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An assessment of the current distribution and potential control options for the introduced brown alga *Sargassum muticum* in Scotland

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Executive Summary

Sargassum muticum (commonly known as Japweed) is an invasive, large brown seaweed, with fronds usually over 1 m in length. This species originates in Asia and, in addition to environmental concerns (i.e. out-competing local species), it may cause serious economic losses in the shellfish industry by smothering bivalves and reducing feeding rates. *S. muticum* has recently been identified in Loch Fyne (June 2006) and the Firth of Lorn (July 2007), west coast of Scotland which are highly productive regions for scallop fisheries and shellfish culture. Eradication methods are typically considered unpractical unless the spread is caught early and all previous attempts at controlling or eradicating established populations of *S. muticum* have proved unsuccessful and have sometimes been counter-productive. The spread of *S. muticum* in Scotland, particularly Loch Fyne and the Firth of Lorn is fortunately still in its early stages and this provides an ideal opportunity to attempt to control the northwards spread of this species. In addition, new techniques for the control of invasive macroalgae have been developed in recent years and their advantages and disadvantages are discussed.

This study has shown that currently, the only practical option for controlling the establishment of *S. muticum* on discovery of this species is the physical removal of unattached or attached plants, either by shore based workers or by SCUBA divers. However, this method requires regular monitoring and repeated removal efforts, especially if the source of the introduction is unknown or can not be controlled. The main problem is the difficulty of locating all individual plants including small individuals and the inconspicuous holdfasts. The plants can rapidly regenerate from overlooked holdfasts and disturbance caused by the removal efforts can create ideal conditions for settlement and rapid growth. An additional concern is that plant fragments accidentally left on the shore following removal efforts could accelerate dispersal of the species by drifting to neighbouring areas. Heat treatment of shellfish prior to translocation is also considered a priority for controlling the spread of *S. muticum* between sites.

Recent advances in the development of species-specific biocides for invasive macroalgae that target physiological processes offer significant advantages over traditional non-selective herbicides and management options which combine treatments, such as biological and chemical control agents could provide a long term solution to eradicating invasive macroalgae, such as *S. muticum*. Further investigation into eradication techniques is crucial, however, to enable the control of this species with minimal impact to the shellfish industry and the wider environment.

Contents

1. Introduction

Sargassum muticum (commonly known as Japweed) is an invasive, large brown seaweed, with fronds over 1 m in length. This species originates in Asia and, in addition to environmental concerns (i.e. out-competing local species) it may cause serious economic losses in the shellfish industry by smothering bivalves and reducing feeding rates. *S. muticum* has recently been identified in Loch Fyne (June 2006) and the Firth of Lorn (July 2007), west coast of Scotland which are highly productive regions for scallop fisheries and shellfish culture.

S. muticum was first reported in Scotland in Loch Ryan in May 2004, since this date it has spread northwards into the Clyde, with populations described from the Isle of Cumbrae and Hunterston deepwater port in 2005 and along the west coast of Scotland. *S. muticum* is considered in the 'top 10' high impact species when evaluating a water body for the Water Framework Directive, however, management procedures for this species are lacking at present. Eradication methods are typically considered unpractical unless the spread is caught early. The spread of *S. muticum* in Scotland, particularly Loch Fyne is fortunately still in its early stages.

The main aim of this project was to develop and deliver options for the management and/ or eradication of *S. muticum* on the west coast of Scotland.

2. Current UK distribution

Sargassum muticum was first recorded in UK waters in Bembridge, east coast of the Isle of Wight in 1973 (Farnham et al., 1973; Jones and Farnham, 1973; Fletcher and Fletcher, 1975a) and it subsequently extended its range along the south coast of England (Critchley et al., 1983). Over recent years, a northerly expansion of its range has been observed along the western coasts of the UK, with *S. muticum* recorded on the north coast of Cornwall in 1991 (Eno et al., 1997), Pembrokeshire in 1998 (Davison, 1999) and north to Anglesey in 2001 (ICES, 2006). *S. muticum* was first recorded in Strangford Lough, Northern Ireland in 1995 (Boaden, 1995) and in Cashel Bay, Co Galway, Republic of Ireland in 2001 (Loughnane and Stengel, 2002). It is now known to occur at several other locations on the south and west coasts of Ireland (Loughnane and Stengel, 2002; Simkanin, 2004; ICES, 2006).

In Scotland, *S. muticum* was first recorded in Loch Ryan, Wigtownshire in 2004 (Pizzolla, 2005) (Table 1). Other established populations have been subsequently recorded on the east coast of the Isle of Cumbrae (Harries et al., 2007) and the adjacent mainland shore at Hunterston Power Station (P. Barnett pers. comm.) since 2005 and Whiting Bay, east coast of the Isle of Arran (H. Wood pers. comm.) and Davaar Bay, near Campbeltown Loch, south-east Mull of Kintyre (R. Harvey pers. comm.) since August 2007. The original point (or points) and time of introduction, however, are uncertain. It is not possible to establish how *S. muticum* was introduced with any certainty (Harries et al., 2007).

Unattached fronds of *S. muticum* have also been sighted in the Clyde Marina, Ardrossan in 2006 and 2007 (Ashton et al., 2006; E. Cook pers. obs.), Loch Fyne (O. Paisley pers. comm.) and for the first time, over 100 km north of the southern end of the Mull of Kintyre, in the Firth of Lorn at the Garvellachs in May 2007 (D. Donnan pers. obs.) and Ganavan Bay (near Oban) in July 2007 (T. Pröeschold, pers. comm.) (Harries et al., 2007). The latter sightings reflects the potential for a significant expansion northwards of this species, as it was thought that the Kintyre Peninsula would provide a temporary physical barrier to the continued spread of this invasive species along the west coast of Scotland. It has been suggested that newly introduced populations of *S. muticum* require several years to build up sufficient breeding stock to allow for rapid expansion (Critchley et al., 1983), however, the rapid spread northwards of this species in the UK since the early 1990s, suggests that a continued expansion of *S. muticum* distribution in western Scotland is likely to occur over the next few years (Harries et al., 2007).

Table 1. Locations and details of recent records of *Sargassum muticum* on the west coast of Scotland (Harries et al., 2007)

Location	**Position (British National Grid, OSGB36 datum)**	**Year**	**Notes**	**Source of record**
Loch Ryan, Wigtownshire	NX046681 NX069677 NX036648	2004	Attached to scattered pebbles on sand. Sparsely distributed on lower shore & sublittoral fringe.	Scottish Natural Heritage
Isle of Cumbrae, Ayrshire	NS175544 to NS182555	2005	Attached to cobbles and pebbles forming dense canopy on lower shore& sublittoral fringe.	University Marine Biological Station, Millport
Hunterston power station,	NS180520 (approx)	2005	Attached.	University Marine Biological Station, Millport

Ayrshire				
Loch Fyne, Argyll	NR900700 (approx)	2006	Unattached drift fragments.	Owen Paisley (Seasearch Coordinator)
Isle of Cumbrae, Ayrshire	NS175543 to NS181593	2006	Attached, further expansion of bed noted in 2005.	Scottish Natural Heritage
Clyde Marina, Ardrossan, Ayrshire	NS226422	2006	Unattached drift fragments.	Scottish Association for Marine Science
Corrie, Isle of Arran	NS026420	2007	Unattached drift fragments.	Scottish Natural Heritage
Whiting Bay, Isle of Arran	NS046259	2007	Attached and well established	Howard Wood (Community of Arran Seabed Trust)
Clonaig, Kintyre, Argyll	NR875560	2007	Unattached drift fragments.	Scottish Natural Heritage
Campbeltown Loch, Kintyre, Argyll	NR754195	2007	Attached	Scottish Association for Marine Science
Garvellachs, Firth of Lorn, Argyll	NM645096	2007	Unattached drift fragments.	Scottish Natural Heritage
Ganavan, Oban, Argyll	NM862327	2007	Unattached	Scottish Association for Marine Science

3. Impact on shellfish species by *Sargassum muticum*

The ecological impact of *Sargassum muticum* is not fully understood. Yet, this species is thought to have the potential to cause significant economic damage, particularly to the aquaculture industry. *S. muticum* is a fast growing species, which is known to form large masses (Farnham, 1980) that can densely cover floating structures (Fletcher and Fletcher, 1975a) and potentially foul mussel ropes and oyster bags reducing water flow to the cultivated species (Critchley et al., 1986). This is particularly relevant to the west coast of Scotland, as this region accounts for a large proportion of the shellfish production in the UK, concentrating on the farming of the blue mussel *Mytilus edulis* and the Pacific Oyster *Crassostrea gigas* with over 90 actively producing sites (Bland and Fraser, 2007). The highest proportion of sites located in the Strathclyde region (58 sites), in which *S. muticum* is currently spreading northwards (Fig. 1).

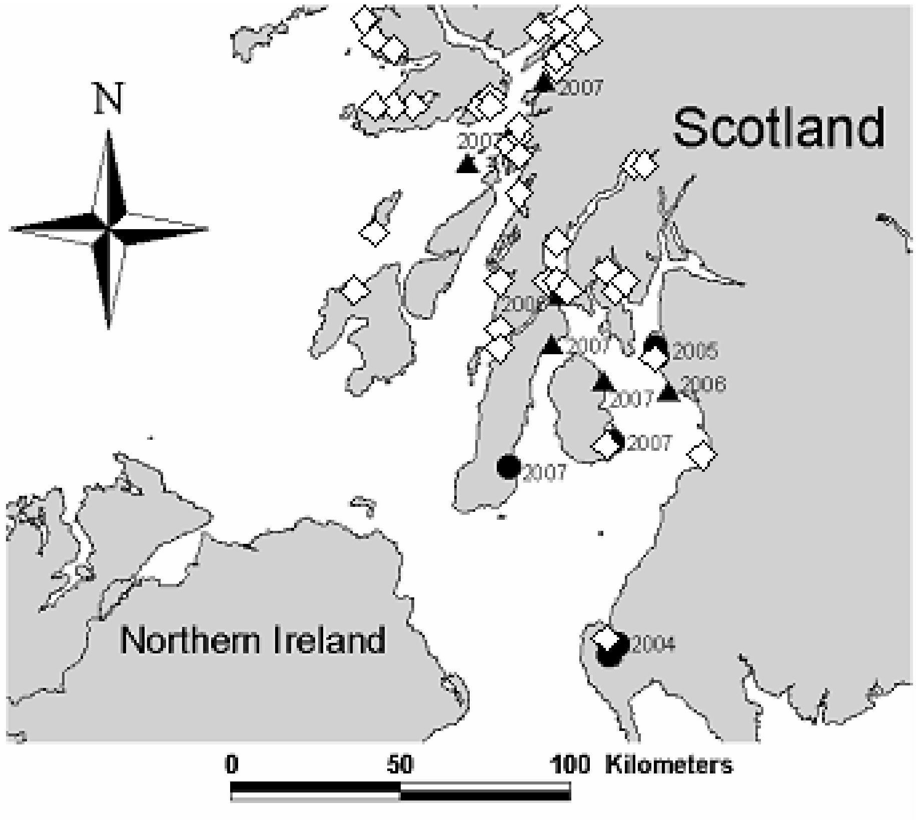

Figure 1. Current distribution of attached (●) and drifting (▲) *S. muticum* at the northernmost limit of it's range in the UK (Harries et al., 2007) and active shellfish production sites (◊) in close proximity to this species (2006) (Bland and Fraser, 2007)

In addition, the spread of *S. muticum* within Europe has frequently been associated with oyster transplantation. Examples include introductions of *S. muticum* to the Mediterranean (Knoepffler-Peguy et al., 1985), Netherlands (Critchley and Dijkema, 1984), Denmark (Staehr et al., 2000) and Strangford Lough in Northern Ireland (Boaden, 1995). It is possible that the introduction of *S. muticum* to Loch Ryan in Scotland may have been caused by oyster transplantation. *S. muticum* is thought to have been introduced to Strangford Lough in the late 1980s (Boaden, 1995) and it is known that during this period oysters were transported from Strangford Lough to Loch Ryan (Howson, 1989). It is important, therefore, that management options are established for shellfish cultivation sites which are at greatest risk to the negative impacts of *S. muticum*, such as Loch Fyne, Loch Etive and Loch Creran and for transplantation practices that pose a high risk of spreading this species to other regions of high aquaculture activity.

4. Raising awareness of *Sargassum muticum* and determining research outcomes

To raise awareness of the spread of *Sargassum muticum* in Scotland and to discuss potential management options for shellfish cultivation sites and for transplantation practices that pose a high risk of spreading this species to other regions of high aquaculture activity, a number of initiatives have been undertaken or established over the last 12 months and these include:

i. Establishment of Scottish *Sargassum* Working Group, including representatives from Scottish Natural Heritage (SNH), JNCC, SAMS, Heriot Watt University, the Marine Biological Station, Millport and SEPA.
ii. Production of 'Invasive Alga – *Sargassum muticum'* leaflet
iii. Establishment of '*Sargassum*' website and email address to report sightings – www.snh.org.uk/wireweed
iv. Presentation at the Association for Scottish Shellfish Growers (ASSG) meeting, Oban (18 – 19 October), followed by discussion session with local growers.
v. *Sargassum* and Marine Aliens leaflets distributed to the Clyde and Firth of Lorn Management Forums.
vi. Presentation given to the Clyde Management Forum (Feb 2007).
vii. Initiation of an SNH commissioned study to investigate management options for controlling dispersal and establishment of *S. muticum*.

5. Potential eradication/ control techniques

All previous attempts at controlling or eradicating established populations of *Sargassum muticum* have proved unsuccessful and have sometimes been counter-productive (Critchley et al., 1986; Davison, 1999). Whatever method has been used, the alga always quickly regrows and effective methods for its permanent removal have not been found, although in the 1980s cutting and suction was proposed as the preferred control method (Farnham et al., 1981; Critchley et al., 1986).

Eradication methods are typically most effective, however, when the spread of an invasive species is caught early. Fortunately, the spread of *S. muticum* in Scotland, particularly in Loch Fyne and the Firth of Lorn is still in its early stages and this provides an ideal opportunity to attempt to control the northwards spread of this species. In addition, new techniques for the control of invasive macroalgae, particularly *Caulerpa taxifolis,* have been developed in recent years and their advantages and disadvantages are described below.

(a) Potential eradication options for established populations of Sargassum muticum

Manual and mechanical removal

Previous attempts at shore-based manual and mechanical removal of established populations of *S. muticum* were extremely time consuming, labour-intensive, ecologically damaging and despite large amounts of macroalgae being removed (Farnham, 1980) the process failed to remove all the holdfasts and regrowth occurred (Fletcher and Fletcher, 1975b). Regrowth was often more dense and vigorous than the previous population because removal of the algal canopy created patches of bare substrate that were favourable to *S. muticum*. It has also been suggested that such attempts could facilitate dispersal by the creation of large numbers of drift fragments (Fletcher and Fletcher, 1975a; Paula and Eston, 1987). In addition, invaded sites were difficult to access, the shoreline was damaged by equipment, the method lacked species-specificity and collected material was difficult to contain and dispose of (Critchley et al., 1986). Manual and mechanical removal attempts have also been made with established populations of the invasive macroalgae, *Codium fragile* ssp. *tomentosoides* (Trowbridge, 1999) and *Undaria pinnatifida* with little success. In both cases, as in the case of *S. muticum*, the main concerns were associated with the regrowth of the plants if the holdfast is not completely removed (Cottalorda et al., 1996; Trowbridge, 1999; Thibaut, 2000), asexual reproduction from fragments (Trowbridge, 1999) and the unintentional spread of thalli with mature propagules which may become detached by the control techniques (Sliwa, 1999)

Physical removal by SCUBA divers, however, may be possible if populations are detected <u>before</u> reproduction occurs. For example, the invasive macroalga *Caulerpa taxifolia* was successfully eradicated from a treated area using manual removal from a National Park in the French Mediterranean in an early stage of invasion in 1994 (Cottalorda et al., 1996; Thibaut, 2000). The eradication method involved the careful removal of thalli and fragments by SCUBA divers, followed by regular monitoring and removal, as necessary (Cottalorda et al., 1996). In addition, *C. taxifolia* was temporarily eradicated in Cala D'Or, Spain in 1992 (Meinesz, 1999) by divers within a month of discovery and by regular monitoring and removal, eradication appeared to have been successful by 1994. This method, however, was extremely labour-intensive with an estimated <1 m^2 to ~3 m^2 area cleared per diver per hour (Zuljevic and

Antolic, 1999). Manual clearing by divers, therefore, could be useful in small areas, such as around marine farms, marine reserves or areas of new incursions, however, it would not be logistically possible to use this method over large areas or at depths greater than a few metres because of safety related restrictions on dive time (Andrews et al., 1996).

If the physical removal of *S. muticum* is to be employed, therefore, either shore based or by SCUBA dives, this method would require ongoing monitoring to be repeated as necessary, especially if the source of the introduction is unknown or can not be controlled. Care would have to be taken to correctly identify and remove all small recruits and holdfasts of *S. muticum.* Where the plants are attached to pebbles or shell fragments the attachment points should be removed in addition to the frond to avoid regeneration from the holdfast. The risk of triggering a release of germlings from reproductively mature fronds could be minimised by placing removed specimens in sealed plastic bags rather than mesh catch bags. All fragments of *S. muticum* would need to be removed from the shore and safely disposed of on land. The use of suction pumps which have been used successfully by divers to remove fragments of *C. taxifolia* should be considered.

At present, a pilot scheme to eradicate *S. muticum* using manual shore-based removal is underway on Lundy Island (SW Wales), although the effectiveness of this scheme is still unknown (K. Hiscock, pers. comm.).

Smothering

The smothering of *S. muticum* through burial with mud had only limited success, as the trial found that this species was far more resistant to burial and decayed more slowly than another macroalgal species, including *Laminaria digitata* (Morrell and Farnham, 1982). The covering of *C. taxifolia* (treated area 512 m^2) with black PVC plastic was reported to have had some success, with on-going monitoring of the area showing no or only sporadic regrowth of this species (Zuljevic and Antolic, 1999). Control programs involving the physical burial or covering of invasive macroalgae with sediments would, however, have to be carefully designed because of their potential to cause significant environmental damage.

Dessication

S. muticum is relatively intolerant to desiccation and does not usually establish in areas that are exposed at low tide (Morrell and Farnham, 1982). Desiccation has been investigated as a potential method for controlling the spread of the introduced seaweed *C. taxifolia* in the Mediterranean Sea (Sant et al., 1996). However, this method is impossible to implement in subtidal areas. Research on the invasive macroalga *U. pinnatifida,* however, found that considerable care should be taken with the disposal of this species after removal from the water (i.e. manual removal, dry docking vessels, removing fouled buoys, ropes, pontoons etc), particularly when fertile, as slightly dried sporophylls which are reimmersed in water quickly released zoospores (Saito, 1975). The gametophytes of *U. pinnatifida* can also survive in small moist crevices in the hull, anchor well etc of vessels in dry dock as well as transportation on land for days up to at least a month (Hay, 1990). If the physical removal of *S. muticum* is, therefore, employed at certain sites, it is crucial that the material removed is contained and any risk of the fertile material becoming reimmersed at the site is minimised.

Salinity manipulation/ Chlorine

The results of experimental testing of salinity tolerance limits are somewhat variable, but it has been estimated that *S. muticum* is be unable to reproduce if salinity is consistently <15ppt and may be unable to compete effectively if salinity is <25ppt, however, this species will grow at salinities from 6.8 to 34ppt (Steen, 2004). Increasing the salinity, by applying salt directly to a site invaded by *C. taxifolia* has been relatively successful in controlling the spread of this species in Australia (Glasby et al., 2005). Chlorine has also been used to control for invasive macroalgae, applied either through gas injection, solutions pumped underneath black plastic used to smother the sediments or placing bags of solution around the target species. In addition, electrolysis of natural seawater is reported to have a lethal effect on *C. taxifolia* after 96 h, however, the effect of hypochlorite was found to be temporary with the macroalga recovering after 8 days (Boudouresque et al., 1996). Sodium hypochlorite has also been unsuccessfully trialled against *S. muticum* in England and France (Critchley et al., 1986; Ribera and Bourdouresque, 1995).

The main disadvantages of these methods, however, are their lack of specificity, the difficulty in maintaining high concentrations in water bodies, particularly for chlorine as this breaks down in sunlight, potential high costs and concern over the wider ecological impacts that the compounds may have on non-target organisms (Ribera and Bourdouresque, 1995; Rajagopal et al., 1997).

Copper compounds

Copper sulphate has been experimentally trialled as a control for *S. muticum* and proved effective, but the low species-specificity and persistence in the environment made it unsuitable for use (Critchley et al., 1986; Ribera and Bourdouresque, 1995). *In situ* experiments in Australia using a commercial copper-based algicide, have examined several methods of applying herbicides to *U. pinnatifida*, including injection into the stipe or midrib, application of a gel formulation, attachment of a sponge saturated with active substance to the thallus, and the release of compounds inside a bag enclosing the thalli (Sanderson, 1996). However results proved to be labour-intensive and had no appreciable impact. Applying copper ions directly to *C. taxifolia* by *in situ* electrolysis has also been shown to result in the death of the macroalga (Gavach et al., 1999; Rebouillon et al., 1999). Pilot laboratory experiments using copper ions in a supersaturated solution of sodium chloride (to produce an application medium denser than seawater) increased the residence time of the copper ions in contact with *C. taxifolia* (Charrin et al., 1999). In addition, it has been shown in laboratory experiments that a copper-ion concentration of >10 ppm (= 10 mg/l), applied for 30 minutes, causes complete mortality of *C. taxifolia* (Uchimura et al., 2000). Copper ion concentrations required to obtain 100% mortality were 100 -10 000 times lower than concentrations of potassium and sodium ions (Boudouresque et al., 1996; Uchimura et al., 2000) (Charrin et al., 1999). Again the main disadvantages of using copper-based compounds are the lack of species-specificity and the environmental impact on non-target species caused by their release.

Species-specific biocides

Chemical methods using herbicides have typically failed due to lack of selectivity, the large doses required and environmental concerns regarding non-target species (Davison, 1999). Recently, species-specific biocides that targeted physiological processes such as photosynthesis or osmoregulation have been successfully developed for the invasive macroalga, *C. taxifolia* (Thresher and Grewe, 2004), although methods of effective *in situ* application have to be devised. This area, however, offers significant advantages over traditional non-selective herbicides and could provide a long term solution to eradicating invasive macroalgae, such as *S. muticum*.

Biological control

Observations on the coast of British Columbia, Canada suggest that in certain circumstances grazers, such as the sea urchin *Strongylocentrotus. droebachiensis* can control *S. muticum* abundance (De Wreede, 1983). However, more recent work (Britton-Simmons, 2004) indicates that *S. droebachiensis* tended to avoid *S. muticum* and did not appear to control plant abundance. Similarly, studies in Scandinavia indicate that although some grazers, such as the sea urchin *Psammechinus miliaris* and the gastropod *Littorina littorea* actively feed on *S. muticum* there was no evidence to indicate control of its abundance (Pedersen et al., 2005; Thomsen et al., 2006).

In Scotland, the sea urchin *P. miliaris* is a common macroalgivore in many of the sea lochs on the west coast (Kelly, 2000) and is known to minimise fouling on aquaculture structures, such as mussel lines and scallop nets, however, it is unlikely that this species would be able to control the spread of *S. muticum*, unless populations were artificially enhanced with commercially reared sea urchins. However, it has also been suggested that grazing pressure may accelerate dispersal by increasing fragmentation of the fronds (Critchley et al., 1986). Control programs involving biological controls, such as sea urchins, therefore, would have to be carefully devised to minimise dispersal of uneaten fragments of *S. muticum*.

(b) Potential eradication options for Sargassum muticum propagules

Shellfish translocations are thought to be one of the major vectors in the spread of invasive algae (Wallentinus, 2002), including *S. muticum* and a recent study has shown that oyster shells cleaned of visible epibionts can still carry a variety of viable propagules (Mineur et al., 2007).

Hot water treatment

In a recent study in France, *S. muticum* was found attached to shells of the Pacific oyster *Crassostrea gigas* amongst a variety of other macroalgal species. Immersion of the oysters in hot seawater (70 ^{o}C) for 20 – 45 s or shorter periods (3 s) at 80 – 85 ^{o}C though was found to have a lethal effect on nearly all macroalgal propagules attached to the shells, without harming the oysters (Mineur et al., 2007). Heat treatment has also been found to be effective in destroying *U. pinnatifida* zoospores (Forrest and Blakemore, 2006). Unfortunately, this control treatment is difficult to implement in open marine conditions unless invaded habitats can be isolated eg. wharf pylons, but could effectively minimise the risk of propagule transfer with the translocation of shellfish between sites if carried out at shore-based facilities. To reduce costs, a combination of heat and chemical oxidants (chlorine or ozone) could be used to allow lower temperatures (30 ^{o}C) and reduce heating costs (Harrington et al., 1997).

Brine immersion

Immersion of *C. gigas* in saturated brine has been shown to be effective against the transfer of *S. muticum* (Lewey, 1976). This was supported in a recent study by Mineur et al. (2007), which found that the survival of macroalgal propagules was significantly reduced when oyster shells were immersed for 30 mins in a brine solution (400 g of sea salt per litre of seawater) at 20 ^{o}C, followed by overnight emersion at room temperature.

Freshwater immersion

This method of control was widely used in the 1970s on Japanese imports of shellfish. Spat were immersed twice in freshwater, before and just after air freight and this did prove lethal to certain organisms (Gruet et al., 1976). However, this method did not prevent the introduction of many Japanese macroalgal species (Gruet et al., 1976) and the long immersion times that are required (Mineur et al., 2007) suggest that this method would be less compatible with shellfish farming practices than the two methods outlined above.

6. Identification of potential management options

Potential management options that could be rapidly employed at invasion site:

- Physical removal to landfill of unattached floating mats of *Sargassum muticum* or fronds entangled in mussel lines or oyster bags taking care to minimise fragmentation and reimmersion of the plant material.
- Cutting and suction of attached fronds at low spring tides in areas adjacent to aquaculture activity, preferably using SCUBA divers to minimise environmental impact. Where plants are established on mixed substrates such as pebbles on sediment, the substrate (pebble) should be removed together with the attached plant. Careful containment and disposal of the material will be crucial to prevent further dispersal as above.
- Inclusion of heat treatment as part of the shellfish transfer protocol from within a specified radius of the invaded site.
- Identification of neighbouring areas where *S. muticum* establishment might cause economic or environmental damage. Implementation of above measures to limit *S. muticum* dispersal to these areas and to control density of growth.
- Establish a process for monitoring effects, particularly where *S. muticum* becomes established in an economically / environmentally sensitive area. Develop a contingency plan of control measures to be implemented if monitoring indicates effects are sufficiently serious.

Potential eradication options requiring further research:

- Investigation into the potential of a *Sargassum*-specific biocide
- Laboratory investigations of grazing preferences of native herbivores for *S. muticum* and effects of grazer abundance on *S. muticum* development

- Evaluation of combined eradication options (e.g., chemical or manual eradication options followed by biological control).
- Evaluation of potential techniques for preventing *S. muticum* completing its life cycle.

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