

**Pilot trial for large-scale
management of *Undaria
pinnatifida* in the Fiordland
Marine Area**

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Executive Summary

Undaria pinnatifida is considered to be one of the most invasive marine algae species in the world. Present in New Zealand since 1987, *U. pinnatifida* is a potential risk to native algal species and ecosystems due to its highly opportunistic nature, fast growth, microscopic life stages and high reproductive output. Consequently, there has been significant effort and money put into control, suppression and eradication. Most effort has centred on populations within the Fiordland (Te Moana o Atawhenua) Marine Area (FMA), where it was first discovered in 2010. The marine ecosystems within the FMA are globally unique and contain exceptional marine biodiversity and valuable marine resources, thus suppression and eradication of *U. pinnatifida* from this region is a high priority. Since 2010, there have been ongoing surveillance and removal activities throughout the FMA, though particularly within Te Puaitaha/Breaksea Sound. Manual hand removal of plants has been the primary removal method and while effective, little research has been carried out to test other methodological approaches which may improve overall removal effectiveness and/or efficiency over a large scale.

In this study, the application of a diver-operated suction dredge was trialled, and compared with manual hand removal to evaluate *U. pinnatifida* removal effectiveness and/or efficiency. In November 2022, three large plots totalling approximately 1 ha in size were cleared of *U. pinnatifida* using a diver-operated suction dredge within Te Puaitaha/Breaksea Sound. The suction dredge used for the trials was set up on a floating barge and towed into position ahead of each site being cleared. The dredge had an eight-inch nozzle and was operated by a diver using a surface supplied breathing apparatus (SSBA). Additional SCUBA divers systematically cleared *U. pinnatifida* from the reef, feeding removed biomass into the dredge as they went. Three large, similar-sized sites in the same area were cleared by hand following the existing methodological approach. All sites were cleared from 0 m to 20 m deep and contained a variety of substrates, habitat types and relief profiles typical of the FMA. Monitoring pre-removal (November 2022), immediately post-removal (November 2022) and four months later (March 2023) provided information on tool effectiveness (reduction in *U. pinnatifida* density) while diver times and removal metrics were used to assess tool efficiency.

We found that the diver-operated suction dredge was an effective tool for reducing *U. pinnatifida* densities. Following removal efforts, monitoring found that *U. pinnatifida* densities were reduced by between 84%–91% at 6 m and 3 m respectively. Although we were not able to directly compare this to current hand removal effectiveness, video monitoring of plots cleared by hand and by suction dredge showed very similar levels of effectiveness. Divers working within the suction dredge plots had limited experience identifying *U. pinnatifida* prior to removal trials and were able to pick up the skills required (clearance technique and identification) in a matter of days. It is expected that effectiveness would improve further as identification and removal experience increased. Consistently high removal rates were found across the range of substrates, habitat types and relief profiles tested.

Within shallow areas (< 9 m), *U. pinnatifida* removal via the suction dredge was significantly faster than hand removal (2.2 m² cleared per minute vs 0.87 m² cleared per minute) and this was consistent across a range of removal biomasses tested. Greater efficiency was likely due to a streamlined removal process which avoided the need to continually place removed biomass into catch bags and ferry these to a support vessel. In depths > 9 m, where *U. pinnatifida* densities were extremely low, suction dredge operations were more cumbersome and largely impractical.

The pilot trial demonstrated that a diver-operated suction dredge is a feasible tool for large-scale management of *U. pinnatifida*, even in remote locations such as the FMA. Managers can expect high levels of removal effectiveness across the range of habitat types, substrates and relief profiles expected to be encountered within the FMA and greater removal efficiency, particularly in shallow areas of dense biomass. This method should be considered when planning future work programmes. Its use, in conjunction with hand removal, is likely to create better overall outcomes for the containment, suppression and potential eradication of *U. pinnatifida* from the FMA.

The following key recommendations are made for improvements to the methodological approach and any future adoption as a management option.

- The use of a suction dredge should be incorporated into future *U. pinnatifida* management plans as a viable tool for addressing shallow water (< 9 m) areas of medium to high density (> 1 plants/m²).
- Dredge use may be beneficial where:
 - Large-scale (> 1000 m²), dense (> 1 plants/m²) infestations have already been identified.
 - The vessel housing the suction dredge has the capacity to immediately process (mulch with or without heat treatment depending on season) biomass and return it to the ocean so that no handling of biomass onboard is required.
 - Dive teams can carry out scouting and surveillance at the beginning of a control trip and identify areas where the dredge would be suitable before it is set up.
- Dredge use may not be beneficial where:
 - The system is set up, but dive teams need to search ‘on the fly’ for suitable areas for dredge use.
 - Densities of *U. pinnatifida* are low (< 1 plants/m²) or only patchy or small areas (< 1000 m²) of dense infestation are present
- Teams operating a suction dredge require divers with experience with suction dredge operations and expertise in identifying and removing *U. pinnatifida* at all life stages and distinguishing between this and native algae species. Divers experienced in *U. pinnatifida* removal and identification are particularly important for ensuring inexperienced divers are brought up to speed quickly.
- The vessel holding the suction dredge equipment needs to be self-propelled to facilitate efficient removal over continuous sections of coastline.
- If suction dredging is to become a major component of the *U. pinnatifida* management programme the purchase, lease or construction of a dedicated vessel (day-use barge or self-sufficient vessel) should be scoped.
- Greater attention to how the risk of spore release from the barge or work vessel is managed is required. This would include assessing options for treating water/plant matter as it came onboard and assessing the trade-off between potential changes in efficiency between plant stands dominated by juvenile or adult plants and the risk of spore spread.

1. Introduction

1.1. Marine bioinvasions

The accidental or intentional spread of organism outside of their native range (termed bioinvasion) can have a profound adverse impact on native biodiversity and ecosystem function (Hobbs & Mooney, 2000). Bioinvasion is considered as one of the major factors influencing global biodiversity declines and can lead to major economic losses for a wide range of industries (including agriculture, horticulture, transport, and tourism; Bax et al., 2003; Hanley & Roberts, 2019).

Bioinvasions are particularly prevalent within marine ecosystems due to the high level of interconnectivity between oceanic bioregions (Epstein & Smale, 2017). The spread of non-indigenous species (NIS) occurs primarily through shipping (e.g. hull fouling, ballast water), however other vectors such as aquaculture and the aquarium trade also play an important role (Bax et al., 2003). While effective border controls are the best protection against the spread of NIS, detection can be difficult as many species have microscopic life stages and occur in relatively inaccessible habitats (Epstein & Smale, 2017). This means that some species will inevitably settle and establish in new locations where they have the potential to significantly impact native species and the surrounding ecosystems (Gallardo et al., 2015). As of 2010, Australia had a record of 248 marine species that were classified as invasive or cryptogenic (Hewitt & Campbell, 2010), New Zealand totaled 377 recorded NIS species in 2018 (Seaward & Inglis, 2018) and the European Union has classified 640 NIS throughout European Waters as of 2023 (European Environment Agency, 2023).

1.2. *Undaria pinnatifida*

Algae species contribute significantly to the overall make up of marine NIS globally. There are examples of non-native algal species on every continent, excluding Antarctica, and within Europe more than 40% of all marine NIS are algae (Li et al., 2023). Invasive algae species can act as ecosystem engineers and have the potential to functionally modify an environment, alter community composition and dynamics, and disrupt important ecosystem services (Epstein & Smale, 2017). Despite this, only two species (the kelp *Undaria pinnatifida* and green seaweed *Caulerpa taxifolia*) are listed by the Invasive Species Specialist Group within the 100 worst invasive alien species (Global Invasive Species Database, 2023).

Undaria pinnatifida is a laminarian kelp native to northeastern Asia, with extensive populations found throughout Japan, China and North and South Korea. As with other kelp species, the *U. pinnatifida* lifecycle includes a microscopic gametophyte phase and a macroscopic sporophyte phase. It tolerates a relatively wide temperature range (5–27 °C), grows on a variety of substrate types and has an annual lifecycle that is characterised by rapid growth and high fecundity (Primo et al., 2010; Schiel & Thompson, 2012). This combination of characteristics has aided its spread globally and it is now found throughout the Pacific and Atlantic Oceans as well as the Mediterranean and North Seas (James et al., 2015; South et al., 2017). This includes New Zealand, where it was first discovered in Wellington Harbour in 1987 and has since been recorded across the entire length of the country (James et al., 2014). Due to the duration of time *U. pinnatifida* has been in New Zealand, it is now one of the most studied bioregions in the world in terms of *U. pinnatifida* dispersal, biology, ecology, and management (as reviewed by South et al., 2017).

1.3. *Undaria* management

Although the level of threat posed by invasive *U. pinnatifida* is highly debated (see reviews by James, 2016 and South et al., 2017) there have been a number of studies investigating control, suppression and eradication techniques (see Keeler-May, 2022). The eradication of a marine NIS often requires a rapid, well-resourced response following the initial detection, however there can be considerable lag between detection, definitive identification, determination of status and action (Epstein & Smale, 2017; Green & Grosholz, 2021). There are also limited operational tools to effectively manage NIS especially on a large scale on natural substrate. This inevitably hinders response speeds to the point where in many situations eradication is no longer possible and effort is directed towards containment and suppression (Green & Grosholz, 2021). *Undaria pinnatifida* management globally has largely focussed on control and suppression with only one study demonstrating 100% eradication. This was the eradication of all plants from the hull of a sunken vessel in 2001 off the coast of the Chatham Islands, New Zealand (Wotton et al., 2004). Here visible sporophytes were removed from the ships hull and then areas where sporophytes had been present were treated with hot water to kill the microscopic gametophytes (Wotton et al., 2004). Follow up monitoring over a three year period confirmed 100% mortality with no evidence of recolonisation.

Manual hand removal of sporophytes is the most common form of removal with most control and suppression programmes, requiring frequent repeat hand clearances over multiple months/years (e.g., Hewitt, et al., 2005; Hunt et al., 2009). This approach has been shown to be highly effective and can achieve between 80%–99% reductions in biomass over time if adequately resourced. Continued monitoring is also important for understanding the effectiveness of control measures, and to detect any new spread away from areas being actively managed. For example, monitoring dives in 2017 outside of the Sunday Cove Control Area within Te Puaitaha/Breaksea Sound, Fiordland, New Zealand identified additional high density stands of *U. pinnatifida* which have since become the target of an expansive, multi-year and multi-agency control and suppression programme (Gnanalingam & Hepburn, 2019).

Fiordland is recognised for its relative isolation and unique, high conservation value and the Fiordland National Park, which encompasses 12,000 km² of land in the southwestern corner of New Zealand's South Island, was established in 1956. The designation of Fiordland as a UNESCO World Heritage Area (WHA) in 1986 further reinforced the environmental significance of this region. Although the National Park and WHA status does not extend into Fiordland's marine environment, it is of no less significance in terms of its uniqueness and value (Gnanalingam & Hepburn, 2019; Keeler-May, 2022). In 2005, the FMA was established alongside the Fiordland Marine Guardians (Guardians), a collective of stakeholders that represent the commercial, recreational, tourism and environmental interests within Fiordland. The Guardians provide advice to specific government agencies on the strategic direction of management within Fiordland's marine environment. Given the isolated nature of Fiordland and the uniqueness of its marine environment, the potential risk posed by *U. pinnatifida* to native ecosystems is considered high and suppression and potential eradication of this species is a priority (Fiordland Marine Guardians, 2022).

Undaria pinnatifida was first discovered in Fiordland in 2010 at Sunday Cove, where a reproductive sporophyte was identified growing on a mooring rope attached to a barge. This triggered a large-scale, multi-agency response which aimed for local elimination (Gnanalingam & Hepburn, 2019). After the initial removal, surveillance and additional removals were carried out through until 2017. The discovery of plants outside of the Sunday Cove search area in 2017 effectively ended the eradication programme with effort shifting to

containing the spread of *U. pinnatifida*. Since 2017, *U. pinnatifida* has been largely restricted within Te Pūaitaha/Breaksea Sound to Beach Harbour, the Harbour Islands, John Islands, First and Second Cove, and the Sunday Cove area (Figure 1). Funding from the Jobs for Nature (J4N) initiative in 2021 provided the capacity for dedicated dive teams, jointly run by the Department of Conservation (DOC) and Environment Southland (ES), to conduct near continual surveillance and biomass removal trips within Te Pūaitaha/Breaksea Sound. It was only after the discovery of *U. pinnatifida* in Tamatea/Dusky Sound in November 2022, dive effort was spread across both fiords.

Containment and density reduction efforts since 2010 have mostly involved manual hand removal, though the use of chlorine under tarpaulins and the translocation of the sea urchin *Evechinus chloroticus*, ‘kina’, to act as a biocontrol agent were also trialed early in the response (Atalah et al., 2013; Gnanalingam & Hepburn, 2019). Plants removed by hand are pulled from the reef, or cut below any visible sporophyll tissue, by divers and placed into a plastic bags (for containment work) or catch bags (for biomass reduction work). Once full each bag is transferred to the surface and replaced with an empty one. Although this has proved to be largely successful in limiting the spread of *U. pinnatifida* to the wider Breaksea/Dusky Sound area there are still areas within Breaksea Sound that contain high densities and wider incursions such as the one in Dusky Sound in 2022 do occasionally occur. The trialling of new approaches, which may yield greater control effectiveness or improve overall efficiencies, has been limited, particularly over the past several years. Given the importance of controlling *U. pinnatifida* within Fiordland and the potential for ongoing work programmes, there is a need for further development of large-scale management approaches.

1.4. Purposes of the report

Alternative approaches to controlling *U. pinnatifida* populations include diver-operated suction dredges. Suction dredging uses compressed air flowing through a venturi nozzle or airlift system to create a vacuum that can effectively lift material from the water column or seabed to a nearby vessel (or directly to the shore) once removed by hand by divers. This removes the need to collect plant or other material in catch bags and return these to the surface periodically when full. The application of a diver-operated suction dredge has been successfully used for controlling other invasive algae species including *Euclima* sp. and *Kappaphycus* sp. from coral reefs in Hawaii (Neilson et al., 2018) and *Caulerpa taxifolia* and *C. prolifera* from soft sediment in Australia and California respectively (Industry and Investment NSW, 2009; Southern California Caulerpa Action Team, 2021) but testing is required to establish its usefulness in the context of *U. pinnatifida* in New Zealand and specifically over large spatial scales within remote coastal environments such as Fiordland.

In 2022, following a request for proposals released by Biosecurity New Zealand, large-scale *U. pinnatifida* removal trials were carried out in Te Pūaitaha /Breaksea Sound using a diver-operated suction dredge. The objective of the project was to trial whether the use of a diver-operated suction dredge could be effectively integrated into future work programmes aimed at the suppression and/or elimination of *U. pinnatifida* in Fiordland. To assess broadscale applicability and viability of techniques, the trials were required to be undertaken on a range of natural substrate types containing *U. pinnatifida* within Fiordland, in continuous areas between neap low water and 20 m depth and cover a minimum area of 1 ha.

This report details the approach taken to meet these objectives and provides a detailed methodological approach for the use of a diver-operated suction dredge within Fiordland. Results of the trials are discussed along with learnings and limitations identified during the

field trials. Key recommendations for further methodological enhancement along with the implementation into future work programmes are provided.

2. Methods

Experimental trials, testing the viability of a diver-operated suction dredge for removing *U. pinnatifida* from low intertidal and subtidal habitats, were conducted around the Harbour Islands, Te Puaitaha /Breaksea Sound (Figure 1), in early November 2022.

Six sites with similar depth profiles and reef characteristics were identified and within each a large experimental plot ($> 2500 \text{ m}^2$) was set up. Plots were randomly assigned to one of two methodological approaches or *U. pinnatifida* removal: diver-operated suction dredge or hand removal. Each methodological approach had three replicate plots and a total removal area of $> 1 \text{ ha}$. Plots where *U. pinnatifida* was not removed (i.e., control plots) were not set up for this trial. Given that J4N were planning to carry out major removal works to follow up on removal work in 2021 around the Harbour Islands between September 2022 and April 2023 and the high risk of spread and reestablishment from remnant patches of *U. pinnatifida*, it was considered inappropriate to leave $\sim 1 \text{ ha}$ of reef unmanaged throughout this time.

The discovery of *U. pinnatifida* at Duck Cove, Tamatea/Dusky Sound in early November 2022 meant that J4N personnel, who were working on clearing *U. pinnatifida* from the hand removal experimental plots, were redeployed to assess the extent of this incursion and remove all identified plants. Redeployment to Duck Cove occurred after suction dredge plots had been fully cleared, but before all hand removal plots in this study had been fully cleared. J4N personnel were able to return to the experimental sites in December 2022 to clear the remainder of the hand removal plots, however, this impacted some components of the data collection. These are specified in the sections below.

2.1. Site selection and experimental plot setup

In consultation with ES and DOC (who jointly managed the J4N *U. pinnatifida* biomass removal work in Breaksea Sound), the northern and western sides of the Harbour Islands were selected as the most appropriate trial locations (Figure 1). These islands are approximately two km northeast of Sunday Cove, the initial *U. pinnatifida* incursion site, and were known to contain high densities of *U. pinnatifida*.



Figure 1: Trial sites within Te Puaitaha Breaksea Sound, Fiordland. Sites in yellow were cleared by hand while sites in red were cleared with the assistance of a diver-operated suction dredge.

Site selection and experimental plot setup was carried out in September 2022 prior to November 2022 trials. The northern and western coastline of the Harbour Islands was snorkelled to identify and mark shallow (< 5 m) sites with high *U. pinnatifida* density (visually estimated at > 4 plants per m²). Because *U. pinnatifida* densities naturally decline with depth, selecting sites with high densities in the shallows was important to ensure that trials were carried out over a wide range of densities (instead of choosing low density sites which would have had broadly consistent densities between 0 m depth and 20 m depth). Sites were to have a minimum width of 50 m and contain rocky reef extended from 0 m (neap tide) to ~ 20 m (lowest astronomical tide; LAT). Once six high density sites were located, an experimental plot was set up within each as follows:

- Weighted leadline (marked at 5-m intervals) was used to define the lateral boundaries of (perpendicular to shore) of each site. Starting in the intertidal, lines were tied off to

overhanging vegetation, marked with flagging tape and reeled out to a depth of 20 m (LAT). A subsurface float and weight were attached to each line at depths of 5, 9, 15 and 20 m. These depths corresponded to the working depth limits for the commercial dive team who would conduct suction dredge removals.

- Weighted leadlines were then reeled out across each site approximately parallel to shore following the 5, 9, 15 and 20 m depth contours. Each line started and ended at the corresponding subsurface float for the given depth contour.
- A final leadline was reeled out down the centre of each site (perpendicular to shore) to divide the removal area in two subsections. Additional subsurface floats were attached to the line at depths of 5, 9, 15 and 20 m.
- The “edge zones” of each site were considered to be from the lateral boundaries to 15 m inside the removal area, with the centre (~ 30 m)

This resulted in each experimental plot containing eight discrete subsections, with two subsections for each depth band (0–5 m, 5–9 m, 9–15 m, 15–20 m; Figure 2). The approximate area of each subsection was calculated by measuring the length of each subsection boundary line (Table 1).

2.2. Ecological monitoring

Ecological monitoring was carried within all suction dredge trial plots in November 2022 immediately prior to and immediately after *U. pinnatifida* removal. A follow up survey (four months later) in March 2023 was also conducted. Ecological monitoring was conducted pre-removal on all hand removal sites, however due to the need to redeploy J4N personnel to address the Duck Cove incursion before all hand removal sites were fully cleared it was not possible for the post removal ecological monitoring to be conducted. Given the lack of post-removal information it was deemed unnecessary to collect ecological information, other than video surveys, from these sites during the March 2023 follow up survey.

2.2.1. Quadrat surveys

Ecological surveys, using 1 m² quadrats, were carried out at two depths: 3 m (0–5 m depth band) and 6 m (5–9 m depth band). Depth bands were depth-corrected so each survey was done at the same depth. Given the likelihood of representing extremely low *U. pinnatifida* densities in the 9–15 m and 15–20 m depth bands in these sampling methods, no quadrats sampling was carried out in either of the deeper depth bands.

At 3 m and 6 m, a 100-m transect tape was rolled out across the width of the site (from the true right margin to the true left margin; Figure 2). Data were then collected from a total of 16 quadrats along the length of the line. To capture any potential edge effects the first four quadrats were placed within 15 m of the true right edge and the last four quadrats were placed within 15 m of the true left edge (collectively termed the edge zones; Figure 2). All other quadrats were collected within the centre of the plot (termed the central zone; Figure 2). Quadrat placement along the length of the line was random within each zone. The following information was gathered from within each quadrat:

- Distance (along transect)
- Depth (as recorded from dive computer and then corrected for tide)
- Dominant substrate type (bedrock, boulder, cobble, gravel, sand)
- Relief (flat/ near flat [$< 10^\circ$], sloping [10° – 60°], vertical/near vertical [$> 60^\circ$])
- Biological habitat:
 - Kelp forest (dominated by brown canopy forming macroalgae from the order Laminariales, i.e., *Ecklonia*, *Undaria*, *Macrocystis*)

- Mixed algae (dominated by an even mixture of fucalean and laminarian species)
- Urchin barren (sea urchin present, devoid of macroalgae, dominated by crustose coralline algae and bare rock)
- Turfing algae (dominated by short [< 5 cm tall] species of algae, urchins may or may not be present)
- Bare rock (bare rock not clearly grazed by sea urchins or other invertebrates)
- Other habitat, e.g., submerged trees
- *U. pinnatifida* density (no. individual plants per m^2)
 - Density of juvenile plants (no reproductive sporophylls present)
 - Density of adult plants (reproductive sporophylls present)
- Native macroalgae densities
 - Density of *Ecklonia radiata* (adult [> 25 cm]/juvenile [< 25 cm] per m^2)
 - Density of *Carpophyllum* sp. (whole plant, adult [> 25 cm]/juvenile [< 25 cm] per m^2)
 - Density of all other fucalean and laminarian species (whole plant, adult [> 25 cm]/juvenile [< 25 cm] per m^2).

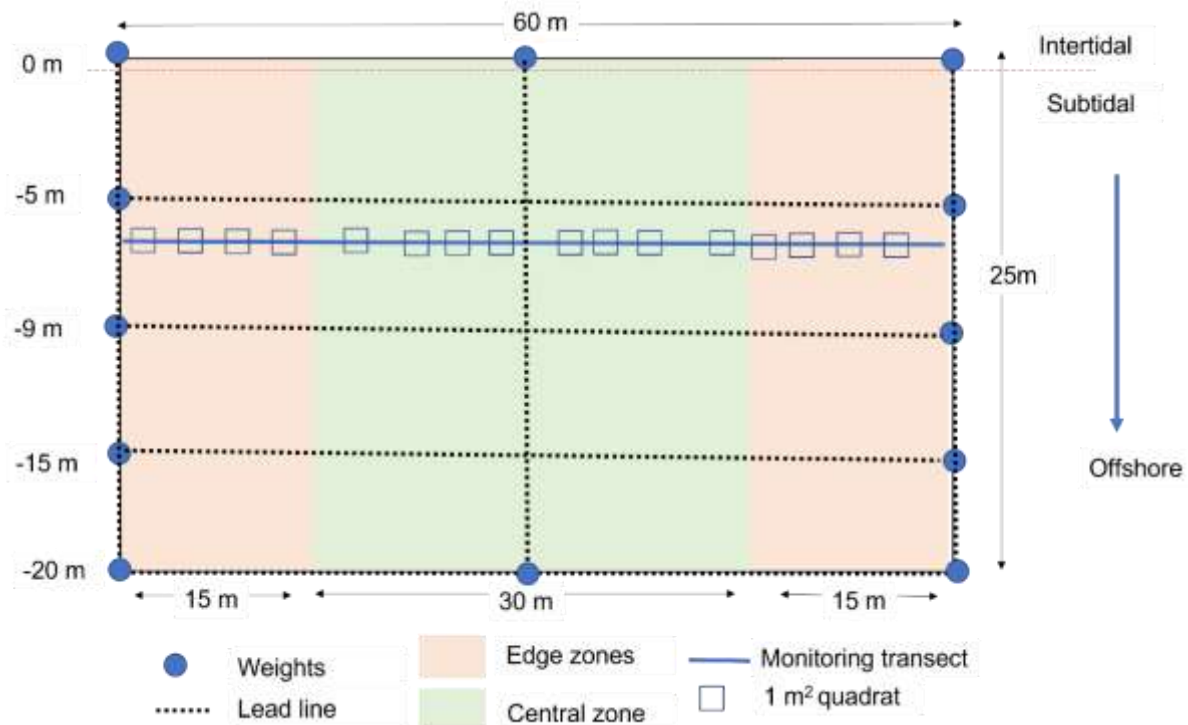


Figure 2: Plot layout and monitoring design. Hypothetical length and width dimensions.

2.2.2. Video surveys

For visual representation of each plot a video survey was also collected within each depth band. Video footage was collected at:

- 3 m (within the 0–5 m depth band) - along same transect as for quadrat survey
- 6 m (within the 5–9 m depth band) - same as quadrat survey
- 11 m (within the 9–15 m depth band)
- 16 m (within the 15–20 m depth band)

All depths were tide corrected before divers entered the water. Video footage was captured using a GoPro™ Hero 9/10 with video lights. A diver swam slowly across the transect ~ 1 m above the seafloor. Because no transect lines were rolled out in the deeper depth bands the 11

m and 16 m depths were chosen so that a diver could use a visible depth contour leadline to help guide a straight path across the plot. Within the shallowest depths, the transect lines were used to guide divers across the plot.

2.3. Removal methods

Following the first ecological survey, divers attempted to remove all *U. pinnatifida* from each of the six plots. For the three plots where the use of a suction dredge was trialled, the removal personnel included four commercial divers and a dive/dredge supervisor. All divers were experienced in the operation of the suction dredge, but not specifically in carrying out *U. pinnatifida* removal. The three hand removal sites were cleared by a five-person J4N team. This included four divers and a dive supervisor. All divers were experienced in carrying out *U. pinnatifida* removal. For all dive operations, one diver in the dive team was always acting as a standby diver when divers were in the water (i.e., in gear on the vessel, monitoring divers and ready to assist in the case of an emergency).

2.3.1. Suction dredge set up, operation and removal process.

The suction dredge used for trial removals was a Texas Pneumatic TX8AM 8" Air Mover 5435 CFM. The dredge was operated using an airlift system which relied on compressed air being pumped into a submerged dropper pipe, creating a pressure differential that enabled water and floating material (in this case removed *U. pinnatifida* plants) to be 'lifted' upwards through the pipe. The main components of this system included:

- A compressor for supplying compressed air to the submerged dropper pipe.
- A 6 m dropper pipe.
- A Camlock system to connect the dropper pipe and airlift.
- An airlift for supplying compressed air into the submerged dropper pipe. The airlift also had lifting eyes which were used to winch the dropper pipe up and down during operation, at the end of each day and while the barge was being towed.
- A second Camlock system to connect the airlift and suction hose.
- A 20 m coil of suction hose.
- A third Camlock system to connect the suction hose and suction headpiece.
- A suction headpiece (nozzle).

A venturi system was also added to the setup as a backup, in case the airlift system failed, or greater lift capacity was required, however this was not needed.

Dredge components were transported to site on M.V. Flightless at the start of the trial and set up on a 6 m non-powered barge. The barge was supplied by Meridian Energy and modified by Meister Solutions and was towed to site prior to the start of the project. This acted as the primary work platform for all trials utilising the suction dredge, with support provided by M.V. Flightless. Along with the suction dredge, the barge contained a sorting table, diver supervisor station with SSBA air supply, a dive platform for easy access to and from the water and fadges for storing removed biomass (Figure 3). The initial setup of the suction system and barge took one day; breakdown at the end of the trial period took half a day.



Figure 3: Primary work platform for suction dredge removal trials: 1) Non-powered barge attached moored using ropes and anchors; 2) Plywood biomass sorting table; 3) 6 m dropper pipe. Picture fully raised but lowered into the water column during operation; 4) Dive supervisor station including SSBA air supply and communications; 5) Low-pressure compressor to supply airlift system; 6) Dive platform. 7) Fades for biomass collection.

For each experimental plot, the barge was towed into position and moored in place using ropes attached to the shore and anchors. Once the barge was moored in place the dropper pipe was winched down to working depth. Divers would then enter the water and attach the camlock, and airlift system to the bottom of the dropper pipe. Ensuring the entire 20 m length of hose was fully submerged and free of air, this would then be connected to the airlift section of the dredge and operations via a Camlock and operations were ready to begin. At this point the diver operating the dredge would signal the system was ready to go live and the compressor was turned on allowing water and plant matter to be ‘lifted’ onto the barge. The compressor typically operated at half capacity and the top of the dropper pipe was centred at the head of the sorting table, allowing rising water and biomass to be sorted on the table before being transferred into the fades.

In water, one diver-operated the dredge unit while the other divers, either one or two depending on depth and *U. pinnatifida* density, removed plants from the substrate and fed them into the dredge nozzle. Divers removing *U. pinnatifida* operated on SCUBA while the dredge operator used a SSBA as per WorkSafe regulations. The diver operating the suction dredge had a full face mask with communication capabilities. Starting from the shallowest subsection on the true right-hand side of each plot *U. pinnatifida* was systematically removed. Plants were removed, preferentially by pulling or levering off the substrate, however if this was not possible, they were cut below any visible sporophyll tissue. The dredge operator continually moved the dredge nozzle so that it was near where the divers were actively clearing plants (Figure 4). In most situations the diver operating the dredge nozzle was also able to clear plants from the area immediately around the dredge. Once

removal was completed the SCUBA divers did a secondary sweep to remove any missed plants and then moved down to the next subsection, repeating the process. Once all subsections on the true right side were cleared the dive team moved on to the true left side, again starting with the shallowest subsection. It was very quickly established that the dredge was impractical to use within the deepest depth band (15–20 m) due to slower, cumbersome movement and limitations in the length of the suction hose (restricting the operational radius). The 15-20 m subsections at Site 6 were cleared via suction dredging, however the 15-20 m subsections at Site 2 and 4 were cleared manually by hand and data associated with this subsection were not used for statistical analysis.



Figure 4: Underwater operation of the suction dredge: 1) *U. pinnatifida* plants (still attached); 2) Diver removing *U. pinnatifida* from the reef; 3) Suction dredge nozzle where plants are fed for transport to the surface.

2.3.2. Hand removal process

The hand removal process was carried out following standard J4N protocols. Teams of three divers would enter the water and remove *U. pinnatifida* from the substrate, either as whole plants or by cutting plants at the base below any present sporophyll tissue. Removed plants were placed in catch bags and taken to the surface where they were transferred to a vessel and replaced with empty bags. When working at depth two divers would actively remove *U. pinnatifida* while the third would snorkel at the surface and manage the catch bag transfer process. Full bags were attached to float lines and hauled to the surface by the snorkeller. These would then be detached, transferred to a supporting tender and the line sent back down to the dive team with empty bags. Dive teams worked systematically across each site starting in the shallowest subsection on the true right side of the plot. Once cleared the team would do a secondary sweep to remove any missed plants and then move on to the true left side of the plot and cleared this before moving down to the next depth band and repeating the process.

Site 1 was fully cleared during the November 2022 field work while Sites 3 and 5 were only partially cleared before J4N personnel were redeployed to Duck Cove. These sites were finished in December 2022.

2.4. Time recording and biomass measurements

Information was recorded detailing the dive time required to clear *U. pinnatifida* from each site and subsection as well as the total biomass collected. For each dive the specific dive number, number of divers (and/or snorkellers) in the water and subsection being worked on was recorded by the dive supervisor for the respective removal approaches. In water, divers noted which subsection they were working on and the dive time that they moved into another section, if this occurred during a dive, to ensure accurate time tracking of each subsection.

As *U. pinnatifida* was lifted onto the barge via the suction dredge, it was sorted into adult (sporophyll tissue present) and juvenile (no sporophyll tissue) plants and counted. After counting, plants were placed into fadges and transferred to the support vessel where they were weighed. Care was taken to ensure plants from different methods and subsections were not mixed so that each subsection had a count of juvenile and adult plants alongside a corresponding total removal weight. Hand removal catch bags were taken directly to the support vessel and placed into fadges for weighing. Partial counting was done for plants removed from Site 1 but not for Site 3 and Site 5.

Plant counts and life stage differentials were not carried out for the two hand removal sites (Site 3 and 5) that were finished in December 2022. This was because these removals fell outside of the allocated fieldtrip timeframe and there was not enough personnel availability to manage this process. For these sites only removal weight was recorded for each subsection.

2.5. Disposal

It was initially intended that disposal via boiling plants in a water bath would be used as part of the project; however, it was quickly established, following a sample trial, that this was feasible given the size of the water bath available and the volume of *U. pinnatifida* being brought onboard. Besides from plants treated with hot water the majority of *U. pinnatifida* was disposed of at the DOC approved disposal site on the mainland behind the Harbour Islands for the J4N biomass removal work.

2.6. Data analysis

Data analysis was undertaken to inform both the effectiveness and efficiency of the suction dredge removal trials.

Effectiveness was measured in terms of density differences between pre- and post- removal monitoring as well as the follow up monitoring carried out in March 2023. It was not possible to compare the quantitative results of the suction dredge removal trials against those of the hand removal trials due to a lack of post monitoring ecological data from the hand removal sites.

Suction dredge effectiveness was assessed in respect to:

- Changes in overall *U. pinnatifida* density,
- Changes in adult *U. pinnatifida* density,
- Changes in juvenile *U. pinnatifida* density,
- Potential edge effects,
- Substrate type,
- Habitat type,
- Relief.

Changes in overall density, adult density and juvenile density were assessed using Two-way ANOVA with Period (Pre-, Post- and Follow up) and Depth (3 m and 6 m) as fixed factors. Changes in overall density near plot edges versus plot central areas was assessed using a

three-way ANOVA with Area (Edge and Centre), Period (Pre-, Post- and Follow up) and Depth (3 m and 6 m) as fixed factors. All tests were run using plot averages ($n = 3$). Data were first tested for normality and equal variance and where these assumptions were not met data were $\log(x+1)$ transformed. All tests were run on log transformed data. Tukey HSD post hoc testing was used to assess significant differences among or between factors.

Data for substrate types, habitat types and relief were only analysed for suction dredge removal plots. For these analyses data were pooled across all three experimental plots. This was because not all substrate types, habitat types or relief profiles were recorded within each plot and pooling therefore enabled sufficient replication for statistical analysis.

Substrate types were grouped into two categories: Boulder/Bedrock (B/BR) and Cobble/Sand/Shellhash (C/S/SH). Each category was analysed separately to minimise the risk of Type III errors in the data due to unbalanced sampling effort (many more samples within the B/BR category than the C/S/SH category). For each category, data failed to meet the assumptions of normality and heterogeneity of variance, even after log-transformation so non-parametric Kruskal-Wallis tests with Period (Pre-, Post- and Follow up) as a fixed factor were used to test for density differences. Wilcox post hoc testing was used to investigate any significant differences between periods.

Relief profiles were similarly tested at the level of individual categories to minimise the risk of Type III errors occurring. For each category (Flat, Sloping, Vertical), data failed to meet the assumptions of normality and heterogeneity of variance, even after log-transformation so non-parametric Kruskal-Wallis tests with Period (Pre-, Post- and Follow up) as a fixed factor were used to test for density differences. Wilcox post hoc testing was used to investigate any significant differences between periods.

A similar number of each habitat type was recorded across the three plots, so these data were analysed as one dataset, unlike substrate or relief. For habitat type the data failed to meet the assumptions of normality and heterogeneity of variance, even after log-transformation, so a two-way ANOVA on ranked data was performed with Habitat (Kelp, Mixed Algae, Turf and Urchin Barren/Bare Rock) and Period (Pre-, Post- and Follow up) as fixed factors. The ANOVA was still run using Type III sum of squares to account for the unbalanced nature of the sampling. Wilcox post hoc testing was used to investigate any significant differences between periods or habitat types.

Suction dredge efficiency was primarily assessed in terms of biomass removal rates. Two different metrics were analysed, the relationship between total dive time (minutes) and total removal weight (kg) and the relationship between removal rates (kg/minute) and biomass (kg/m^2). Both metrics were assessed at the level of subsection. Total dive time, removal rates and average site biomass were calculated as:

Total dive time = Sum of dive time per dive \times number of divers and snorkelers per dive.

Removal rate = total removal weight per subsection/total diver time per subsection.

Biomass = total removal weight per subsection/subsection area.

Total diver time did not include surface support time, e.g., standby diver and diver supervisor time because these are necessary for any operation regardless of the methodological approach.

An error in how the suction dredge time records were kept meant that the shallowest two subsections (0–5 m and 5–9 m) and deepest two subsections (9–15 m and 9–20 m) on either side of the plot (true right and true left) were recorded as a single time unit. Weight and area

values were therefore combined for each giving a 0–9 m and 9–20 m subsection on either side of each plot (a total of four subsections per plot instead of eight). For consistency the time, weight and area values in the hand removal sites were also combined. Because the deepest sections (15–20 m) within Site 2 and Site 4 were removed by hand (see [Section 2.3.1](#)), the time keeping error meant it was not possible to accurately account for clearance data associated with the suction dredge and hand removal within the deeper subsections, so these were excluded from statistical analysis. Efficiency analyses therefore focused on the shallow subsections only, with each site having two subsections (TR 0–9 m, TL 0–9 m) totalling six replicates per method.

Both relationships were assessed using linear mixed effects models with random slopes to account for the non-independence of time and weight values collected from different subsections within the same trial plot. The model testing the relationship between total dive time and total biomass removed had Method (Suction Dredge and Hand Removal) and Removal Weight as fixed factors while the model testing the relationship between removal rate and average site biomass had Method (Suction Dredge and Hand Removal) and Average site Biomass as fixed factors. Both models had total biomass (or average biomass) nested within Subsection \times Site as a random factor. The optimal models were fitted using backwards elimination of non-significant interaction terms.

Additional linear mixed effects models were also used to model the relationship between:

- number of plants removed (n) and total required dive time (minutes)
- total number of plants removed (n) and the total removal biomass (kg)
- the ratio of juvenile to adult plants (n) and removal rates (plants/minute)
- plant density (plants/m²) and plant removal rate (plants/minute)

These data were only available for suction dredge removal sites, so each model included one fixed factor (either total number of plants removed, ratio of juvenile to adult plants or average site density) and all had number of plants (or ratio of juvenile to adults, or average density) nested within subsection \times site as a random factor.

3. Results

3.1. Removal metrics

Three discrete plots were cleared of *U. pinnatifida* using a suction dredge in November 2022. This equated to a total clearance area of 1.14 ha (Table 1). An additional three sites were cleared by hand in November and December 2022 totalling 0.96 ha. (Table 1). Ecological monitoring prior to removal efforts found that average *U. pinnatifida* densities across the six sites were similar (Figure 5, Table 2, $F = 3.81$, $p = 0.06$). Average densities (\pm SE) were 12.8 ± 0.8 plants/m² and 5.1 ± 1.5 plants/m² at 3 m and 6 m respectively within the dredge removal sites and 17.5 ± 2.8 plants/m² and 9.7 ± 3.6 plants/m² within the hand removal plots. There was a significant depth effect across all sites ($F = 10.61$, $p = 0.001$), with higher *U. pinnatifida* density found at 3 m than at 6 m. Densities were largely driven by an abundance of juvenile plants. On average all sites had a higher number of juvenile plants than adults and the juvenile:adult ratio was greater at 6 m than at 3 m.

Suction Dredge:

In total 2401.4 kg of *U. pinnatifida* were removed from the suction dredge sites with > 99% of this (2383.4 kg) being removed from the 0–9 m depth band (Table 1). Removal consisted of 12443 adult plants and 35293 juvenile plants (Table 1). There was a significant positive relationship between the total number of plants removed and the total removal biomass ($t =$

8.98, $p = < 0.001$). Total dive time across all three sites within the 0–9 m depth band, where teams exclusively used the suction dredge, was 2428 minutes, or 40.5 hours (Table 1). Teams of two to three divers were in operation at any given time and SCUBA divers would return to the surface and change out tanks if they were running low before immediate return to clearance activities. An additional 798 minutes, or 13.3 hours was spent clearing the deeper sections, although this time was split between dredge use and manual hand clearance.

Hand removal sites:

In total 4932.5 kg was removed from the hand removal sites and again $> 99\%$ of this (4922.5 kg) was removed from the 0–9 m depth band (Table 1). Total diver time required for hand removal within the 0–9 m depth band was 6686 minutes or 111.4 hours (Table 1). Teams of two to three were in operation for any given dive, with a combination of two divers, three divers or two divers and a snorkeller depending on depth and biomass. Dives were limited to a maximum of 60 minutes and all divers returned to the surface at or before this time limit for each dive. An additional 208 minutes, or 3.35 hours was spent clearing the deeper sections of Site 1 and 3. The deeper sections of Site 5 were not cleared.

Within the 0–9 m depth band, where most of the time was spent, average dive times for the team working within the suction dredge removal areas were double those of the team working within the hand removal areas (84 ± 9.5 minutes vs. 42 ± 2.5 minutes), but clearance of all three sites was achieved in fewer dives (12 dives total vs. 55 dives total).

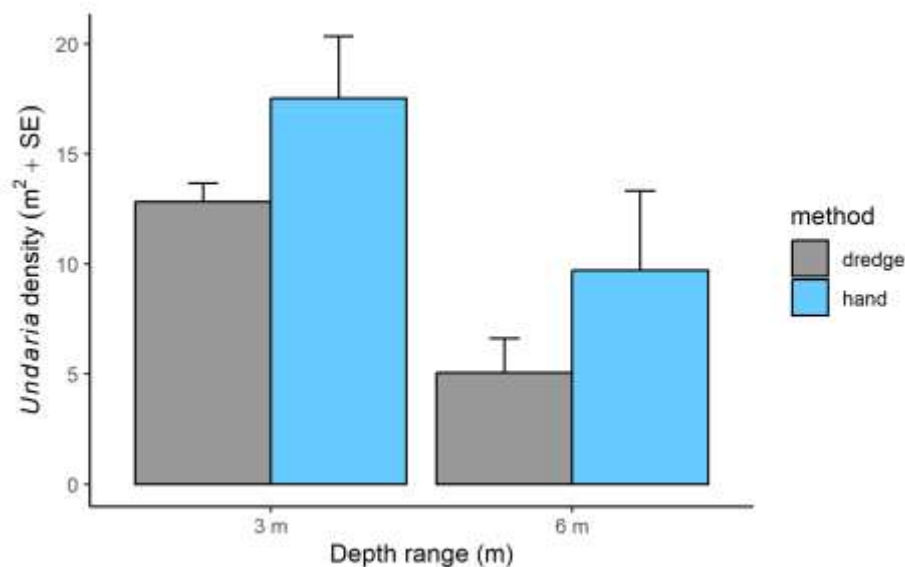


Figure 5: Average *U. pinnatifida* density (all plants) prior to removal efforts at 3 m and 6 m. Grey bars represent average densities within plots subjected to suction dredge removal, blue bars represent average densities within plots subjected to hand removal.

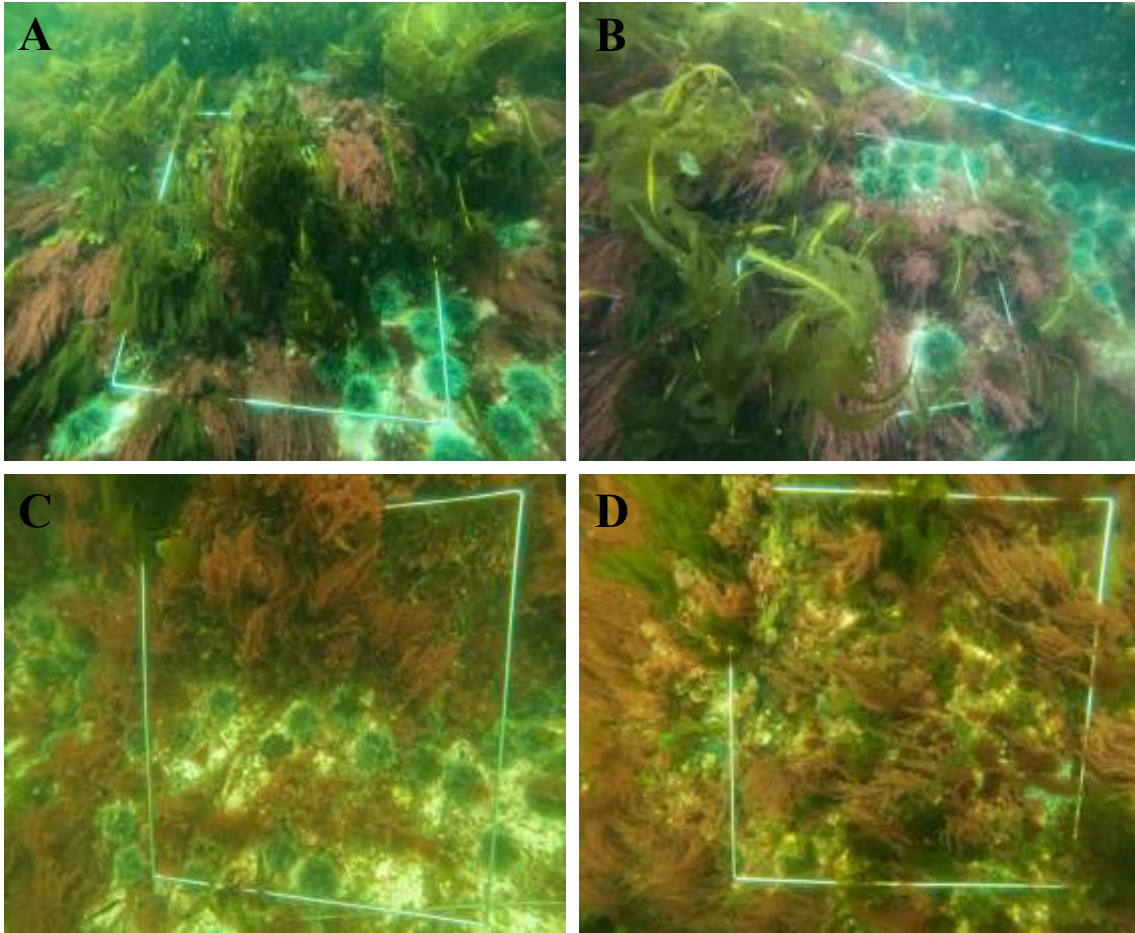


Figure 6: Images pre- and post- suction dredge removal showing changes in *U. pinnatifida* density at Site 2 along the 3 m monitoring transect. Images **A)** and **B)** show densities of *U. pinnatifida* within 1 m² monitoring quadrats at Site 2 prior to suction dredge removal. Images **C)** and **D)** show *U. pinnatifida* densities at similar locations along the 2 m transect post suction dredge removal. Note that *U. pinnatifida* is entirely absent from images C) and D).

Suction dredge removal	Depth Band	Metric	Site 2	Site 4	Site 6	Total	Hand Removal	Depth Band	Metric	Site 1	Site 3	Site 5***	Total
	0-9 m	Removal weight (kg)		666.5	458.9	1258		2383.4	0-9 m	Removal weight (kg)		1093.5	2668.5
Adults removed			3557	2302	6584	12443	Adults removed**						
Juveniles removed			12040	5667	17622	35329	Juveniles removed**						
Area (m ²)			1934	1548	1980	5462	Area (m ²)			2148	1727	1424	5299
Removal time (diver minutes)			874	627	927	2428	Removal time (diver minutes)			1631	3073	1982	6686
Average ±SE						Average ± SE							
Biomass* (kg/m ²)			0.34	0.30	0.64	0.43 ± 0.08	Biomass (kg/m ²)			0.51	1.55	0.81	0.95 ± 0.25
Removal Rate (kg/min)*			0.76	0.73	1.36	0.95 ± 0.16	Removal Rate (kg/min)			0.67	0.87	0.56	0.71 ± 0.07
Total						Total							
9-20 m*		Removal weight (kg)		0.17	17.51	0.02	18	9-20 m		Removal weight (kg)		2.5	7
	Adults removed		3	52	1	56	Adults removed**						
	Juveniles removed		10	125	0	135	Juveniles removed**						
	Area (m ²)		1638	2087	2215	5940	Area (m ²)			2050	2100		4150
	Average ±SE						Average ±SE						
	Biomass (kg/m ²)		0.0001	0.0084	0.0000	0.003 ± 0.003	Biomass (kg/m ²)			0.0012	0.0033		0.002 ± 0.001

Table 1: Removal metrics from sites cleared using diver-assisted suction dredge and hand clearance. *Lower sections (15-20 m) of the suction dredge trials at Site 2 and Site 4 were cleared by hand. Data included to demonstrate extremely low densities of *U. pinnatifida* found below 9 m.**Complete counts of juvenile and adult plants not made for hand removal sites. *** No removal was carried out in the 9–20 m depth band for Site 5.

A) Average overall <i>U. pinnatifida</i> density (plants/m²)				
Method	Depth	Pre	Post	Follow up
		Density ± (SE)	Density ± (SE)	Density ± (SE)
dredge	3 m	12.8 (0.8)	1.2 (0.3)	0.4 (0.3)
hand	3 m	17.5 (2.8)		
dredge	6 m	5.1 (1.5)	0.8 (0.4)	0.45 (0.2)
hand	6 m	9.7 (3.6)		
B) Average adult <i>U. pinnatifida</i> density (plants/m²)				
dredge	3 m	2.8 (0.9)	0.01 (0.01)	0.4 (0.3)
dredge	6 m	0.3 (0.2)	0 (0)	0.5 (0.2)
C) Average juvenile <i>U. pinnatifida</i> density (plants/m²)				
dredge	3 m	10.0 (1.1)	1.1 (0.3)	0.02 (0.02)
dredge	6 m	4.8 (1.5)	0.8 (0.4)	0 (0)

Table 2: Average *Undaria pinnatifida* densities for sites cleared with a suction dredge and by hand. A) Average overall density (juvenile and adult plants combined), B) average adult density, C) average juvenile density. Densities were not recorded during post- or follow up monitoring for sites cleared by hand.

3.2. Suction dredge effectiveness

Following suction dredge removal trials there was a significant drop in overall *U. pinnatifida* densities in both the 3 m ($p < 0.001$) and 6 m ($p = 0.003$) depth bands (Figure 6 and 7A, Table 2). Densities were reduced by 91% at 3 m and 84% at 6 m. Densities fell further between the post-removal period and follow up survey at 3 m ($p < 0.001$) but not at 6 m ($p = 0.99$, Figure 7A, Table 2). Monitoring immediately after suction dredge removal showed near complete removal of adult plants from both depth bands, with remaining densities dominated by juvenile plants (Figure 7B and 7C, Table 2). During the follow up dives the opposite was found, with most identified plants being adults (Figure 7B and 7C, Table 2). Initial removal efforts were similar across edge and central areas of the experimental plots and there was no evidence of greater reestablishment following removal close to the margins of the site (i.e., an edge effect), between the post and follow up survey periods (Figure 7D).

Removal efforts were effective on large (bedrock and boulder) and small (cobble, sand and shell hash) substrate types with an 89% and 100% drop in *U. pinnatifida* density respectively following suction dredge trials (Figure 8A). The dredge was also effective across flat, sloping and vertical sections of reef with a density reduction of $> 85\%$ seen over all relief profiles and $> 90\%$ density reductions on flat and vertical sections (Figure 8B). The four major habitat types which were recorded during the ecological monitoring surveys were kelp forest, mixed algal forest, turfing algae and urchin barrens/bare rock. Results showed clear declines in *U. pinnatifida* density following suction dredge removal, with similar dredge performance within all habitat types ($F = 1.99$, $p = 0.11$, Figure 8D).

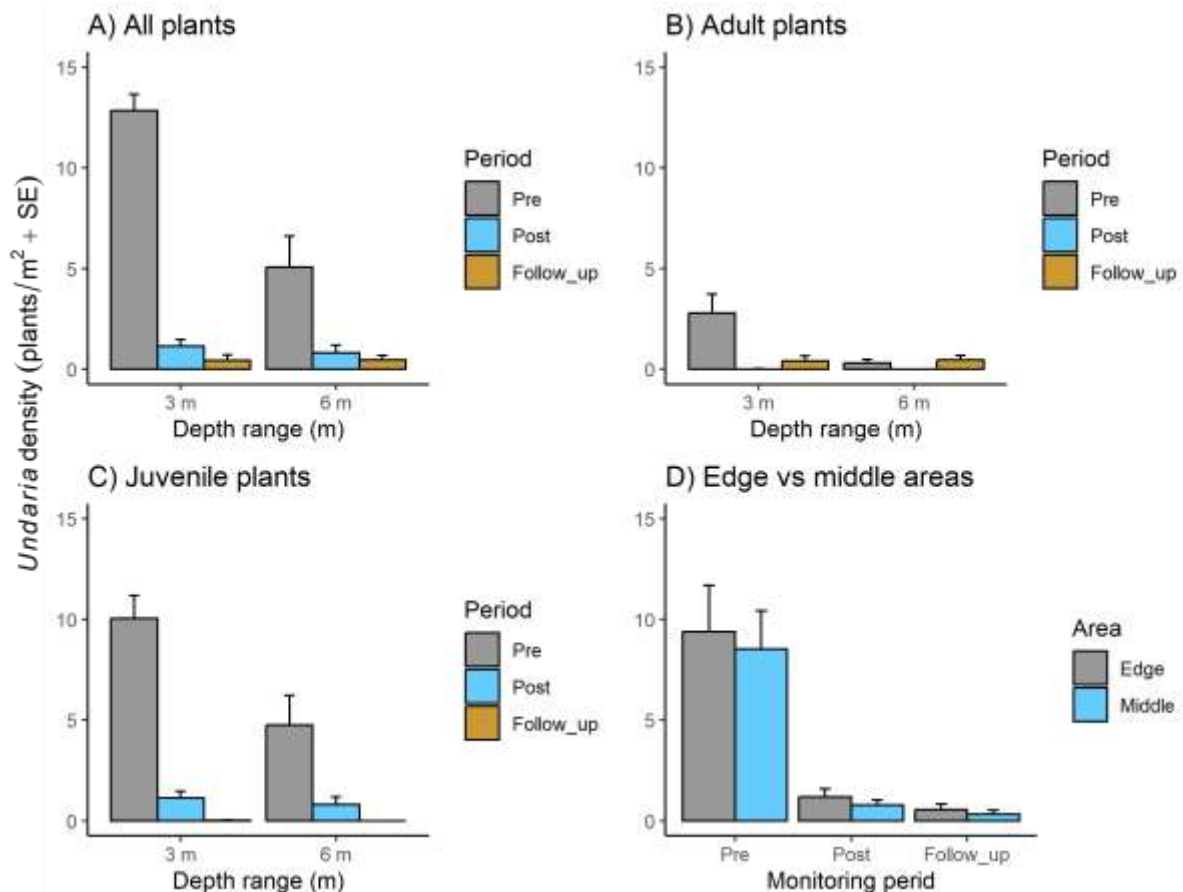


Figure 7: **A)** Average *U. pinnatifida* densities (all plants) at 3 m and 6 m depth within dredge removal plots during the pre, post and follow up sampling periods. **B)** Average adult *U. pinnatifida* densities at 3 m and 6 m depth within dredge removal plots during the pre-, post- and follow up sampling periods. **C)** Average juvenile *U. pinnatifida* densities at 3 m and 6 m depth within dredge removal plots during the pre-, post- and follow up sampling periods. **D)** Average *U. pinnatifida* densities (all plants) near the edge, and within the central zone of dredge removal plots during the pre-, post- and follow up sampling periods.

3.3. Suction dredge efficiency

With increased total *Undaria* biomass removed, the total dive time required to clear by suction dredge and hand removal trials also increased, indicating a positive relationship between the two variables ($t = 6.03$ $p < 0.001$, Figure 9A). The relationship was very strong ($R^2 = 0.85$) for areas cleared by hand and was more variable, though still strong ($R^2 = 0.6$), for areas cleared by suction dredge. Time requirements increased at a relatively consistent rate for both methods, however removal activities were significantly faster for a given total biomass removed when the suction dredge was in operation compared to removal by hand alone ($t = 2.80$, $p = 0.02$). There was no interaction between removal biomass and removal method and the interaction term was not included in the final model.

Average *U. pinnatifida* removal rates when using the suction dredge within the 0–9 m depth band were 0.95 ± 0.16 kg/min (Table 1). This was higher, but not significantly so ($F = 1.19$, $p = 0.34$), than the average hand removal rate of 0.71 ± 0.06 kg/min observed within 0–9 m depth band (Table 1). Based on average site biomass and removal rates (Table 1), divers were able to clear 2.2 ± 0.08 m² of reef /min with the aid of the suction dredge. This was significantly greater clearance area per minute than achieved by divers removing exclusively by hand (0.87 ± 0.18 m² of reef /min; $F = 31.38$, $p < 0.001$). No analysis was done for

removal rates within the 9–20 m area. For all sites, *U. pinnatifida* was rare within this band and extremely low removal rates were reflective of this.

As average site biomass increased within the 0–9 m depth band so too did removal rates for both removal methods, however the relationship between these two variables was modest to weak ($R^2 = 0.43$ for suction dredge and 0.27 for hand removal; Figure 9B). At the level of subsection there was no significant difference in removal rates from subsections with higher or lower site biomass ($t = 1.27$, $p = 0.23$), nor were removal rates higher for a given subsection biomass for either method. Despite suction dredge removal rates appearing to increase at a much greater rate than those of the hand removal sites there was no significant difference detected in rate of removal increase between methods ($t = -1.65$, $p = 0.13$).

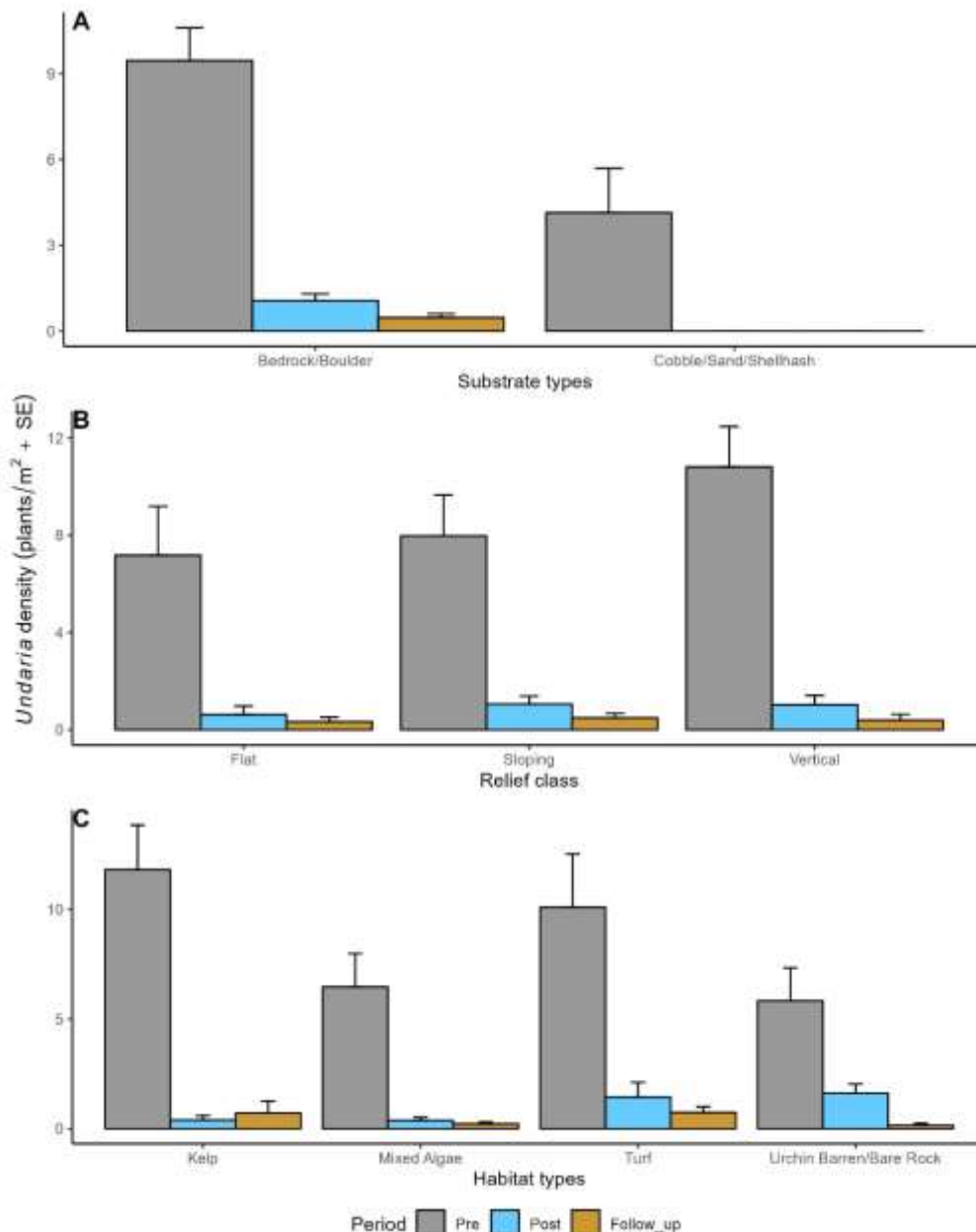


Figure 8: Average *U. pinnatifida* densities (all plants) in dredge removal plots during pre-removal, post removal and follow up survey periods. **A)** surveyed densities within on different substrate types, **B)** surveyed densities on areas differing relief profiles, **C)** surveyed densities within different habitat types. For all plots grey bars represent densities pre-removal, blue bars represent densities post-removal, gold bars represent densities during the follow up period.

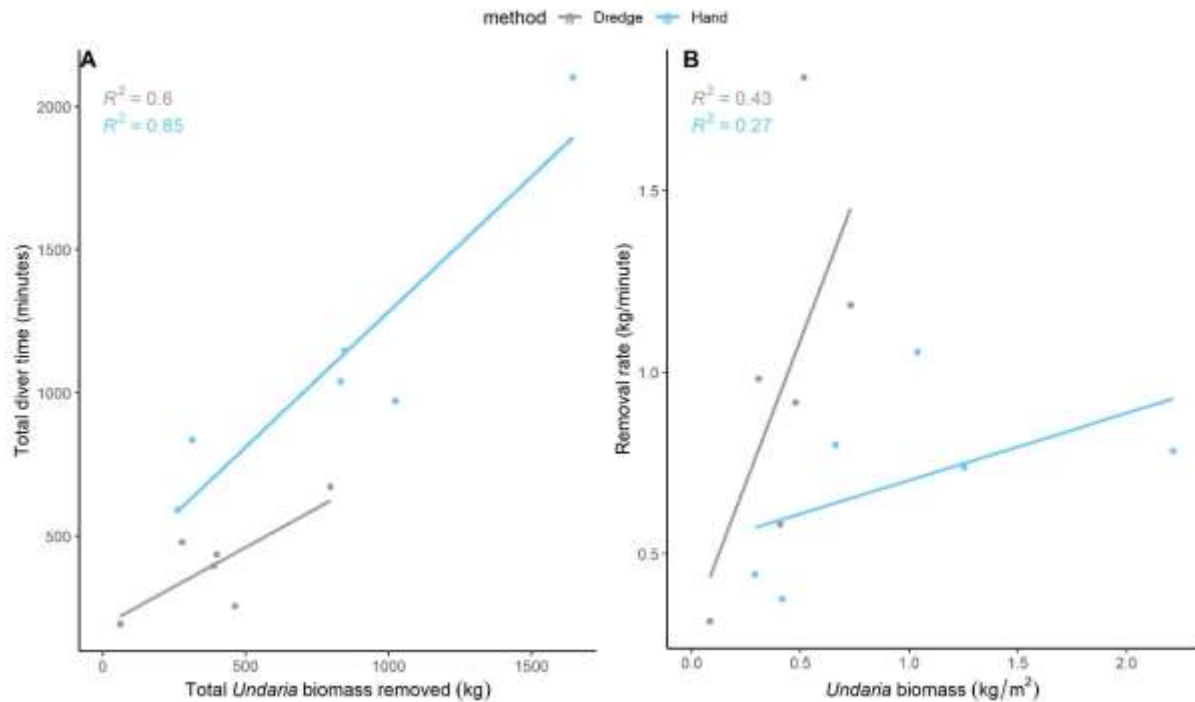


Figure 9: Efficiency of suction dredge and hand removal of *Undaria pinnatifida* in the 0–9 m depth band. **A)** Relationship between total weight of *U. pinnatifida* removed from each site subsection and the total diver time required. **B)** Relationship between average *U. pinnatifida* biomass and removal rates within each site subsection. For both figures grey circles represent values for subsection within suction dredge sites and blue circles represent values for subsection within hand removal sites.

The relationship between the total number of plants removed and total removal time as well as the relationship between *U. pinnatifida* density and plant removal rates were both positive however neither relationship was significant based on statistical testing ($t = 2.28$, $p = 0.84$ and $t = 1.59$, $p = 0.19$ respectively; Figure 10A and 10B). Although data indicated an increase in removal rates as average site density increased (Figure 10C), there was a very weak negative relationship between plant removal rate and the ratio of juvenile to adult plants removed from each site (Figure 10D). This relationship was not significant ($t = -1.43$, $p = 0.22$) but highlights a potential decrease in efficiency within sites dominated by juvenile plants.

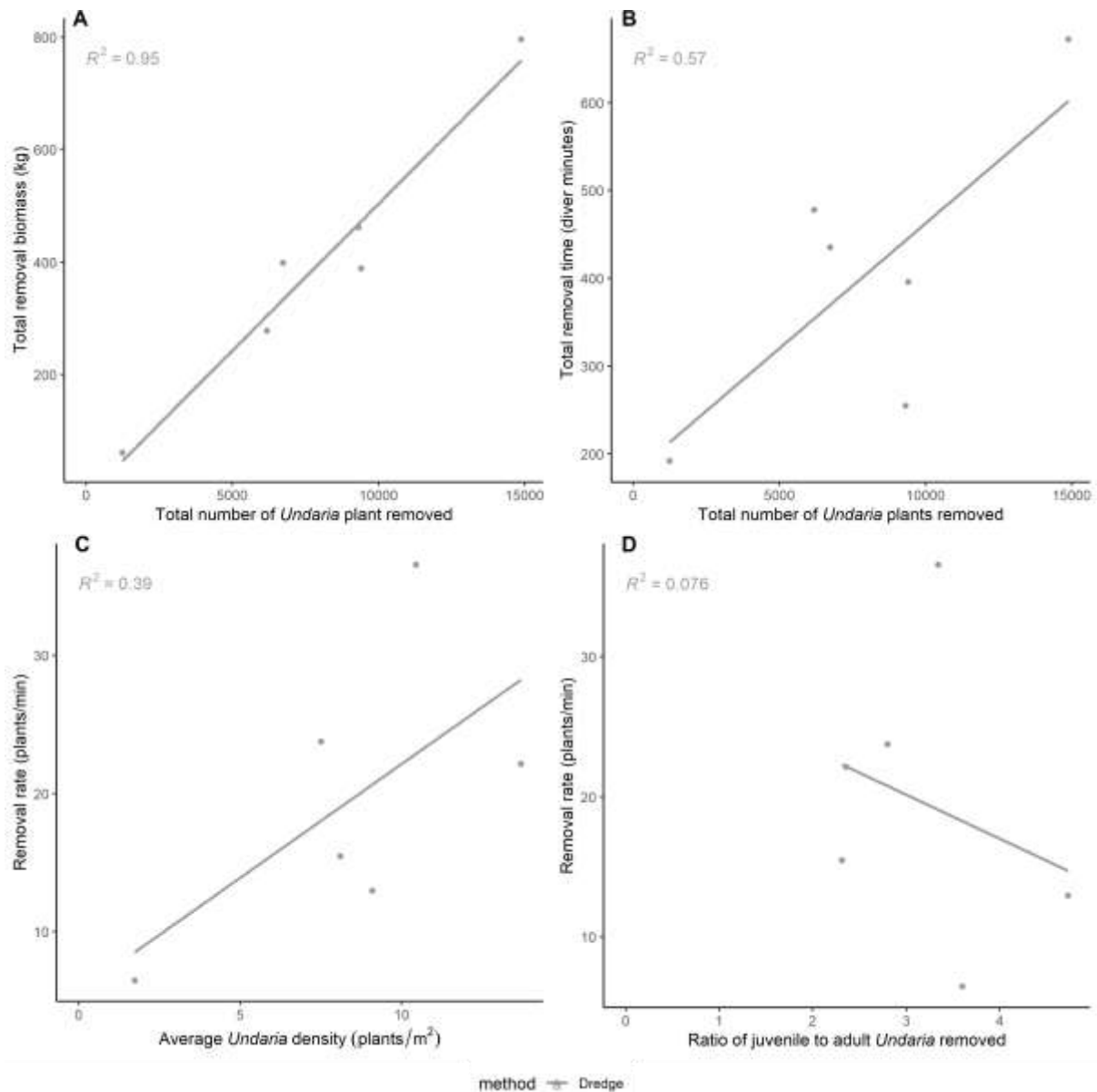


Figure 10: Suction dredge efficiency in the 0–9 m depth band. **A)** Relationship between total weight of *U. pinnatifida* removed from each site subsection and the total number of plants removed. **B)** Relationship between time required for *U. pinnatifida* removal within each site subsection and the total number of plants removed. **C)** Relationship between plant removal rates and average *U. pinnatifida* densities. **D)** Relationship between plant removal rates and the ratio of juvenile to adults plants removed within each subsection

4. Discussion

Since 2010, the suppression and containment of *U. pinnatifida* has been an ongoing and critically important task within Fiordland, and especially Te Puitaha/Breaksea Sound, yet there has been very little trialling of different methods that may improve control efforts and help to achieve localised eradication on a large scale. Here large-scale (total area of 1 ha) removal of *U. pinnatifida* was trialled using a five-person dive team operating a suction dredge. Trials were designed to evaluate the effectiveness and efficiency of using a suction dredge across habitats, substrates and relief profile typically found within Fiordland, provide comparison to the existing methodological approach—hand removal—and inform the feasibility of tool implementation into potential future work programmes to protect against further impacts from this unwanted species. Overall, trials showed that the suction dredge

was effective in lowering *U. pinnatifida* densities and was particularly efficient in shallow (< 9 m) areas with *Undaria* density greater than ~ 2 plants/m². Under these conditions, total removal times were significantly less than those of hand removal alone. The results suggest that the use of a diver-operated suction dredge may increase efficiency of large-scale *U. pinnatifida* suppression and containment, particularly at high density. The trial outcomes along with learnings and limitations identified are discussed in detail below. Recommendations are provided to help guide implementation or further evaluation of diver-operated suction dredge usage within Fiordland.

4.1. Suction dredge effectiveness

The suction dredge was effective at removing *U. pinnatifida* across all substrate types and relief sampled within kelp, mixed algae, turfing algae and barren habitat types. These results are not unexpected as the methodological approach still requires the manual removal of plants from the substrate, similar to the existing hand removal method, which has successfully been implemented for controlling *U. pinnatifida* in Fiordland (Keeler-May, 2022), southern New Zealand (Hunt et al., 2009) and Australia (Hewitt, et al., 2005). We were not able to directly compare density reductions between hand removal and suction dredge removal in this study, but we found suction dredge removal effectiveness was between 84% (6 m) and 91% (3 m). Video footage from sites cleared by hand and by suction dredge indicated very similar efficiencies between methods. In Tasmania, Hewitt et al., (2005) found an approximate 95% drop in sporophyte densities following hand removal efforts in Tasmania. However, the study sites were quite different, as our study areas had significantly higher initial densities (5–13 plants/m² versus 1.05 plants/m²) and were much larger, thus the likelihood of missing individual plants was also higher. Most plants remaining on the reef after the suction dredge trial had finished were juveniles. The dive team operating the suction dredge had limited prior experience in identification and removal of *U. pinnatifida*. Given the high densities of juvenile plants within the trial plots, and the relatively limited prior experience in identification and removal of *U. pinnatifida* of the dive team, it is likely that misidentification (juveniles look similar to native *Ecklonia radiata*) resulted in some plants being missed. Prior knowledge of a species and training are important for accurate species identification (Katrak-Adefowora et al., 2020). As dive teams becomes more familiar with a target species, identification and overall removal effectiveness will likely increase. If suitable training is provided, upskilling inexperienced divers in identification and correct removal techniques is relatively quick, and with proper in-water training can be achieved within a matter of days, as was the case within these trials.

Effective removal, in which all or the majority of biomass present is removed, is important for limiting the spread and recolonisation of invasive species (Blackwood et al., 2010). *Undaria pinnatifida* has extremely high fecundity, and a single sporophyte may release 700 million spores over its annual lifecycle (Primo et al., 2010; Schiel & Thompson, 2012). Spore release in New Zealand predominantly occurs between September to December, but may continue through until February (Schiel & Thompson, 2012). Given the quick maturation of this species (30–50 days), multiple generations can grow within the same year (James, 2016). Following suction dredge removal, we found no evidence of significant recolonisation in the four-month period between the post-removal and follow up ecological surveys. Overall densities remained very low and during the follow up monitoring the surveyed population mostly consisted of sparse adult plants at advanced stages of senescence. This was despite the likelihood of ongoing spore release (from surrounding plants), spore settlement, and growth occurring throughout this period between surveys. A sparse population of mature, dying individuals was more likely to reflect maturation of juveniles missed by the suction dredge

removal rather than site recolonisation. High densities of mature and dying individuals were observed near the boundaries of the removal sites in the video surveys. Based on these findings, if significant site recolonisation had occurred, we would have expected higher densities of plants to be present within the removal area, particularly near the edges given the short dispersal range of spores from standing plants (< 10 m; Forrest et al., 2000). Encouragingly, we found no evidence of any form of edge effect and densities were consistently low across the width of the site in the follow up survey.

Wider dispersal of spores typically occurs when fragments or whole plants are detached from the reef by wave action or currents and subsequently drift through the water column (Forrest et al., 2000; Russell et al., 2008). During hand removal operations plants are typically removed from the substrate and placed within catch bags. Once full a bag is then transferred to the surface and onto a surface vessel, newly empty bags are returned to the water. Although this may only represent a low-risk vector for spore spread, porous catch bags and plants not fully placed into the bag have the potential to spread spores as they are transported across the removal site. The use of a suction dredge minimises the time detached plants are in the water column as, once removed, they are immediately fed into the dredge nozzle and transferred to the support vessel. There are, however, considerations as to the control of spore release once biomass is brought onboard. The continual flow of water from the dredge onto the barge may facilitate the flushing of spores off the barge and back into the water column where they can remain motile for up to three days and viable for 10 days (Hay & Luckens, 1987; Forrest et al., 2000). Heat treatment as biomass came onboard would have been ideal, however in these trials the placement of large quantities of biomass into a water bath, at the frequency it was coming onboard, was not sustainable. The water bath could not maintain the temperatures required (60–90 °C), continually leading to backlogs in the sterilisation process and eventual abandonment. If a purpose-built suction dredge vessel was used for this work, a closed system whereby biomass was directly fed from the dropper pipe into a mulcher (to reduce and homogenise the size of plant matter) and then heat treated would be ideal, however scoping of the cost, practicality and environmental considerations (discharge of hot water) is needed. In the absence of this, *Undaria* biomass should immediately be placed within containment bins or bags (fades were used for the trials) to ensure no biomass is lost overboard. Continual water flushing across this contained material should be avoided. Alternatively, dredging during the spring months, while the majority of plants are still juveniles, may greatly reduce the risk of spore dispersal. Plants could be fed directly into a mulcher system without the need for heat treatment. Mulched fragments could then be returned to the water as there is no risk of regrowth from plant fragments alone. Investigating whether any trade-offs exist between effectiveness of removal activities and the risk of spore release when operating at different times of the year (Sept.–Mar.) should be carried out.

Despite the overall high level of effectiveness of *U. pinnatifida* removal with the use of a diver assisted suction dredge, it is important to note that this method of removal will still only remove visible plants. Microscopic spores and gametophytes will be unnoticed and will persist on the reef following removal efforts, eventually growing into new sporophytes (Epstein & Smale, 2017). Therefore, multiple removal efforts (within the same season and/or across multiple years) or a multi-tiered approach, which incorporates new removal methods as they become available, will be required to effectively suppress or eradicate *U. pinnatifida* from an area (Hewitt, et al., 2005; Hunt et al., 2009; Gnanalingam & Hepburn, 2019; Keeler-May, 2022) unless removal efforts are also able to address microscopic spores and gametophytes (e.g., through heat treatment [Wotton et al., 2004]). However at present applying heat treatment on areas of natural substrate over realistic spatial scales would be impossible.

4.2. Suction dredge efficiency

The suction dredge demonstrated a high level of effectiveness in terms of removing biomass from all trial conditions, however it will prove useful only if it demonstrates an efficiency advantage over traditional methods.

We found that over large areas of shallow reef (< 9 m deep), the use of a diver-operated suction dredge allowed for faster *U. pinnatifida* removal than was achievable through hand removal alone. Findings were consistent across a range of total removal biomasses assessed. The advantage of the suction dredge is likely related to the process of dealing with biomass once it is removed from the reef. When clearing by hand, divers need to place picked or cut plants into catch bags. Bags are of limited size, must be continually opened and closed, divers must ensure plants are fully contained within the bag and once full are ferried to the surface and switched out for empty bags. Often this required a diver to act as a snorkeller whose primary task was bag transfers instead of active removal. In contrast, when using the suction dredge, divers were not required to store cut biomass underwater and could immediately offload cut plants into the dredge nozzle and continue removing. The diver operating the suction dredge nozzle was also, in many cases, able to remove plants at the same time. This often resulted in three divers clearing the reef and quicker overall removal times. Plant matter lifted to the surface via the dredge hose was placed into large fadges and once full these could be easily swapped out without disrupting diver activities.

However, the device became cumbersome in the deeper depth bands (9–20 m) where standing biomass was incredibly sparse (average of 0.003 plants/m² between 9–20 m across all six sites). Between 9–15 m there were no operational issues with the use of the suction dredge, however divers reported that the dredge nozzle and hose could not be moved fast enough to keep up with SCUBA divers quickly scanning the reef for the very sporadic plants present. Below 15 m, the length of the hose available was also an issue and limited the operational radius of the dredge without requiring the barge to be moved. Use was abandoned within the 15–20 m depth band at Site 2 and Site 4 in favour of hand removal. Because most *U. pinnatifida* occurs in shallow water (< 9 m), there is unlikely to be a need to operate the dredge in deeper water and SCUBA divers would be a more efficient use of resources for clearing these areas. Similarly, in shallow waters where large areas of low-density (e.g., < 1 plants m²) infestation occur, the dredge would be impractical. In these situations, hand removal on SCUBA should continue with the dredge being on standby for when high-density infestations are encountered.

Suction dredge removal rates (biomass/minute and plants/minute) increased as average site biomass and density increased, though the relationship was not statistically significant. As *U. pinnatifida* is relatively easy to remove from the reef, increased removal speed at higher densities is expected, as less time is spent searching and moving between plants. For kelp restoration, Miller & Shears (2023) similarly found an increased manual removal rate of kina (kina/min) as kina densities increased, and that removal rate per area was more consistent across different densities as faster removal rates at high densities could offset the higher numbers of kina needed to be removed. Increased removal rates were not necessarily reflected in the total dive time required for biomass removal (time increased at a consistent rate as biomass removed increased); however, the data were based off a relatively small sample size, with considerable variability. The strength and significance of this relationship is likely to become more apparent as more data become available. An interesting point that was worth noting with the suction dredge methodology was that although the overall rate of removal increased as site biomass and plant density increased, there were indications that the ratio of juvenile to adult plants present had a negative impact on removal rates. Smaller plants

were harder for the suction dredge team to identify (due to limited prior experience), were often fully or partially obscured by other algae and could not always be cut or pulled from the reef as easily as adult plants, which may have slow down removal speeds. Although the trend was not significant, it may suggest removal rates are slower earlier in the season (when most plants are juveniles) than later in the season (when more plants are mature, and mostly reproductive, and consequently larger). We could not compare the effect of juvenile to adult ratios on removal rates between methods, but it is likely that the same relationship exists for hand removals also. We suggest further investigation of this potential source of increasing efficiency.

Because most of the removal effort, regardless of methodology, occurs in shallow water there is minimal risk that bottom times will be exceeded over the course of each day. Average dive times were longer for the commercial divers working within suction dredge areas, but removals took fewer total dives. The J4N divers were working on restrictive dive tables and no dive times were longer than 60 minutes. In contrast, the average dive time for commercial divers operating on SCUBA around the suction dredge was 84 minutes. Commercial divers were operating off their dive computers and if low on air, would ascend to the surface, switch to a new tank and promptly return to the removal area. The diver operating the suction hose could stay down for extended periods of time due to the use of a SSBA. This method of fewer, longer dives is likely to be more efficient because there is less interruption to the workflow from having to end dives for all dive members after a certain time period. Even when divers returned to the surface to switch out tanks in the suction dredge trials, the diver operating the suction dredge could continue to clear biomass, meaning there was always at least some form of clearance occurring while divers were in the water. There is likely to be a trade-off between the amount of time a diver can spend in the water and their concentration levels. Although not specifically tested, discussion aboard the work vessel during the trip concluded that four hours in the water per diver per day (for all divers involved in dredge removal activities) was a good medium between total work time per diver and continual high-quality clearance.

4.3. Additional learnings and limitations

In addition to data collection, several key observations about the process were made over the course of the trials. These included operational tweaks which improved the workflow and limitations that should be considered and/or addressed before wider adoption of this tool within Fiordland, or other parts of the country.

4.3.1. Limitations of a non-powered barge

For this trial the barge supplied by Meridian Energy was non-powered, and once towed to each site it was moored in place, effectively limiting the operational area. Depending on depth, the diver operating the suction dredge had a maximum working radius of 25 m and the only movement possible was to alter the barge position by lengthening and shortening the mooring and anchor lines.

Movement in this manner is feasible and was the primary means of barge movement throughout the course of the trial. It is, however, relatively inefficient and requires calm conditions, adequate mooring points on the shoreline and shallow enough depths to put out anchors. There is also a risk associated with damaging benthic organisms as the anchors are deployed.

These issues, and in general more effective movement across a site or extended stretch of coastline could be overcome by having a self-propelled barge. This would provide greater

flexibility and ensure that divers could move freely across a site without the need for continued alterations of the mooring and anchor lines.

4.3.2. *Disruptions due to weather*

Over the first four days of the trial period, adverse weather conditions restricted which sites could be accessed for removal activities. Strong winds and swell meant that only the two most sheltered sites could be cleared (Sites 1 and 2). Weather conditions impacted both suction dredge and hand removal operations. Once these sites had been cleared, weather conditions had not improved enough to allow access to the other sites. The decision was made to move to a sheltered site where a continuous suction dredge removal trial was carried out over a seven-hour period. This helped to familiarise divers with the removal approach and introduced the scientific dive team (J4N workers) to dredge operations. The site selected had been previously surveyed and was known to contain high *U. pinnatifida* biomass.

As discussed above, the barge in use was not self-propelled and operational use was inefficient where low *U. pinnatifida* densities were found. If the suction dredge was being used for future control work and adverse weather conditions prevented operations within the primary work area, having known secondary high-density removal site in sheltered locations would allow effort to easily shift until weather conditions improved. The suction dredge would be highly inefficient if divers needed to search for high-density infestation on the fly (while the dredge nozzle was in the water) or if secondary areas only contained sparse populations. In these situations, switching back to manual hand removal and the use of catch bags would be appropriate. If divers working by hand come across areas of high density, they could return to the surface and signal for the dredge to be readied for use. In this way highly efficient operations could continue on secondary areas until the weather conditions improved.

4.3.3. *Operational improvements*

The trials proved invaluable for identifying operational improvements that would benefit any future adoption of a suction dredge.

Species identification

Divers with limited experience in the identification of *U. pinnatifida* quickly improved with time spent in the water and would be expected to further upskill as more removal work was carried out. Initial snorkel sessions were conducted to familiarise divers with *U. pinnatifida*, and we recommend this for any new divers undertaking clearance activities with limited knowledge of the species. Further in-water familiarisation, particularly around the identification of very small juveniles, resulted in noticeable increases in the quantity of biomass removed. Having divers who are highly familiar with all life stages of *U. pinnatifida* would be valuable as part of any team operating a suction dredge. This would provide additional onsite guidance for inexperienced divers and ongoing quality assurance around correct species identification for removal.

Suction strength, suction hose, and suction nozzle

For the trials, an 8-inch suction hose and nozzle were used. A major health and safety concern was the potential for a large pressure differential to exist around the suction nozzle due to the lifting effect; however, it was quickly established that the suction pressure was very gentle and there was no risk of diver's arms being sucked up the pipe as they fed plants into the nozzle.

The decision to use an 8-inch hose and nozzle was made because there was a risk that a smaller 4-inch hose could have more frequent blockages, particularly in areas of high-density adult biomass. Blockages can restrict airflow into the dropper pipe, reducing suction strength and risks creating airlocks (pockets of air that get stuck within the hose system). If enough air is trapped in the same space, this section of pipe will become buoyant, rising to the surface and interrupting operations. The system worked well throughout the course of the trials, with only two minor airlocks reported when divers were working in very shallow areas due to surge and rapidly changing water depths occasionally causing air to be sucked into the hose. When this happened, the system was shut down and divers would swim up the length of the suction hose, submerging it as they went to expel any air pockets. This process, from system shutdown to system restart, took approximately fifteen minutes.

Most of the time, the compressor operating at half capacity provided enough air for appropriate lift. Where dense patches of adult plants were encountered, and suction strength noticeably dropped, the compressor could then be turned up to provide greater lift capacity.

The only system holdup of note was a kink that formed in the suction hose towards the very end of the trial period. The kink was fixed by cutting and removing the kinked section of hose. Future risk of hose kinking could be minimised by having the connection between the hose and airlift be at a 90-degree angle with the ability to swivel.

Divers reported that the 8-inch nozzle was relatively heavy and quite difficult to operate over areas of vertical relief. In these situations, divers removing *U. pinnatifida* had to bring plants to the nozzle as opposed to the nozzle coming to them. It also restricted the ability of the diver operating the dredge to clear plants from vertical surfaces at the same time, which would have impacted efficiency. The most practical solution for this would be to add additional buoyancy to the nozzle to make it neutrally buoyant.

There were some limitations to the use of a 20 m hose. Although hose use at depth was primarily limited by the cumbersome nature of the hose and nozzle when working in low-density areas (i.e., conditions at depth), the length of the hose available for the trial also restricted movement. The operational radius around the barge, without mooring ropes being shifted, was limited by hose length. The suction hose can be lengthened as required, which would provide a greater range of movement for divers, but has the additional risk of a longer pipe coil which may be harder to manage. Given the high likelihood that suction dredge operations would be restricted to shallow-water areas where densities are higher, the investment in a barge that can be self-propelled, enabling more responsive movement as the divers are clearing a site, is likely a better option than extending the length of the pipe.

There is also the potential to use two hoses off the same set-up which would allow multiple divers to operate suction dredges at the same time. Some efficiency may be gained by this, but likely only when larger dive teams are available or very large areas of high-density biomass need to be removed. The compressor used for this trial would not have had the required capacity to reliably operate two hose systems simultaneously.

Personnel and work platform

At present there are restrictions around the operation of a suction dredge underwater and dive regulations require that any surface-supplied suction tools be operated by a diver on SSBA and that this diver holds a Commercial Dive Certificate of Competence (CoC). This would mean that scientific divers (e.g., the J4N dive teams with Scientific CoC) would not be able to operate the suction dredge and a minimum of two commercially certified divers (for contingency) would be required for any operational dive team. A major revamping of

scientific dive certifications are planned to be enacted in 2023; it is uncertain if training pathways could be established for the use of a suction dredge under scientific diving certifications (i.e., micro-credentials). This would enable a wider pool of divers to be available to control programmes but would be entirely subject to discussion and approval from WorkSafe New Zealand.

For this project the cost for the commercial dive team was \$2900/day but this did not include dive gear (supplied by Pure Salt), vessel costs, food, transport and accommodation. This would need to be factored into the costing of the project and would be expected as part of any trip. The costs associated with the equipment required for dredge operations (as outlined in [Section 2.3.1](#)) were approximately \$19,000. These components would need to be purchased outright or hired on a trip-by-trip basis depending on the project scope and duration.

A dedicated, self-contained vessel that housed all the necessary componentry to operate independently for the day, or multiple days, would create greater efficiency, though it would come with the additional cost involved with initially setting this up. If the suction dredge were to become a significant component of future *U. pinnatifida* control work programme, then the feasibility and cost of purchasing, leasing or constructing a self-contained vessel should be investigated. This should include scoping an efficient system that could effectively treat biomass coming onboard to minimise the risk of spore dispersal from the vessel.

The air supply for SCUBA divers could be run through a series of G cylinders as opposed to continual filling via a compressor. This would greatly free up labour onboard the barge.

For a non-self-contained barge, the minimum dive crew required would be four. This would include a three-person dive team and a dive supervisor. In a four-person crew, two divers would be in the water at any given time while the other was on standby. The standby diver would assist the dive supervisor with cylinder filling and ensuring biomass was correctly transferred into the containment fadges. A smaller team would impact efficiency but would have a lower daily cost—this trade-off would need to be considered when resourcing a project.

The initial intent was to capture biomass in floating nets secured to the end of the barge. This idea was quickly abandoned in favour of using canvas fadges. The nets presented greater risk of the loss of plant material and the potential spread of spores. The fadges were also easy to move by hand when full, and could be transferred to a tender and transported back to the support vessel, or potentially to shore for disposal with ease.

Working in intertidal areas

Working to neap tide required teams to have a good awareness of tide levels and to work the site with the tide, moving into the very shallow areas as the tide permitted. There were no issues with the suction dredge itself operating at very shallow depths.

5. Conclusions and recommendations

The pilot trial has demonstrated that a diver-operated suction dredge is a feasible tool for large-scale management of *U. pinnatifida* in a location as remote as Fiordland. Managers could expect high levels of removal effectiveness (density reductions) across the range of habitat types, substrates and relief profiles likely to be encountered within Fiordland and greater removal efficiency, particularly in shallow areas of dense biomass. This method should be considered when planning future work programmes, and its use in conjunction with hand removal is likely to create better overall outcomes for the containment, suppression and potential eradication of *U. pinnatifida* from the FMA.

The following key recommendations are made for improvements to the methodological approach and any future adoption as a management option.

- The use of a suction dredge should be incorporated into future *U. pinnatifida* management plans as a viable tool for addressing shallow water (< 9 m) areas of medium to high density (> 1 plants/m²).
- Dredge use may be beneficial where:
 - Large-scale (e.g., > 1000 m²), dense infestations have already been identified.
 - The vessel housing the suction dredge has the capacity to immediately process (mulch with or without heat treatment depending on season) biomass and return it to the ocean so that no handling of biomass onboard is required.
 - Dive teams can carry out scouting and surveillance at the beginning of a control trip and identify areas where the dredge would be suitable before it is set up.
- Dredge use may not be beneficial where:
 - The system is set up, but dive teams need to search ‘on the fly’ for suitable areas.
 - Dense infestations are isolated and small (e.g., < 1000 m², or work is only being carried out in areas of low-density (e.g., < 1 plants infestations).
- Teams operating a suction dredge need to include commercially certified divers who are experienced in the use of a suction dredge, but should also include divers with suitable expertise in identifying *U. pinnatifida* at all life stages and distinguishing between this and native algae species. This would be particularly important early in the programme to assist less experienced divers with identification and effective removal techniques. An optimal dive team would likely include commercial and scientific divers.
- The vessel holding the suction dredge equipment should have the ability to be self-propelled to facilitate efficient removal over continuous sections of coastline.
- If suction dredging is to become a major component of the *U. pinnatifida* management programme, the purchase, lease or construction of a dedicated vessel (day-use barge or self-sufficient vessel) should be scoped.
- Greater attention is required towards how the risk of spore release from the barge or work vessel is managed. This would include assessing options for treating water/plant matter as it came onboard and assessing the trade-off between potential changes in efficiency between plant stands dominated by juvenile or adult plants and the risk of spore spread.

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