also collaboratively - communicating/sharing information to ensure the success of both objectives.

In assessing whether removals are having a positive effect the two key considerations are:

(a) Has *Undaria* spread to new sites outside of the previous year's incursion boundary?
(b) Has the biomass of *Undaria* removed relative to effort, increased since the previous year?

If monitoring answers yes to either question, then a decision will have to be made early the following year about whether to modify/adapt the control programme and how to do so (Fig 9). At the end of five years i.e. early 2025, a decision should be made as to whether the control response continues or not based on an assessment of control efforts to date and the feasibility of continued control (Fig 9).

3.3 Measures to Support Steps 1-5

Additional to Steps 1-5, supporting measures namely (1) research focused on the impact of *Undaria* in Fiordland and new tools for control (2) and vector management will play an important role in increasing the chance of successfully controlling *Undaria* in Breaksea Sound.

3.3.1 Research to support Control Efforts

Ecological Effects of Undaria in Fiordland

Existing studies on the ecological effects of *Undaria* do not provide any clear answers as to whether *Undaria* has positive or negative impact on invaded ecosystems. There is also in particular, a lack of information, on *Undaria's* possible effect on community structure and ecosystem function in Fiordland – a system that differs markedly from other coastal marine systems. Research that tests the physiological limits of *Undaria* relative to light and salinity, impacts on black coral, and pre/post biomass removal effects will be informative for control efforts and several of these have already been assigned as student projects at the University of Otago.

Tool Development

Given that *Undaria* is likely to be a continued threat to Fiordland, there is also significant scope for research into new tools for control/eradication. These may include physical tools like the super sucker dredge used in Hawaii (1.1.1(c)), or genetic tools for identification of *Undaria* (eDNA/eRNA), or the elimination of individuals (e.g. Gene Drive, Webber et al. 2015, Collins 2018). While there are considerable avenues for the development of new tools in the fight to control invasive species the reality is this will require significant investment both in terms of time and money – and this should be entirely separate from the operation of a robust control programme.

3.3.2 Vector Management

At present, there are four primary mechanisms used to manage human mediated pathways for *Undaria* into Fiordland additional to the Biosecurity Act 1993, and International Guidelines for ballast water management (Section 2.5). One of the four, the Southland Regional Pest Management Strategy is currently under review (as the proposed Southland Regional Pest Management Plan) thus it will not be described here except to mention that *Undaria* is listed under the strategy, as a containment pest.

The Fiordland Marine Biosecurity Plan (FMBP)

The FMBP provides a framework for interagency operational activities related to marine biosecurity in the Fiordland Marine Area. This plan is focused primarily on preventative measures with response preparedness and control measures following as secondary objectives. MPI is the lead agency under the FMBP, responsible for its implementation however coordination and cooperation with partner agencies (DOC, ES, MfE, and the Guardians) is a key component of the plan and ES take the lead on many aspects of this work. Operational activities under the FMBP relevant to the *Undaria* incursion in Breaksea Sound include consultation with stakeholders on marine biosecurity in Fiordland, development of the Fiordland Marine Regional Pathway Management Plan, vessel monitoring in Bluff Harbour and Stewart Island, and maintenance/enforcement of anti-fouling requirements.

Fiordland Marine Regional Pathway Management

The Fiordland Marine Regional Pathway Management Plan 2017 ("Marine Pathways Plan") established under the Biosecurity Act 1993 and launched in April 2017, is aimed at minimising the risk of marine pests including *Undaria* from being transported into the Fiordland Marine Area. The principal measures implemented under the Marine Pathways Plan include requiring vessel owners/operators entering or operating within one nautical mile of the FMA to hold a Fiordland Clean Vessel Pass, clean hull, gear, residual seawater, and bilge water procedures, monthly hull inspections at Bluff and Stewart Island, and compliance, enforcement, and communications programmes. The management agency responsible for implementing the Marine Pathways Plan is the Southland Regional Council/ES.

Controlled Area Notice

On December 21 2017, Environment Southland created a controlled area, under Section 131 of the Biosecurity Act 1993 that extends along the southern edge of Breaksea Sound, including the John Islands, and the Harbour Islands. Within the controlled area vessels are prohibited from anchoring and can only occupy a mooring for a maximum duration of 48 hours. In addition, marine gear or equipment cannot be transported out of the area, dive gear used within the controlled area must be treated or dried prior to use outside of the controlled area, and residual seawater collected within the area must be treated or discarded within the controlled area (Controlled Area Public Notice, Environment Southland). Persons found to be non-compliant with the controlled area notice may be subject to penalties under the Biosecurity Act 1993, including the loss of items that have been moved in contravention of the Controlled Area Notice.

Ensuring Compliance

In remote locations, regulatory mechanisms can be difficult to enforce. Since implementation of the Marine Pathways Plan for example, more than 250 Clean Vessel Passes have been issued but there are still operators (local and visiting) who are non-compliant. In January 2019, a vessel in Fiordland with an expired CVP was suspected of carrying the invasive Mediterranean fanworm (*Sabella spallanzanii*), and another two vessels were found in Fiordland without CVPs. Operators who do not have a CVP cannot be fined for non-compliance, but are liable for the costs of hull inspections and clean up.

To prevent the spread of *Undaria* throughout Fiordland, it is imperative that vessels, particularly those that frequent Breaksea Sound are subject to regular inspections to ensure compliance with CVP requirements and Controlled Area rules.

Other containment measures

There are a number of artificial structures within the incursion area including mooring lines, mooring blocks, and vessels. These structures are potential colonising substrate for *Undaria* and more importantly possible vectors for transport of *Undaria* out of Fiordland. Thus restricting movement of these vectors (i.e. quarantine) or requiring regular inspections and/or decontamination of these structures would minimise their risk. The authority to require this, is contained within the Biosecurity Act 1993 provision used to create the Controlled Area however provided there is cooperation from affected users (e.g. owners of moorings) voluntary movement controls could suffice. Public awareness materials i.e. increased signage, could also aid in ensuring compliance.

Part 4. Conclusions

The Fiordland marine area is exceptional - unlike no other in New Zealand, and indeed the world. Invasive species like *Undaria,* pose a threat to the structure and function of this marine ecosystem thus something must be done in response. While the extent of the current *Undaria* incursion in Breaksea Sound appears to be too large for eradication to be a viable option given existing resources and tools, controlling *Undaria* within Breaksea with a robust programme should be possible. By implementing a well-informed, control programme supported by research and vector management, the potential for *Undaria* to disperse throughout Fiordland should be reduced and we will buy some time for new technologies for eradication to be developed.

Key to the success of a control programme are a number of operational requirements including funding, capacity, and expertise. Without consistency and reliability in these, any control response will be undermined. In addition, decisions need to be evidence based and the control response needs to be adaptable: flexible enough to incorporate what is learned from previous efforts, thus increasing efficiency and the likelihood of success.

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Appendix 1: Summaries of unsuccessful *Undaria* eradication attempts

A1.1 Southland

As had been the case in the Marlborough Sounds, Golden Bay and the Firth of Thames, the introduction of *Undaria* was thought to be related to aquaculture. In April 1997, DOC conducted a survey of Big Glory Bay and a formal monitoring and removal programme was initiated by the Southland Conservancy. Cabinet subsequently allocated \$163 000 in funding to DOC for eradication. Eradication from Big Glory Bay was believed to be possible because the invasion was restricted to a few marine farms, farm equipment and one section of shoreline. Action consisted of monthly sporophyte removals from artificial structures and natural habitats plus monitoring and removal of sporophytes from infected vessels. This action was extended to Bluff Harbour on the discovery of *Undaria* in 1998. Concurrent to the monthly control surveys vessels in ports further north (Oamaru, Timaru, Moeraki, Otago) were also monitored for sporophytes, and heat and chemical treatments were trialled as a means to target gametophytes. Sodium hypochlorite was trialled for floating structures in Big Glory Bay, while brominated microbiocide Amersperse 261-T was considered in Bluff harbour.

From 1997 to 2004, the annual number of sporophytes that was removed from Big Glory Bay went from approximately 17 000 to 200 representing close to 1% of the initial density. In Bluff, the number of sporophytes was reduced to just 4-5% of the initial density. During this time approximately \$2.2 million was invested in the response programme, however, the removals did not result in eradication (Stuart & Chadderton 2001). Alarmingly, *Undaria* was recorded on 39% of all vessels monitored between 1998-2001 (Forrest & Hopkins 2013). In 2004, *Undaria* discovered at Half Moon Bay (Stewart Island) indicated a failure by the response to prevent the spread of *Undaria*. Despite the Sinner et al. report recommending that the focus for response be on areas of high value, Cabinet in 2004 chose not to continue funding for the *Undaria* response program given the continued spread of *Undaria*. Thus, the only management response that remained in force for *Undaria* was through general vector management i.e., inspections of vessels travelling to the sub-Antarctic Islands.

After a 3-year hiatus, renewed concerns over the threat of *Undaria* spreading to Fiordland prompted efforts at control again in 2007. This time, efforts were concentrated at Bluff Harbour and consisted of the removal of *Undaria* from wharf piles and seabed areas immediately adjacent to vessel berths, and vessel monitoring. While there were some manual removals, the primary control method was encapsulating wharf piles and parts of the seabed in plastic to kill *Undaria* via shading and anoxia (Coutts & Forest 2007). Efforts were discontinued in 2009 when partial control was deemed ineffective (Forrest & Hopkins 2013).

A1.2 Victoria, Australia

Undaria was first detected in Victoria in 1996, on a shallow basalt reef near Point Wilson in southwest Port Phillip Bay (Crockett et al. 2017) An *Undaria* control research project was initiated in which volunteer divers removed *Undaria* by hand from three adjacent 200 x 50 m plots near Point Wilson. Divers (between 21-33) removed 45 000 plants from the plots with 95 hours of diving spread over three months. Surveys following removals found that *Undaria* abundance increased, even on the plot that received 54 hours of clearance effort. Thus, eradication was considered unfeasible at this site (Officer 1997 cited in MES11, 2015). Surveys in years following found *Undaria* in patches on the west coast of Port Philip Bay and in St Kilda Harbour but not in between. The initial introduction was attributed to contaminated ballast water or ship hull fouling, while the patchy spread of *Undaria* throughout Port Phillip Bay is believed to have been caused by recreational or fishing vessels (Primo et al. 2010).

In 2009 *Undaria* was found in Apollo Bay (124km south west of Port Phillip Bay), and it is now one of the dominant kelp species in the area. Options for eradication were considered, but the population is currently being managed to reduce the risk of further spread. *Undaria* is harvested from Apollo Bay during the active growing season (Sept-Dec) and between 2012-2014 there was a noticeable decline in biomass. Surveillance includes, two divers swimming transects equating to 0.3-1.1% of total reef area in the 0-5m depth range in Apollo Bay harbour. Given the area being surveyed (< 1% potential *Undaria* habitat) the probability of detection is very low. Anecdotally, half the vessels berthed in Apollo Bay harbour have *Undaria* growing on them which does not bode well for containment.

In September 2018, a significant infestation of *Undaria* was also found at Port Welshpool (150km south east of Port Phillip Bay). Given the extent of the incursion, eradication does not appear to be feasible (Kelly 2018).

1.3 Tasmania, Australia

Undaria was first discovered in Tasmania in 1988 at Rheban on the east coast of Tasmania (Sanderson 1990), although anecdotally, the species had been present since 1982 (Sanderson 1990). Its introduction was believed to be the result of ballast water discharge from ships transporting woodchips between Triabunna in Tasmania and Japan (Sanderson 1990). It has since spread northwards up to 150km and southwards 80km. In January 1997, 351 *Undaria* sporophytes were found in the Tinderbox Marine Reserve, (approximately 100km south west of the original incursion) an area of diverse habitats and high biodiversity value. Because of the high value of the marine reserve and its proximity to a CSIRO Marine Laboratory, a controlled experiment evaluating the effectiveness of regular manual removal was conducted. In July 1997, four permanent belt transects perpendicular to shore were established. Measuring 50 x 4 m, they encompassed an area 50 x 16 metres. Divers swam transects monthly (September 1997-April 1998 and June 1998-March 1999) removing sporophytes from 2 x 2 m quadrats. Manual removal significantly reduced sporophyte density in the targeted area but did not result in permanent eradication (bearing in mind the experiment was not designed as an eradication programme) and concerns were raised over the long term effect of diver associated ‘trampling’ on native biota during the removals (Hewitt et al. 2005)

1.4 Monterey Bay, California

Undaria was found in Los Angeles harbour in 2000 (Silva et al. 2002) and soon spread to other southern California ports. It currently ranges from San Francisco Bay (170 km north of Los Angeles) to Ensenada, Mexico (287 km south of Los Angeles) (Zabin et al. 2009, Kaplanis et al. 2016). In many locations *Undaria* has been found attached to floating docks in harbours typically depauperate of other macroalgae (Thornber et al. 2004).

In August 2001, immature *Undaria* was discovered in Monterey Bay, an area of high value, known for its natural and economic importance. Divers surveying boats and docks throughout Monterey Harbour later discovered and removed 79 individuals in October 2002 and a topside survey of floating docks in 2003 found that *Undaria* had spread widely throughout the harbour. In response, the Monterey Bay National Marine Sanctuary (MBNMS) sought external funding to support systematic removal of *Undaria*. The goal of the *Undaria* Management Program, a collaboration between MBNMS, the City of Monterey, and the California Department of Fish and Game, was to control the species in Monterey Harbour using manual removal. Beginning in December 2002, volunteers (divers and topside) removed *Undaria* by hand from docks in Monterey Harbour. The goal was to remove all visible *Undaria* before they matured. *Undaria* removed by divers was placed into ‘goodie’ bags and brought to the surface where it was processed by dockside volunteers then disposed of in dumpsters. Dockside volunteers kept track of the number of individuals collected from each site, their lengths, whether there was evidence of damage and their reproductive status. Data from these collections was entered into an excel database maintained by MBNMS staff and volunteers. Between December 2002 and July 2008, 17 522 individuals from 120 field days were removed and entered in the database (though the numbers removed are likely to be higher because when removal densities are high, *Undaria* was subsampled). Removal was thought to reduce the rate of spread both within and outside of Monterey Harbour, restore the native community, and reduce the reproductive capacity of the existing population (Lonhart & Bunzel 2009). Removals occurred monthly for six years.

Systematic dive surveys were also conducted within the harbour with extra attention given to rocky substrate, pier pilings, and other man-made structures. Dives were timed searches ranging from 2-10m in depth and occurred monthly with 2-4 divers. If *Undaria* was found in a new area, divers would use belt transects or survey the entire structure and adjacent structures. Surveillance dives were also conducted each October from 2004 to 2007, outside Monterey Harbour by the California Department of Fish and Game. By February 2005, *Undaria* density was significantly lower (< 100 individuals) in the majority of the harbour. Unfortunately, removal efforts appear to have ceased as of 2010 because of a lack of funding (sanctuarysimon.org) and *Undaria* is still prevalent within Monterey Harbour.