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# Methods for controlling or eradicating aquatic invasive species

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# Contents

# Executive Summary

## Keywords

Aquatic non-native species, control measures, eradication, invasion pathways

## Background

Since the adoption of the EC Water Framework Directive (WFD), much work has been carried out on the impact of alien invasive species on the ecological status of surface waters. The WFD 'programmes of measures' provide a mechanism for improving the state of the aquatic environment and for tackling the ecological and economic problems caused by invasive species. Programmes of measures need to include early and urgent action on new invasions, identify and control external sources of potential recolonization, as well as long-term management using appropriate tools and techniques.

This report covers control measures for 13 high or moderate impact, and one 'alarm' species on the UKTAG list that were not covered by the Aldridge report for Natural England. It draws information from published and unpublished literature, listed best practices, technical reports, unpublished reports, project websites and expert knowledge. For each species, a report was written to present essential background information about the ecology and biology of the species. This is followed by a list of invasion pathways and known techniques to limit further spread. The third section lists successful control measures that encompass biological, chemical, physical and environmental approaches. A final section on further research acts to identify potential knowledge gaps.

## Key findings/recommended control measures:

- *Azolla filiculoides*: Physical removal with weed bucket /fine nets. Biocontrol with *Stenopelmus rufinasus* weevils or chemical control with glyphosate requires approval.
- *Myriophyllum aquaticum*: Repeated cutting/pulling (if plant fragments can be contained); floating plastic covers. Biocontrol with grass carp and chemical control with glyphosate requires approval.
- *Lagarosiphon major*: Benthic matting; physical removal.
- *Elodea canadensis*: Floating plastic covers or dyes to create shade. Biocontrol with grass carp requires approval.
- *Elodea nuttallii*: Repeated cutting; benthic matting.
- *Spartina anglica*: A combination of cutting, smothering and/or glyphosate although approval is required for the latter. Control measures are only required if the species is considered locally problematic.
- *Cabomba caroliniana*: Repeated cutting; benthic matting; floating plastic covers.
- There are no control measures currently available for *Hemimysis anomala* and *Eriocheir sinensis*.
- *Crepidula fornicata*: Dredging/manual collection; smothering with sediment.
- *Styela clava*: Manual collection; plastic wrapping; acetic/lime/saline sprays or immersions for aquaculture stocks.
- *Urosalpinx cinerea*: Dredging/manual collection with or without tile traps.
- *Didemnum vexillum*: Sprays/immersions; manual cleaning; air exposure, smothering with sediment or plastic wrapping.
- *Ocenebra inornata*: Manual collection.

# 1.0 Introduction

## 1.1 Aim

Since the adoption of the EC Water Framework Directive (WFD), much work has been carried out on the impact of alien invasive species on the ecological status of surface waters. The WFD 'programmes of measures' provide a mechanism for improving the state of the aquatic environment and for tackling the ecological and economic problems caused by invasive species. Programmes of measures need to include early and urgent action on new invasions, identify and control external sources of potential recolonization, as well as long-term management using appropriate tools and techniques.

The species included in this report are all listed on the UKTAG list and classified according to their level of impact (UKTAG, 2015). The objectives of this project were to (i) undertake a review of methods for controlling or eradicating 13 high and moderate impact species, and one 'alarm' species (ii) to investigate the invasion pathways for these species and possible techniques for preventing their further spread.

## 1.2 Species covered

This report covers control measures for 13 high or moderate impact, and one 'alarm' species on the UKTAG list that were not covered by the Aldridge report for Natural England (Table 1) (Aldridge *et al*., 2015). Some species from this list were omitted as the necessary information was already available.

## 1.3 Approach

In the first instance we conducted a systematic search for reviewed scientific literature on Web of Science and Google Scholar with the species name (including synonyms in the case of *Ocenebra inornata*). If fewer than 10 records resulted, then all were screened. For most species, additional search terms were entered: 'control' or 'control measure' or 'control method' or 'eradication' or 'management', with and without 'invasive'. The resulting abstracts were screened and records deemed appropriate were retained and read in full. This search was supplemented with listed best practices, technical reports, unpublished reports, project websites and, where appropriate, expert knowledge. Little information was found on other *Myriophyllum* or *Didemnum* species and the reports are based on the species *M. aquaticum* and *D. vexillum.*

**Table 1**: Aquatic invasive non-native species covered in this report.

| Category | Species |
|---|---|
| High impact | *Azolla filiculoides* |
| | *Myriophyllum aquaticum* (and other *Myriophyllum* species) |
| | *Lagarosiphon major* |
| | *Elodea canadensis* |
| | *Elodea nuttallii* |
| | *Hemimysis anomala* |
| | *Spartina anglica* |
| | *Eriocheir sinensis* |
| | *Crepidula fornicata* |
| | *Styela clava* |
| | *Urosalpinx cinerea* |
| | Non-native *Didemnum* spp. |
| Moderate impact | *Cabomba caroliniana* |
| Alarm list | *Ocenebra inornata* |

## 1.4 Background to species reports

Species reports are designed to stand alone with minimal cross-referencing to other species. Much information about the basic biology and ecology is to be found elsewhere, but a basic synopsis is included for convenience.

Invasion pathways were categorised as deliberate (e.g. for commercial or ornamental reasons), escapes (e.g. from fish or shellfish farms), aided by human transport (e.g. commercial/industrial or leisure craft and/or equipment, or in water ballast or sea chests), or natural (e.g. tides, water flow, currents, floods, transported by other organisms).

Control measures were categorised as biological, chemical, physical or environmental, or a combination of two or more of these. It was not possible to include all unsuccessful control measures in this report. Therefore, these have only been included where they contradicted successful or partially successful control measures in order to advise on the circumstances or degree to which measures may be effective. Evidence for control methods was summarised at the start of each section as:

- ✓ Method is appropriate and has been used in practice
- ? A possible method which could be used but which still requires further investigation and/or field testing or is a chemical (see **1.5 Use of chemicals**) or non-native species (see **1.6 Non-native species for biocontrol**).
- \- Evidence for method's success is inconclusive, effects are limited/short term
- × Evidence suggests that the method is not likely to, or does not work.

Each control method is outlined in greater detail with appropriate references and background information enabling the reader to gain a better understanding of practical application. Control methods were classed according to their effectiveness at either reducing abundance or biomass: poor <30%; moderate 30-60%, good > 60-99%. The term 'eradication' has only been used where a control measure has been shown to be 100% effective.

The final section identifies potential knowledge gaps which currently limit the identification of invasion pathways, or successful control or eradication methods. These include a lack of understanding of the biology and/or ecology of the species or species groups.

## 1.5 Use of chemicals

The application of chemicals in or near water is likely to have impacts on biodiversity and the environment and thus should only be considered if other methods have failed to control the invasive species in question. The use of herbicides in or near water is governed by the Control of Pesticides Regulations 1986 and permission must be sought from the respective environment agency: Scottish Environment Protection Agency, Environment Agency (for England), Natural Resources Wales or Northern Ireland Environment Agency. Application forms can be found on the respective agency websites or from local offices. Chemical use must comply with the product label or published approval method and be confined to the treatment area. Users must be competent, had appropriate training and licenced (if required). The application of lime or acetic acid falls under the European Union regulation (EC 1907/2006) known as REACH (the Registration, Evaluation, Authorisation and Restriction of Chemicals). Users should contact their local environmental agency office for advice prior to application.

## 1.6 Non-native species for biocontrol

A licence may be required for the release of non-native species. Information and advice should be sought from the respective Government organisation: Marine Scotland or Scottish Natural Heritage, Natural England, Natural Resources Wales or the Department of Agriculture, Environment and Rural Affairs, Northern Ireland. Additional information is available from the GB Non-native Species Secretariat (www.nonnativespecies.org).

# 2.0 Invasive Plants

## 2.1 Water fern *Azolla filiculoides*

RECOMMENDED CONTROL MEASURES: Physical removal with weed buckets/fine nets. Biocontrol with *Stenopelmus rufinasus* weevils and chemical control with glyphosate would require approval from regulatory bodies.

### 2.1.1 Species profile

**Description:** Very small free-floating fern (Kelly and Maguire, 2009).

**Origin:** North, Central and South America (Hill, 1999; Kelly and Maguire, 2009).

**UK distribution:** Widespread but currently uncommon in Scotland (Dadds *et al.,* 2007).

**Habitat:** Static and slow-flowing fresh waters such as drainage channels, ponds, lakes, canals and rivers (Newman, 2004a). It is intolerant of fast-flowing water (Kelly and Maguire, 2009).

**Reproduction:** Mainly vegetatively but also via the production of spores (Newman, 2004a); potential to double every 4-5 days under optimal conditions (Lumpkin and Plucknett, 1982).

**Impact:** *Azolla filiculoides* floats on the water and can create dense mats of vegetation which out-compete native species and reduce light levels under the water. During decomposition, *A. filiculoides* creates anaerobic conditions, leading to poor water quality with effects on fish and invertebrates (CABI, 2014; Pratt *et al.,* 2014; ). It can block pumps, water filters and intakes and impede flow at lochs and weirs (Newman, 2004a). Opportunities for recreational activities such as fishing and water skiing can be reduced (CABI, 2014) and the aesthetic appearance of water bodies diminished (McConnachie *et al*., 2003). Safety of children and livestock can be compromised due to the illusion of 'dry land' (Newman, 2004; CABI, 2014).

**Legislation:** Wildlife and Countryside Act 1981; Wildlife (Northern Ireland) Order 1985.

### 2.1.2 Invasion pathways and techniques to limit spread

| DELIBERATE: ornamental |
|---|
| • Banned from sale in England by Defra. Legislation elsewhere should be strengthened. |
| **HUMAN TRANSPORT: recreational boats/equipment** |
| • Good sanitation should be encouraged including removing plant fragments from boat hulls, propellers and the boat trailer. All equipment and wading gear should be thoroughly rinsed and dried for 5 days before moving to another site. |
| **NATURAL: waterfowl** |
| • No techniques available to limit spread via this mechanism. |

**Further information**

Under the Wildlife and Countryside Act 1981 it is an offence to plant or allow the spread of this plant in the wild and Defra has banned the sale of *A. filiculoides* in England since April 2014. The plant can be easily spread between water bodies by waterfowl (Hill and Cilliers, 1999) and on machinery and boats (Kelly and Maguire, 2009).

### 2.1.3 Summary of control measures and evidence of success

| BIOLOGICAL: co-evolved, host-specific predators |
|---|
| ? A replicated study in South Africa demonstrated eradication from 81% of sites within 11 months using *Stenopelmus rufinasus* weevils.<br>? A review of before-and-after effects showed eradication was achieved 10 weeks after releasing weevils at two UK sites and 8-15 weeks at 4 sites in Belgium/Netherlands. |
| **BIOLOGICAL: fungal-based herbicides** |
| ? Fungal pathogens have been identified but not tested as biological control agents. |
| **BIOLOGICAL: leaf extracts** |
| ? A replicated, controlled laboratory study using water resuspensions of *Artemisia dracunculus* and *A. vulgaris* leaf extracts showed reductions in biomass of between 13 and 78%. |
| **CHEMICAL: herbicides** |
| ? Expert opinion considers glyphosate as effective in controlling *Azolla filiculoides*. |
| **PHYSICAL: harvesting** |
| ✓ Weeds buckets or fine nets are effective in removing *A. filiculoides* if used repeatedly and on small water-bodies. |

### 2.1.4 Biological control using co-evolved, host-specific herbivores

**Key findings**

- A replicated study in South Africa found that the release of 100 *Stenopelmus rufinasus* weevils cleared 81% sites with *Azolla filiculoides* within 11 months (McConnachie *et al.*, 2004).
- A review of before-and-after effects of weevil application in the UK at a density of 5-12 per m$^2$ resulted in good control of *A. filiculoides* after 6 weeks (one study) and eradication after 10 weeks (two studies) (Pratt *et al.*, 2014).
- A review of natural infestations in Belgium and the Netherlands resulted in very good control after 18 weeks (one study) or eradication after 8 to 15 weeks (four studies) (Pratt *et al.,* 2014).

**Further information**

*Stenopelmus rufinasus*, a weevil which feeds on *A. filiculoides* in its native range was introduced to South Africa where *A. filiculoides* had invaded many water bodies (Hill and Cilliers, 1999). Laboratory studies showed high host specificity for *A. filiculoides* (Madeira et al., 2016), leading to consent for the release of the weevil as an agent of biological control in South Africa (Hill, 1998). Release of *S. rufinasus* at 112 sites infected by *A. filiculoides* in South Africa proved highly successful with 81% of sites being completely cleared of *A. filiculoides* within 11 months (McConnachie *et al.*, 2004). *Azolla filiculoides* is now considered to be under full control in South Africa (Hill *et al.*, 2008).

*Stenopelmus rufinasus* has been present in the UK since 1921. It is thus considered as 'ordinarily resident' in the UK and therefore no restrictions apply to its use as an agent of biological control in England, Wales or Northern Ireland (Pratt *et al.,* 2013). The species is not subject to free release in Scotland, however, and advice should be sought from Scottish Natural Heritage (see section **1.6 Non-native species for biocontrol**). CABI supplies weevil larvae for control of *A. filiculoides* and is currently monitoring the success of the releases. Circumstantial evidence suggests that *S. rufinasus* has been successful in controlling *A. filiculoides* in Ireland (Baars, 2011). A massive outbreak of the weevil in the UK in 2002 and subsequent decline/eradication of the fern provides further circumstantial evidence of its effectiveness (Gassmann *et al.,* 2006). A study in England used questionnaires (n = 30) to gauge users' opinion on the effectiveness of *S. rufinasus* to control *A. filiculoides*. The results indicated that eradication was achieved in more than 50% of cases, with moderate or good control achieved in a further 32% of cases (Pratt *et al.*, 2014). In a review of before-and-after effects of weevil application in the UK, mass rear and release of between 5-12 weevils per m$^2$ of *A. filiculoides* resulted in good control of *A. filiculoides* after 6 weeks (1 study) and eradication after 10 weeks (2 studies) (Pratt *et al.,* 2014). In the same review, natural infestations in Belgium and the Netherlands resulted in very good control after 18 weeks (one study) or eradication after 8 to 15 weeks (four studies) (Pratt *et al.,* 2014).

### 2.1.5 Biological control using fungal-based herbicides

**Key finding**

- Fungal pathogens of *Azolla* species have been identified but their potential to control *A. filiculoides* has not been investigated.

**Further information**

Seventeen fungal genera have been observed in association with *Azolla* species in the Philippines (Garcia, 1986).

### 2.1.6 Biological control using leaf extract resuspensions

**Key findings**

- A replicated, controlled laboratory study using water resuspensions of *Artemisia dracunculus* leaf extracts showed a 41% and 13% reduction in the biomass of established and growing *A. filiculoides* populations after 10 days (Oduro *et al.*, 2005).
- A replicated, controlled laboratory study using water resuspensions of *Artemisia vulgaris* leaf extracts showed

a 78% and 64% reduction in the biomass of established and growing *A. filiculoides* populations after 10 days (Oduro *et al.*, 2005).

#### Further information

Leaf extracts from certain plants can have toxicological effects on others. In the laboratory, the effects of leaf extracts were tested on established and growing populations of *A. filiculoides*. Ethanol and methyl chloride leaf extracts of *Artemisia dracunculus* (tarragon) and *A. vulgaris* (mugwort) were resuspended in water to provide a more realistic field-based approach. When applied to growing populations of *A. filiculoides*, biomass was reduced by 64% (*A. vulgaris*) and 13% (*A. dracunculus*) after 10 days (Oduro *et al.*, 2005). In established populations, the biomass was reduced by 78% and 41% respectively after 10 days (Oduro *et al.*, 2005).

### 2.1.7 Chemical control using herbicides

#### Key finding

- Expert opinion considers glyphosate as effective in controlling *A. filiculoides* (Newman, 2004a). Glyphosate is approved for aquatic use in the UK (but see **1.5 Use of chemicals**).

#### Further information

Floating fronds of *Azolla filiculoides* can be sprayed with glyphosate which is effective but more than one application would be required to remove all remaining fronds (Newman, 2004a). Diquat and terbutryn are also considered effective (Newman, 2004a); however these two are not licenced for aquatic use in the UK.

### 2.1.8 Physical removal by harvesting

#### Key finding

- Harvesting using weed buckets or fine nets has been effective in small water bodies if repeated in subsequent years (Newman, 2004a).

#### Further information

Harvesting is considered to be an effective method of controlling *A. filiculoides* (Hussner *et al.*, 2017) and has been successfully employed for other free-floating species (Clayton, 1996; Laranjeira and Nadais, 2008). Weed buckets or fine nets can be used to collect it or baffle boards can be inserted into the water body allowing *A. filiculoides* to be removed once it has accumulated against the board (Newman, 2004a). However, these methods are only suitable for small water bodies and may need to be repeated in subsequent years if small fragments or spores remain in the water as these can quickly lead to further infestations (Hill, 1999; Newman, 2004a).

### 2.1.9 Further research

Although the taxonomy, biology and ecology of some species is well known, for others there are uncertainties which, if addressed, would enable development of new methods of control and eradication. Some groups of aquatic plants that include both invasive and non-invasive species (e.g. *Azolla*) are not satisfactorily resolved taxonomically (Madeira *et al.*, 2013).

Few species are currently controlled through biocontrol methods and many opportunities have already been identified. However, many questions still remain which prevent these methods being applied successfully in practice. For example, genetic analysis of *A. filiculoides* and its herbivore *S. rufinasus* would help understanding the interaction between these species and potential control. The development of mycocides holds great promise and indeed fungal pathogens have been identified for *A. filiculoides*.

## 2.2 Parrot's Feather *Myriophyllum aquaticum* (and other *Myriophyllum* species)

RECOMMENDED CONTROL MEASURES: Repeated cutting/pulling (if plant fragments can be contained); floating plastic covers. Biocontrol with grass carp and chemical control with glyphosate would require approval from regulatory bodies.

### 2.2.1 Species profile

**Description:** Perennial rooted aquatic plant that has both a submerged and an emergent form (Haberland, 2014).

**Origin:** Central and South America (Hussner and Champion, 2011; Haberland, 2014).

**UK distribution:** First recorded in the wild in the UK in 1960 (Dadds et al., 2007; CABI, 2014; Plantlife, 2016b ) and now present at around 300 sites (CEH, 2004). It has a predominantly southern distribution but extending as far north as Dumfriesshire, Southern Scotland (Dadds *et al.*, 2007; NBN Gateway, 2016 ).

**Habitat:** Slow-flowing, eutrophic waters (CEH, 2004) such as ponds, reservoirs, gravel pits, ditches, swamps and canals (Dadds *et al.*, 2007). It can grow as a terrestrial plant when water bodies dry out (CEH, 2004).

**Reproduction:** All plants in the UK are female (Dadds *et al.*, 2007). It reproduces vegetatively from fragments which easily break away from adult plants (Dadds *et al.*, 2007).

**Impact:** It can clog whole water bodies, excluding native plants and animals by creating anoxic conditions and reducing light and depriving other species of nutrients (Dadds *et al.*, 2007). Dense growth leads to potential flooding problems and impedes recreational activities such as fishing and boating (Haberland, 2014).

**Legislation:** Wildlife and Countryside Act 1981. Wildlife (Northern Ireland) Order 1985. Banned in the UK under new European Union legislation (EU 2016/1141).

**Global listing:** *Myriophyllum aquaticum* is listed on the IUCN list of problematic alien species (Global Invasive Species Database, 2016a).

### 2.2.2 Invasion pathways and techniques to limit spread

| |
|---|
| **DELIBERATE: ornamental** |
| • Banned from sale in England and Wales by Defra. Legislation elsewhere should be strengthened. |
| **HUMAN TRANSPORT: recreational boats/equipment** |
| • Good sanitation should be encouraged including removing plant fragments from boat hulls, propellers and the boat trailer. All equipment and wading gear should be thoroughly rinsed (ideally with hot water) and dried for 5 days before moving to another site. |
| **ESCAPE: horticulture, hitch-hiker** |
| • Proper disposal of plants from ponds/aquaria.<br>• Ensure Horticultural Codes of Practice are followed. |
| **NATURAL: hydrochory** |
| • Containment of propagules during removal operations from water bodies and proper disposal of plants. |

**Further information**

Grown in water gardens for ornamental reasons since 1878, and it's initial spread resulted from incorrect disposal and escape from ponds and aquaria (CABI, 2007; Angling Trust, 2016). Accidental spread has continued to occur through contaminated soil of other water plants sold in garden centres (Dadds *et al.*, 2007) or as a result of ineffective containment when *M. aquaticum* has been physically removed from water bodies. *Myriophyllum aquaticum* itself was banned from sale in garden centres in England and Wales in April 2014 (Plantlife, 2016a) and planting or allowing the spread of *M. aquaticum* in the wild is prohibited under the Wildlife and Countryside Act 1981 (Dadds *et al.*, 2007) and new EU legislation (EU 2016/1141) (Plantlife, 2016a). Despite this, it is still available to buy under the names *Myriophyllum brasiliense* or *proserpinacoides* (Plantlife, 2016b).

Simple practices are recommended for recreational users to prevent the spread of *M. aquaticum* and other aquatic invasive plants based on controlled, replicated experiments in which plant fragments were placed inside mesh bags, submerged in water and then either washed in hot water (45°C) or dried. This process mimics the attachment of plant fragments to anglers' nets during a fishing trip. For *M. aquaticum*, 100% mortality is achieved within an hour using hot water and within a day by drying (Jerde *et al.*, 2012; Anderson *et al.*, 2015).

### 2.2.3 Summary of control measures and evidence of success

**BIOLOGICAL: non-native predators**

? In a controlled exclusion study, high stocking densities (100 fish per vegetated ha) of grass carp reduced *M. aquaticum* by up to 100% in a reservoir in North Carolina.

? *Lysathia* leaf beetles reduced *M. aquaticum* coverage in a water body in South Africa from 50% to 20% after 3 years.

**CHEMICAL: herbicides**

? A controlled, replicated study found 2,4-D amine to be 100% effective after 23 days.

? Four controlled, replicated studies found glyphosate at concentrations >2.2 kg $ha^{-1}$ reduced biomass by >94% but regrowth occurred.

? A controlled, replicated pot and field trial found triclopyr (at 4-8 kg a.i. $ha^{-1}$) reduced biomass by up to 100% with little/no regrowth.

? Two controlled, replicated experiments found imazamox at concentrations of >560 g a.i. $ha^{-1}$ reduced biomass by up to 81%.

? Two controlled, replicated experiments showed 560 g $ha^{-1}$ imazapyr reduced biomass by 93% and >584 g $ha^{-1}$ eradicated it.

**PHYSICAL AND MECHANICAL: cutting, hand-pulling**

- Cutting of *M. aquaticum* in a drained irrigation channel resulted in complete removal but after 30 days plants began to re-establish.

✓ Before-and-after trials have shown mechanical dredging and hand-pulling to be effective if propagules are prohibited from spreading.

**COMBINED PHYSICAL + CHEMICAL: dredging + herbicide**

? Expert opinion considers mechanical dredging followed by glyphosate as effective in controlling *A. filiculoides.*

**ENVIRONMENTAL: suppression**

? Benthic mats have been used to control other *Myriophyllum* species.

✓ Expert opinion suggests a sheet placed over the water for 12 months achieves good control.

**ENVIRONMENTAL: water-level drawdown**

? In a controlled, replicated mesocosm study, summer drawdown resulted in only 18% survival after 12 weeks.

### 2.2.4 Biological control using non-native herbivores

**Key findings**

- High stocking densities (100 fish per vegetated ha) of triploid (sterile) grass carp controlled an infestation of *M. aquaticum* in a reservoir in North Carolina (Garner *et al.*,2013).
- The leaf beetle *Lysathia* reduced *M. aquaticum* coverage from 50% to 20% of a water body in South Africa over 3 years (Cilliers, 1999).

**Further information**

Herbivorous grass carp (*Ctenopharyngodon idella*) have been used to control a number of invasive aquatic plants. They do not preferentially feed on *M. aquaticum* but in an experiment conducted in a reservoir in North Carolina, Garner (2013) found that they can be used to control it when stocked at high densities (100 fish per vegetated ha) without causing any detrimental changes to water chemistry. However, the fish will also eat native vegetation and are very difficult to remove, although UK waters are too cold for them to breed in (see Fowler, 1984). Biocontrol with grass carp would require approval from regulatory bodies. See section **1.6 Non-native species for biocontrol**.

The leaf beetle *Lysathia* (Coleoptera, Chrysomelidae) naturally controls *M. aquaticum* in its native range in South America (Hussner *et al.*, 2017). When the beetle was introduced to South Africa it showed promise as a biocontrol agent (Cilliers and Mabulu, 2002). Over 3 years, a water body with 50% coverage of *M. aquaticum* was reduced to 20% coverage (Cilliers, 1999). Host specificity testing would be required before it could be considered for use in the UK and it would be important to ascertain whether it could complete its full life-cycle under UK climatic conditions.

Several other insect herbivores of *M. aquaticum* have been identified - the weevil *Listronotus marginicollis* and moths *Argyrotaenia ivana*, *Choristoneura parallel* and *Parapoynx allionealis* (Cilliers, 1999). However, none are currently in use for controlling *M. aquaticum*.

### 2.2.5 Chemical control using herbicides

**Key findings**

- A controlled, replicated plot study in Brazil found that herbicide containing the active ingredient 2,4-D amine was 100% effective after 23 days (Negrisoli *et al.*, 2003).
- Three controlled, replicated studies found that glyphosate at concentrations of 2240, 2800 and 3360 g $ha^{-1}$ reduced biomass by 94, 100 and 99 % respectively (Machado and Rocha, 1998; Negrisoli *et al.*, 2003; Emerine *et al.*, 2010). However, two of these studies reported subsequent regrowth (Machado and Rocha, 1998; Negrisoli *et al.*, 2003).

- A controlled, replicated pot and field trial found triclopyr (at 4-8 kg a.i. $ha^{-1}$) to be the most effective and long lasting of six herbicides (Hofstra *et al.,* 2006).
- Two controlled, replicated experiments found imazamox at concentrations of >560 g a.i. $ha^{-1}$ reduced biomass by up to 81% (Wersal and Madsen, 2007; Emerine *et al.*, 2010).
- Two controlled, replicated experiments showed 560 g/$ha^{-1}$ imazapyr reduced biomass by 93% (Emerine *et al.,* 2010) while >584 g $ha^{-1}$ eradicated it (Wersal and Madsen, 2007).

#### Further information

Several herbicides are effective against *M. aquaticum* but none are currently licensed for aquatic use in the UK, although one-off applications in particular circumstances may be approved (Hussner *et al.*, 2017).

In the greenhouse, a concentration of 2240 g a.i. $ha^{-1}$ glyphosate reduced *M. aquaticum* biomass by 94% (Emerine *et al.*, 2010). In a controlled field experiment, glyphosate was applied to flowering *M. aquaticum* in drained irrigation channels in Portugal. A tractor-mounted sprayer was used to deliver 500 L $ha^{-1}$ of water at a pressure of 6 kg $cm^{-1}$ and a rate of 2800 g $ha^{-1}$ active ingredient (Machado *et al.*, 1998). Glyphosate was applied to five out of six plots, each measuring 50 m x 4.2 m. Treatment efficacy was c.50% after 10 days and 100% after 60 days. However, after 370 days re-infestations began and *M. aquaticum* covered 2.5% of the channel surface 442 days after treatment (Machado *et al.*, 1998). Other researchers have also reported glyphosate as only being temporarily effective with regrowth occurring (Negrisoli *et al.,* 2003; Hofstra *et al.*, 2006). Thus, the Environment Agency (EA, 2010) advised two applications to the emergent vegetation at a concentration of 6 L $ha^{-1}$ between March and October and better results are achieved where an adjuvant top film is used. On mixed marginal vegetation, application of glyphosate with a weed-wiper has been suggested (EA, 2010).

In controlled pot and field trials, Hofstra *et al.* (2006) found fluridone at 0.5 kg $ha^{-1}$ to be ineffective but triclopyr at 4 kg $ha^{-1}$ reduced biomass by 100%, endothall at 15 kg $ha^{-1}$ reduced biomass by 90% and dichlobenil at 20 kg $ha^{-1}$ reduced biomass by 99%. However, only triclopyr had any long-lasting effect (Hofstra *et al.*, 2006). Imazamox applied at concentrations of 560 g $ha^{-1}$ or more, reduced biomass by more than 60% and up to 81% (Wersal and Madsen, 2007; Emerine *et al.*, 2010). In the greenhouse, imazapyr at a concentration of 560 g $ha^{-1}$ reduced the biomass of *M. aquaticum* by 93% (Emerine *et al*., 2010). However, in an outdoor mesocosm experiment, concentrations greater than 584 g $ha^{-1}$ were sufficient to eradicate the species (Madsen, 2007).

Negrisoli *et al.* (2003) found 2-4-dichlorophenoxyacetic acid (2,4-D) applied at rates of 670 and 1340 g ha-1 to be 100% effective 23 days after application (Negrisoli *et al.*, 2003). The Centre for Ecology and Hydrology (CEH, 2004) recommended application of 2,4-D in early April. In tests, diquat was found to be 99% effective after 20 days but regrowth occurred (Negrisoli *et al.*, 2003). See section **1.5 Use of chemicals**.

### 2.2.6 Physical and mechanical control using cutting, dredging or hand-pulling

#### Key findings

- A controlled field study found that cutting *M. aquaticum* in a drained irrigation channel initially resulted in complete removal, but after 30 days plants began to re-establish (Machado *et al.*, 1998).
- Mechanical dredging achieves effective control if propagules can be prevented from spreading (Angling Trust, 2016).
- Hand-pulling is a recommended control measure for use in small areas (CEH, 2004; EA, 2010; Plantlife, 2016b).

#### Further information

Physical removal has been identified as a suitable method for controlling large infestations of *M. aquaticum* but care needs to be taken to prevent fragments moving downstream which can quickly start new infestations (CEH, 2004). Different types of physical removal can be used including cutting the vegetation in drained water bodies (Machado *et al.*, 1998) and hand pulling while the water is present (EA, 2010).

Machando *et al.* (1998) carried out an investigation to determine the effectiveness of harvesting *M. aquaticum* using an excavator with a cutting blade. This was conducted in drained irrigation channels. Five 50 m x 4.2 m plots were harvested and one control left vegetated. Complete removal was initially observed, but after 30 days plants began to re-establish. After 80, 370, 406 and 422 days following treatment the efficacy of the harvesting decreased to 87%, 79%, 66% and 58% respectively. Even though some degree of control was achieved, draining infested water bodies before harvesting is unlikely to be possible or desirable in many cases. Furthermore, as the species spreads vegetatively, any method which involves cutting stems or rhizomes is likely to increase spread (Global Invasive Species Database, 2016a).

The Angling Trust (2016) reported that mechanical dredging achieves effective control if propagules can be prevented from spreading (e.g. via netting the area). Although somewhat intrusive, mechanical dredging not only removes the existing *M. aquaticum* but also reduces the silt layer making conditions less suitable for plant re-establishment (Angling Trust, 2016).

There are mixed reports as to the success of hand pulling for species such as *M. aquaticum* which have brittle shoots (Boylen *et al.*, 1996; Kelly, 2006) and great care has to be taken to remove the whole plant (Plantlife, 2016b). The Environment Agency suggested this is carried out every 6-9 weeks from March to October to weaken the plants (EA, 2010). However, Wersal *et al.* (2011) studied the phenology and starch allocation of *M. aquaticum* in Mississippi and found that starch concentrations in stolon tissues and emergent vegetation were both reduced between October and March. They suggested that the plant may be weakest during this period of low energy reserves and therefore control messures are more likely to be effective (Wersal *et al.,* 2011). However, for this to be applicable to the UK, similarities between the seasonal patterns of the UK and Mississippi need to be considered and it would only be appropriate if the plant did not die off completely during the winter months. Studies on similar *Myriophyllum* species have shown that hand removal significantly lowered regrowth and was a relatively inexpensive control method (Bailey and Calhoun, 2008).

### 2.2.7 Combination chemical and physical control using dredging and herbicides

#### Key finding

- Mechanical dredging followed up by herbicide application has been recommended for large, dense *M. aquaticum* infestations (Angling Trust, 2016).

#### Further information

Herbicide application is most effective against thinner mats of vegetation by allowing good contact and reducing the risk of deoxygenation of the water body (Angling Trust, 2016). Thus, in some circumstances, mechanical dredging following by herbicide application may be necessary (Angling Trust, 2016). See section **1.5 Use of chemicals.**

#### 2.2.8 Environmental control via plant suppression

**Key findings**

- Benthic mats can control other *Myriophyllum* species but have not been tested for *M. aquaticum*.
- A sheet placed over the water for 12 months achieves good control (CEH, 2004).

**Further information**

Environmental manipulation can reduce *M. aquaticum* such as narrowing water channels, shading, reducing nutrient status of the water body and drawdown. Narrowing the water channel increases water flow making conditions unsuitable for *M. aquaticum* and thereby reduces its' abundance (CEH, 2004). Reducing nutrient inputs to water is advocated for long-term eradication (CEH, 2004). Shading deprives the plant of light and restricts photosynthesis. A sheet placed over the water for 12 months achieves a good level of control (CEH, 2004) but will also negatively impact other species. For other *Myriophyllum* species, the use of benthic mats significantly reduced coverage but as the cost is relatively expensive it is only recommended for small areas (Bailey and Calhoun, 2008).

#### 2.2.9 Environmental control via water-level drawdown

**Key finding**

- In a controlled, replicated mesocosm experiment, summer drawdown resulted in only 18% survival of *M. aquaticum* after 12 weeks (Wersal *et al.*, 2013).

**Further information**

Drawdown is the process of removing water from a water body allowing the plants to dry out. It is thus limited to waters with controlled outflows. In the United States, herbicide is sometimes applied after drawdown as this allows good contact with the plant foliage and minimises the risk of herbicides getting into waters (Hussner *et al.*, 2017). However, *M. aquarium* is iconsidered fairly resistant to desiccation; in fact it is reported to occur on a council rubbish tip in Cornwall (Dadds *et al.*, 2007).

Results from a mescocosm experiment at Mississippi State University, which simulated winter drawdowns for 2, 4, 6, 8 and 12 weeks, showed poor control of *M. aquaticum* because the soil never completely dried out. Survival was 70, 80, 68, 68 and 78 % for 2, 4, 6, 8 and 12 week drawdowns respectively. In contrast, during the summer drawdown, soil moisture fell below the complete soil saturation point and survival after a 12 week period was only 18% (Wersal *et al.,* 2013). Although the results of the simulated summer drawdown were much better than those of the winter drawdown it is doubtful that sufficiently warm conditions would occur in the UK for the soil to dry out completely.

#### 2.2.10 Further research

The taxonomy of the genus *Myriophyllym,* which includes both invasive and non-invasive species, is still not fully resolved (Van de Wiel *et al.,* 2009). Further investigation would also need to address the suitability of the chrysomelid beetle *Lysanthia* to the UK climate and what impact it could have on native species, before any decision could be made on its potential as a biocontrol agent. Benthic jute matting has been successfully employed for a number of invasive plant species, including other *Myriophyllum* and therefore specific testing for *M. aquaticum* may be useful. Water-level drawdown and nutrient reductions have been suggested for several species but there is little empirical evidence.

## 2.3 Curly pondweed or water-thyme *Lagarosiphon major*

RECOMMENDED CONTROL MEASURES: Benthic matting; physical removal.

#### 2.3.1 Species profile

**Description:** A dioecious, perennial aquatic plant that can grow in dense mats up to 2-3 m thick (CABI, 2008b; Angling Trust, 2016).

**Origin**: Southern Africa (Champion and Clayton, 2001; Dadds *et al.,* 2007).

**UK distribution**: *Lagarosiphon major* was introduced as an oxygenating plant for ponds and aquaria (Dadds *et al.*, 2007). It escaped and became established in the wild in 1944 (Newman, 2004b; Dadds *et al.*, 2007). The species has a predominately southerly distribution in the UK but is present at sites in central and southern Scotland (NBN Gateway, 2016).

**Habitat**: It grows best in still or slow flowing waters with silty or sandy bottoms such as lakes, reservoirs, wetlands, drainage ditches, riparian zones and rivers (Newman, 2004b; CABI, 2008b). It declines in waters which are very eutrophic (CABI, 2008b).

**Reproduction**: Vegetatively from plant fragments (Dadds *et al.*, 2007).

**Impact**: Extensive mats clog waterways, reducing space for native vegetation, increasing flood potential (Angling Trust, 2016) and reducing amenity access (Dadds *et al.*, 2007). It can also create unsuitable conditions for other vegetation by increasing water pH (Newman, 2004b) and decreasing oxygen by limiting water circulation and increasing decomposition (CABI, 2008b).

**Legislation**: Wildlife and Countryside Act 1981. Wildlife (Northern Ireland) Order 1985. *Lagarosiphon major* is also listed on the IUCN list of problematic alien species. It is banned in the UK under new European Union legislation (EU 2016/1141).

#### 2.3.2 Invasion pathways and techniques to limit spread

**DELIBERATE: horticulture**

- Banned from sale in England and Wales by Defra. Legislation elsewhere should be strengthened.

**HUMAN TRANSPORT: recreational boats/equipment**

- Good sanitation should be encouraged including removing plant fragments from boat hulls, propellers and the boat trailer. All equipment and wading gear should be thoroughly rinsed (ideally with hot water) and dried for 5 days before moving to another site (Anderson *et al.*, 2015).
- Public education of lake users necessary to prevent spread (CABI, 2008b).

**ESCAPE: aquaria, horticulture, hitch-hiker**

- Proper disposal of plants from ponds/aquaria.
- Ensure Horticultural Codes of Practice are followed.

**NATURAL: hydrochory**

- Containment of propagules during removal operations from water bodies and proper disposal of plants (CABI, 2008b).

**Further information**

*Lagarosiphon major* is listed on the Wildlife and Countryside Act 1981 and new European Union regulations (EU 2016/1141), making it an offence to plant, or allow the spread of this species in the wild (Dadds *et al*., 2007). Initial spread into the wild was due to inappropriate disposal of unwanted aquarium plants (Newman, 2004b; Dadds *et al*., 2007) and it reproduces vegetatively from stem fragments which can easily be transferred between water bodies (Dadds *et al*., 2007) and attached to other water garden plants (CABI, 2008b).

Transport between water bodies by recreational boats, trailers, nets and equipment are also likely mechanisms for this species to spread (Cronk and Fuller, 1995; McGregor and Gourlay, 2002; Dadds *et al*., 2007). Anderson *et al*. (2015) investigated decontamination methods experimentally. Plant fragments of *L. major* (mimicking those which would remain attached to anglers' nets) were placed inside polyester bags with a 2 mm mesh (i.e. similar to an angler's keep net) and placed in water for 1 hour to represent a fishing trip. They were then subjected to either hot water or drying treatments, or a combination of the two. The results showed that placing the nets in hot water (45°C) resulted in 97% *L. major* mortality within 1 hour. When hot water was followed by drying, 99% mortality was achieved in 1 hour. Drying alone was the least effective treatment, taking 3.21 days of drying time to achieve 90% mortality (Anderson *et al*., 2015).

### 2.3.3 Summary of control measures and evidence of success

**BIOLOGICAL: co-evolved, host-specific predators**

? In a controlled, replicated laboratory test, the leaf-mining fly *Hydrellia lagarosiphon* was found to negatively impact *L. major* growth and establishment success.

? A study in its native range observed that the midge *Polypedium tuburcinatum* halted growth of *L. major*.

**CHEMICAL: herbicides**

? In replicated, controlled greenhouse and field trials, endothall was found to be 100% effective at concentrations of 0.5 and 5 mg $L^{-1}$ respectively.

? Expert opinion considers diquat effective against *L. major*.

**PHYSICAL AND MECHANICAL: cutting, hand-pulling**

✓ Mechanical cutting and/or hand-pulling achieves poor to moderate control of *L. major*.

**ENVIRONMENTAL: suppression**

✓ A before-and-after trial demonstrated *L. major* decomposed at six out of seven sites under jute matting in 4 months.

### 2.3.4 Biological control using co-evolved, host-specific herbivores

**Key findings**

- In controlled, replicated laboratory tests, the leaf-mining fly *Hydrellia lagarosiphon*, at densities of 3-4 larvae per shoot, halted growth and reduced establishment success of *L. major* (Mangan and Baars, 2011; 2016).
- Field observations in its native range suggest that the midge *Polypedium tuburcinatum* prevented further growth of *L. major* (Earle *et al*., 2013).

**Further information**

*Lagarosiphon major* does not have any close relatives in Europe with a similar growth habit making it a candidate for biological control using a host-specific herbivore. Baars et al. (2010) conducted a survey of *L. major* in its native range assessing plants for insect damage. Damaged plants were collected, brought back to the lab for dissection and natural herbivores reared for identification. One of several herbivores identified was the leaf mining fly *H. lagarosiphon* (Diptera, Ephydridae). The fly was imported under quarantine to University College Dublin (Ireland) and its biology and impact on *L. major* plants was assessed. Pre-release efficacy assessments were carried out on *H. lagarosiphon*. These showed that just 3-4 larvae per shoot tip are sufficient to halt growth with negative effects on shoot tip length and biomass (Mangan and Baars, 2011). For example, undamaged shoot fragments produced 100% more shoot biomass in 70 days compared with those exposed to larval damage (3-4 larvae) (Mangan and Baars, 2016). Subsequent establishment by apical shoot fragments is also reduced to 85 and 25% with 3 or 5 larvae per shoot respectively (Mangan and Baars, 2016). Furthermore, damage from repeated generations of *H. lagarosiphon* caused negative effects at both low and high larval densities (Mangan and Baars, 2011). Mangan and Baars (2013) studied the development time of *H. lagarosiphon* and concluded that stable or increasing populations could be achieved across most of Europe.

In 2011, another herbivore was imported under quarantine - *Polypedium tuburcinatum* (Diptera, Chironomidae) (Andersen *et al*., 2015). Unusually for midges, larvae of this species feed on living plants and damage to the main and side shoots of *L. major* in the field was shown to be severe, stunting the growth of the plant (Earle *et al*., 2013). See section **1.6 Non-native species for biocontrol.**

### 2.3.5 Chemical control using herbicides

**Key findings**

- A controlled, replicated greenhouse experiment, found endothall at a concentration of 0.5 mg $L^{-1}$ to be 100% effective after 19 days (Hofstra and Clayton, 2001).
- A replicated, controlled field trial showed endothall at a concentration of 5 mg $L^{-1}$ to be 100% effective after 53 days (Wells and Champion, 2010).

**Further information**

Several herbicides are effective on *L. major;* however, none of these are licensed for aquatic use in the UK. Diquat is reportedly highly effective against *L. major* (Clayton, 1996). In greenhouse experiments in New Zealand, endothall was effective in killing L. major in 19 days when applied at a concentration of 0.5 mg $L^{-1}$ (Hofstra and Clayton, 2001). Triclopyr and dichlobenil were also trialled but found to be only poorly effective or ineffective respectively (Hofstra and Clayton *et al*., 2001). Wells and Champion (2010) looked at the effectiveness of endothall in a field context using small shallow ponds in New Zealand. Endothall was applied to each pond at different concentrations (5, 2.5, 1, 0.5, 0.11 and 0 mg $L^{-1}$). The results showed that no *L. major* remained after 53 days when treated with endothall at 5 mg $L^{-1}$ while browned shoots with no evidence of re-growth were found in ponds treated with 0.11 mg $L^{-1}$ (Wells and Champion, 2010). However, in a pond treated with 0.5 mg $L^{-1}$, some re-growth of *L. major* was seen after 10 months indicating that at very low concentrations success can be variable. Other species in the pond, including species native to New Zealand, were not affected by the herbicide (Wells and Champion, 2010). See section **1.5 Use of chemicals**.

### 2.3.6 Physical and mechanical control via cutting and hand-pulling

**Key finding**

- Mechanical cutting and hand-pulling are considered poor-moderately successful tools for controlling *L. major* (Angling Trust, 2016).

**Further information**

*Lagarosiphon major* can be physically removed from sites by mechanical cutting, using the most appropriate tools for the site, or in small shallow areas, by hand-pulling (Angling Trust, 2016). Care must be taken to net the location and dispose of plant material appropriately to avoid disseminating propagules (Newman, 2004b; Angling Trust, 2016). Since the plant collapses over winter in more northerly regions it has been suggested that cutting should take place in April when the plant has started to grow again; the exception being the south of the UK where it may be possible to cut plants earlier in the year (Newman, 2004b). Hussner *et al*. (2017) stated that mowing (by boat) and suction-dredging combined with other methods are suitable for all submerged species. Suction-dredging removes the plants together with their roots, is highly species-specific and is effective in small areas (Hussner *et al.*, 2017).

### 2.3.7 Environmental control by plant suppression

**Key finding**

- In a before-and-after trial, *L. major* decomposed at six out of seven sites under jute matting in 4 months (Caffrey *et al*., 2010).

**Further information**

Biodegradable matting placed on the bottom of water bodies is a technique which has been used to suppress unwanted aquatic plants. It is limited to small areas with static or slow flow, and limited wind or wave exposure (Hussner *et al.*, 2017). The effectiveness of using jute matting for controlling *L. major* was investigated in Lough Corrib Lake, Ireland (Caffrey *et al.*, 2010). The extent of the *L. major* infestation was recorded before the matting was placed at seven sites within the lake. The matting was left in place for between 4 and 17 months. At all but one site the results showed that *L. major* had decomposed after the matting had been in place for 4 months. Observations showed that the matting remained in good condition up to 7 months after installation, after 10 months it was intact but easily torn and after 17 months it easily disintegrated on contact (Caffrey et al., 2010). Furthermore, after the mats had been in place for 7 or more months some native plants began to establish on the mats (Caffrey *et al.*, 2010). This is encouraging as it shows that the native vegetation is quickly able to recolonise these areas. Hussner *et al*. (2017) suggested dye application as an appropriate control measure for submerged species in shallow water bodies but this has not been specifically tested for *L. major.*

### 2.3.8 Environmental control via altered flow

**Key finding**

- Altering flow is a potential control measure for *L. major* but has not been tested (Newman, 2004b).

**Further information**

Growth could be reduced by increasing the flow of water although this could also lead to increased fragmentation of the plant and inadvertently lead to its spread (Newman, 2004b). Water-level drawdown is another measure which may be suitable but is untested for *L. major* (Hussner *et al.*, 2017). Nutrient reduction may be beneficial in controlling all species (Hussner *et al.,* 2017).

### 2.3.9 Further research

Altered flow, water-level drawdown and nutrient reductions are potential control measures for *L. major* but have not been tested.

## 2.4 Canadian pondweed *Elodea canadensis*

RECOMMENDED CONTROL MEASURES: Floating plastic covers or dyes to create shade. Biocontrol with grass carp would require approval from regulatory bodies.

### 2.4.1 Species profile

**Description**: A perennial, submerged aquatic plant (Newman and Duenas, 2010a).

**Origin**: North and South America (Holm *et al*., 1969; Newman and Duenas, 2010a; Hussner, 2012; Alaska DNR, 2016).

**UK distribution**: *Elodea canadensis* was introduced to Europe in the 19th Century and first seen in the wild in the UK in 1842 (Abernethy *et al*., 1996; Dadds et al., 2007; Zehnsdorf *et al*., 2015). Originally introduced as an ornamental, it is commonly used as an oxygenating plant in aquaria (Dadds *et al*., 2007; Zehnsdorf *et al*., 2015). Spread has slowed somewhat since its initial expansion and it is now frequently replaced by *E. nuttallii* (Dadds *et al.*, 2007). It is widespread and common across much of the UK with the exception of the Highlands, Western Isles and Shetland (NBN Gateway, 2016).

**Habitat**: Slow moving water such as lakes, ponds, canals and reservoirs (Newman and Duenas, 2010a).

**Reproduction**: In the UK, it reproduces entirely vegetatively (Bowmer *et al*., 1995).

**Impact**: Dominates and outcompetes native vegetation (Dadds *et al*., 2007). *Elodea canadensis* can also alter invertebrate communities with knock-on effects for their fish predators (Kornijów *et al.*, 2004). All *Elodea* species take up metals from the sediment and release them into the water.

**Legislation**: Wildlife and Countryside Act 1981. Wildlife (Northern Ireland) Order 1985. *Elodea canadensis* is also listed on the IUCN list of problematic alien species.

### 2.4.2 Invasion pathways and techniques to limit spread

**ESCAPE: horticulture, aquaria**

- Proper disposal of garden and aquaria waste.

**HUMAN TRANSPORT: recreational boats/equipment**

- Vehicles, boats, equipment and clothing should all be checked for fragments of the plant to prevent *E. canadensis* from being spread into new locations (RAFTS, 2006).

**NATURAL: birds, animals**

- No techniques available to limit spread via this mechanism.

**Further information**

*Elodea canadensis* is sold in garden centres and/or through aquarium trade and subsequently escapes into the wild via discarded pond and aquaria waste. *Elodea canadensis* can establish new populations from small fragments transported on equipment and boats (Dadds *et al*., 2007) and thus good practice surrounding the movement of recreational boats and equipment could help in its control (Alaska DNR, 2016). It is also potentially moved between waterways by birds and animals.

### 2.4.3 Summary of control measures and evidence of success

| BIOLOGICAL: non-native herbivores |
|---|
| ? In a before-and-after trial, grass carp resulted in a 91% reduction in aquatic macrophytes including *Elodea*. |
| ? Another before-and-after trial resulted in 100% removal of aquatic macrophytes (*Elodea* included) after 7 years using a stocking density of 33 grass carp $ha^{-1}$. |
| **CHEMICAL: herbicides, lime** |
| ? Diquat is effective in controlling *E. canadensis*. |
| ✓ High application of lime (to pH 10.8-11) completely suppressed root growth and reduced biomass in a controlled, replicated laboratory experiment. |
| **PHYSICAL AND MECHANICAL: cutting** |
| × A controlled, replicated laboratory experiment found that cutting increased plant length, biomass and the number of lateral shoots. |
| ? Cutting twice reduced plant length by 44% and biomass by 59% in a controlled, replicated experiment. |
| **ENVIRONMENTAL: altered flow** |
| ? A controlled, replicated experiment in which water levels were lowered for 5-8 days resulted in 100% mortality. |
| **ENVIRONMENTAL: shading** |
| ✓ Shading by trees, materials or dyes completely controls *E. canadensis.* |

### 2.4.4 Biological control using non-native herbivores

**Key findings**

- Grass carp resulted in a 91% reduction in aquatic macrophytes (*Elodea* included) in a before-and-after trial in the USA (Mitzner, 1978).
- A before-and-after trial resulted in 100% removal of aquatic macrophytes (*Elodea* included) with a stocking density of 33 grass carp $ha^{-1}$ after 7 years (Maceina *et al*., 1992).

**Further information**

Grass carp (*Ctenopharyngodon idella*) have been used to control a number of invasive aquatic plants (see 2.2.4). In two before-and-after trials, these herbivorous fish reduced overall coverage of aquatic invasive plants, which included *E. canadensis*, by 91% (Mitzner, 1978) and 100% (Maceina *et al*., 1992). Maceina *et al*. (1992) used a stocking density of 33 fish $ha^{-1}$ but did report changes in water chemistry, specifically increases in phosphate, total phosphorus and ammonium. Biocontrol with grass carp would require approval from regulatory bodies. See section **1.6 Non-native species for biocontrol.**

A fungus (*Fusarium* sp.) has been identified in Brazil which causes damage to a similar plant, *Egeria densa* (Department of Ecology State of Washington, 2016). However, no further information is available on the potential for using this fungus in the UK to control *Elodea*.

### 2.4.5 Chemical control using herbicides or lime

**Key findings**

- In a controlled, replicated greenhouse study, 0.09 mg $L^{-1}$ diquat effectively reduced *E. canadensis* biomass by >90% (Glomski *et al*., 2005).
- A before-and-after trial showed fluridone at 5-10 µg $L^{-1}$ reduced biomass by >90% (Alaska DNA, 2016).
- High application of lime (to pH 10.8-11) completely suppressed root growth and reduced biomass in a controlled, replicated laboratory experiment (James, 2008).

**Further information**

Since *E. canadensis* grows beneath the surface, herbicides cannot be applied to foliage. In a greenhouse study, 3 weeks after treatment with diquat at application rates as low as 0.09 mg $L^{-1}$ and with exposure times as short as 4 hours, a 96-100 % reduction in *E. canadensis* was revealed (Glomski *et al*., 2005). However, this could be dependent on the environment in which the plant is growing because Browner (1982) found a reduction in herbicide uptake where the plants had a surface coating of clay particles, algae, bacteria and detritus. Fluridone has been successful in reducing biomass of *E. canadensis* in Alaskan lakes by more than 90% when used at concentrations 5-10 µg $L^{-1}$ (Alaska DNR, 2016). Diquat and fluridone are not licensed for aquatic use in the UK. See section **1.5 Use of chemicals.**

The addition of lime is an alternative method for controlling *E. canadensis*. It works by limiting growth by reducing dissolved inorganic carbon (DIC) available as $CO_2$ for photosynthesis and replacing it with $HCO_3^-$ which can only be used by certain plants (James, 2011). Although *E. canadensis* is able to utilise $HCO_3^-$ for photosynthesis, this ability is pH dependent. Thus by increasing pH above 9.8, James (2008) demonstrated supressed growth. In an outdoor laboratory experiment in the United States, using tanks filled with tap water (pH 7.8) and planted with *E. canadensis*, low, moderate and high applications of lime were made to the water with the aim of increasing the pH to 9.8-10, 10.3-10.5 and 10.8-11 respectively. The results showed net root growth was supressed under low and moderate lime applications and ceased under high application with a loss of biomass also detected. James (2008) suggests this can be attributed to a decrease in DIC (both $CO_2$ and $HCO_3^-$) and an increase in $CO_3^{2-}$ inhibiting photosynthesis.

### 2.4.6 Physical control by cutting

**Key findings**

- A controlled, replicated laboratory experiment found that cutting increased plant length, biomass and the number of lateral shoots (Mielecki and Pieczynska, 2005).
- Cutting twice reduced plant length by 44% and biomass by 59% (Abernethy *et al.*, 1996).

**Further information**

*E.canadensis* can be removed physically using whatever tools are suited to the nature of the site (e.g. removal by hand, raking, chains, weed buckets, weed boats or dredging (Newman and Duenas, 2010a; Hussner *et al.*, 2017). For any plant that reproduces readily from small fragments, there is always the risk that cutting will be ineffective. There is specific evidence that *E. canadensis* regains its biomass within 10 days (LeYi, 1999) and can increase in dominance after cutting (Howard-Williams *et al.*, 1996). A laboratory experiment by Mielecki and Pieczynska (2005) measured the growth (defined as the length and biomass) and the number of new lateral shoots of both whole *E.canadensis* plants and their fragments. They found greater growth of cut plants compared with whole plants. More lateral shoots also developed on cut plants compared with whole plants.

If cutting is implemented, then more than one cut appears to be required. A laboratory experiment conducted using tanks with pot grown plants investigated the reduction in plant length and biomass following cutting. Plants were subject to one of three treatments. Control plants were left uncut; others were cut to a height of 5 cm after 35 days and the final set of plants were cut to a height of 5 cm after 35 days and again after 66 days. Plant length was measured 123 days after the start of the experiment. The results showed no significant difference (relative to the control) in plant length after the first cut whilst a 44% length reduction was seen after two cuts (Abernethy *et al.*, 1996). This corresponded to a 41% biomass reduction after the first cut and a 59% biomass reduction after the second cut (Abernethy *et al*., 1996). Newman and Duenas (2010a) suggest repeated cuttings of *Elodea canadensis* for 1-2 months in summer or alternatively cutting annually in early spring to delay the peak biomass period, with the expectation that repeat cuttings will eventually lead to its demise.

Hussner *et al*. (2017) listed suction dredging as a control measure for submerged plants such as *Elodea* spp. However, this requires a skilled operator and scuba.

### 2.4.7 Environmental control by water-level drawdown

**Key finding**

- A controlled, replicated experiment resulted in 100% mortality of *E. canadensis* plants 8 weeks after a 5-8 day drawdown (Barrat-Segretain and Cellot, 2007).

**Further information**

Drawdown leading to desiccation of plants has shown promising results for reducing *E. canadensis*. A laboratory experiment using fragments of plants and small non-anchored plants showed that drawdown for as little as 2 days reduced the survival of whole *E. canadensis* plants (Barrat-Segretain and Cellot, 2007). Furthermore, no fragments of *E. canadensis* survived after 8 weeks following a drawdown of 5-8 days (Barrat-Segretain and Cellot, 2007). However, this study only considered non-anchored plants and fragments rather than the dense anchored vegetation which is likely to occur naturally.

### 2.4.8 Environmental control by shading

**Key finding**

- Shading by trees, materials or dyes completely controls *E. canadensis* (Newman and Duenas, 2010a).

**Further information**

Providing shading by planting trees on the south side of water bodies or floating opaque material on the water surface has been suggested for reducing or completely controlling *E. canadensis* (Newman and Duenas, 2010a). Alternatively dyes can be applied to the water before the plant starts to grow in the spring or when water temperatures are less than 8-10 °C, and then repeated 6-8 weeks later to restrict the light available to the plants and reduce growth (Newman and Duenas, 2010a; Hussner et al., *2017).* Timing appears to be critical as other evidence suggests that *E. canadensis* plants and fragments still grow well in low light conditions (Mielecki and Pieczynska, 2005). Bottom-shading benthic barriers are suitable for other submerged species but have not been tested for *E. canadensis* (Hussner *et al.*, 2017). All invasive aquatic species are likely to be suppressed by nutrient reductions to water bodies (Hussner *et al.*, 2017).

### 2.4.9 Further research

Shading has been reported as a successful control measure for *C. canadensis* but benthic matting has not been tested. Lime appears to be effective but has not been used in a field setting. Water-level drawdown requires further investigation into its effectiveness for this species.

## 2.5 Nuttall's pondweed *Elodea nuttallii*

RECOMMENDED CONTROL MEASURES: Repeated cutting; benthic matting.

### 2.5.1 Species profile

**Description**: A dioecious, perennial, submerged-root aquatic plant with floating flowers (CABI, 2010a).

**Origin:** Native to North America where it is considered threatened (Newman and Duenas, 2010b; Hussner, 2012).

**UK distribution:** *Elodea nuttallii* was brought to the UK as an oxygenating plant for aquaria and first recorded in the wild in the UK in 1966 (Dadds *et al.*, 2007). It is now widespread across central and southern England, Wales and central Scotland, with scattered records elsewhere (NBN Gateway 2016).

**Habitat:** It thrives in slow-flowing eutrophic waters, often replacing *Elodea canadensis* (Dadds *et al*., 2007; Newman and Duenas, 2010b).

**Reproduction:** It reproduces readily from small plant fragments (CABI, 2010a).

**Impact:** The species is able to form extensive mats which can impede recreational use of water bodies and is considered detrimental to native plants and animals (CABI, 2010a; Dadds *et al.*, 2016). However, evidence is inconclusive in determining whether *E. nuttallii* causes the decline in native plants or whether they are already declining due to changing environmental conditions and *E. nuttallii* is better able to exploit the new conditions (Scott Wilson, 2009).

**Legislation:** Wildlife and Countryside Act 1981. Wildlife (Northern Ireland) Order 1985.

### 2.5.2 Invasion pathways and techniques to limit spread

**ESCAPE: horticulture, aquaria**

- Restrictions on sale and planting (CABI, 2010a).
- Public awareness and education necessary to prevent spread.
- Proper disposal of garden and aquarium waste.

**NATURAL: waterfowl, currents**

- No techniques available to limit spread via this mechanism.

**Further information**

Inappropriate disposal of unwanted aquarium plants and escapes from garden ponds are the likely mechanisms for the establishment of this species in the wild (CABI, 2010a).

### 2.5.3 Summary of control measures and evidence of success

| BIOLOGICAL: non-native herbivores | |
|---|---|
| ? | Expert opinion advised grass carp and common carp as effective control agents. |
| ✓ | In a replicated field experiment, the removal of rudd led to 100% domination by *E. nuttallii* after 14 months. |
| ✓ | In a controlled, site manipulation experiment, the removal of fish led to ~100% domination by *E. nuttallii*. |
| **PHYSICAL AND MECHANICAL: cutting** | |
| ✓ | A controlled, site comparison showed cutting once or twice reduced biomass by 72% and 97% respectively. |
| ✓ | Expert opinion recommended multiple cuts from February throughout the summer as the most effective cutting strategy. |
| **ENVIRONMENTAL: suppression** | |
| ✓ | In a controlled, replicated field trial, *E. nuttallii* was reduced by 50-75% in areas covered by 0.5 mm 300 $gm^{-2}$ mesh jute matting. |
| **ENVIRONMENTAL: water-level drawdown** | |
| × | A study of a natural drawdown event suggested no effect on *E. nuttallii*. |
| ? | In a replicated, controlled laboratory experiment, no plant fragments survived after 8 days drawdown. |
| × | In the same experiment, whole plants were unaffected by 5-8 days drawdown. |
| **ENVIRONMENTAL: shading** | |
| ? | Expert opinion suggests shading may help control *E. nuttallii*. |

### 2.5.4 Biological control using native herbivores

**Key finding**

- There is no evidence beavers are consuming *E. nuttallii* in Scotland (Willby *et al*., 2011).

**Further information**

Beavers are potential consumers of *E. canadensis* as well as dispersal agents (Scott Wilson, 2009) but there is little evidence they are having much effect at Knapdale island (Willby *et al.*, 2011).

### 2.5.5 Biological control using non-native herbivores

**Key findings**

- Expert opinion advised grass carp and common carp as effective control agents (Newman and Duenas, 2010b).
- In a replicated field experiment, excluding rudd led to 100% domination by *E. nuttallii* after 14 months, compared with 1% cover in control areas with stocking density 297 kg $ha^{-1}$ (Van Donk and Otte,1996).
- In a controlled, site manipulation experiment, the fishless site became dominated (~100% coverage) by *E. nuttallii* (van de Haterd and Ter Heerdt, 2007).

**Further information**

Newman and Duenas (2010b) suggested grass carp (*Ctenopharyngodon idella*), as well as common carp (*Cyprinus carpio*) and other bottom feeding fish, as effective control agents for *E. nuttallii*. In a manipulation experiment, Van Donk and Otte (1996) investigated the effects of common rudd (*Scardinius erythrophthalmus*) on the species composition of submerged macrophytes in Lake Zwemlust, Netherlands. The lake was already stocked with 297 kg rudd $ha^{-1}$. Six wire exclosures were placed on the bottom of the lake at a depth of 2 m. The density of rudd in the exclosures was manipulated to range from 0 to 1575 kg $ha^{-1}$. The vegetation in the exclosures was considered comparable with that found in the wider lake prior to stocking. After 14 months, *E. nuttallii* dominated (up to 100% cover) in the exclosures where rudd had been excluded while outside the cages in the wider lake *E. nuttallii* reached only 1% cover. A similar effect was found in Lake Terra Nova, Netherlands. Removal of cyprinid fish from a 0.5 ha experimental site led to domination by *E. nuttallii* (~100% coverage) compared with fish-stocked and control areas which showed greater vegetation diversity (van de Hasterd and Ter Heerdt, 2007). Biocontrol with grass carp would require approval from regulatory bodies. See section **1.6 Non-native species for biocontrol.**

### 2.5.6 Physical removal by cutting

**Key findings**

- A controlled, site comparison showed cutting once or twice reduced biomass by 72% and 97% respectively (Di Nino *et al*., 2005).
- Expert opinion recommended multiple cuts from February and throughout the summer as the most effective cutting strategy (Newman and Duenas, 2010b).

**Further information**

An experiment in a French river tested the effectiveness of two cutting treatments. One site received a single harvest in February (the beginning of the growing season) and the other received a harvest in February and a second in May (just before the plant starts to fragment). A control reference site was included for comparison. Regrowth and biomass production were monitored up until the end of October. Biomass was significantly reduced at the site harvested twice compared with that harvested just once (mean 14 g DW $m^2$ compared to 120 g DW $m^2$) (Di Nino *et al*., 2005). Both had significantly lower biomass than the reference site (556 g DW $m^2$) (Di Nino *et al*., 2005).

The Centre for Ecology and Hydrology (Newman and Duenas, 2010b) suggest that *E. nuttallii* is best cut before July to achieve maximum effectiveness but if cutting takes place before the end of June a second cut will also be required. To limit growth at the beginning of the season cutting can commence in mid-February, followed by regular treatments at 6-8 week intervals throughout the summer. This will reduce the biomass produced. By September the plant will have begun to take on an overwintering form, therefore the final cut should take place before September (Newman and Duenas, 2010b). Additionally, Hussner *et al.* (2017) listed mowing (by boat) or suction-dredging particularly when combined with other methods, as suitable for all submerged species Regardless of the method used, it is important to use nets or other means to retain any loose fragments which may arise from harvesting and thus prevent further spread of this species (CABI, 2010a).

### 2.5.7 Environmental control via suppression

**Key finding**

- In a controlled, replicated field trial, *E. nuttallii* was reduced by 50-75% in areas covered by 0.5 mm 300 $gm^{-2}$ mesh jute matting (Hoffmann *et al.*, 2013).

#### Further information

Jute matting has been used to cover *E. nuttallii* infestations with the aim of shading out the plant. This technique has proved successful in the short-term (first year) (Hoffmann *et al*., 2013). Mesh size is important, and in a laboratory experiment Hoffmann *et al*. (2013) found that *E. nuttallii* was restricted by 0.5 mm 300 $gm^{-2}$ mesh. This mesh was further tested at experimental sites in two lakes. The jute matting was placed in April 2011 and visited every two weeks by divers until November 2011. *Elodea nuttallii* was reduced by 50-75% in the covered areas compared with the uncovered control areas (Hoffmann *et al*., 2013).

### 2.5.8 Environmental control via water-level drawdown

#### Key findings

- A study of a natural drawdown event suggested no effect on *E. nuttallii* (Barrat-Segretain and Cellot, 2007).
- In a replicated, controlled laboratory experiment, plant fragments (although not whole plants) were killed by a drawdown of 8 days (Barrat-Segretain and Cellot, 2007).

#### Further information

*Elodea nuttallii* is believed resilient to desiccation, surviving drawdown much better than *E. canadensis*. Observations on an isolated meander of the River Ain, France, which experiences natural drawdown, seemed to support this theory (Barrat-Segretain and Cellot, 2007). Surviving plant fragments in the moist river bed (below 5 cm) were credited with the species' persistence. Controlled laboratory experiments showed no effect on whole plants, but mortality of plant fragments increased after 5 days drawdown and none survived 8 days drawdown (Barrat-Segretain and Cellot, 2007).

### 2.5.9 Environmental control via shading or nutrient reduction

#### Key finding

- Expert opinion suggests that shading by trees, sheets, opaque material or dyes may reduce biomass (Newman and Duenas, 2010b; Hussner *et al*., 2017).

#### Further information

Shading has been suggested as a possible method for controlling *E. nuttallii.* This could be achieved by planting trees on the south side of water bodies, placing floating sheets or opaque material over the infestation, or adding dyes to static water before the plants start to grow in the spring (Newman and Duenas, 2010b; Hussner *et al.*, 2017). In the latter case the authors note that this may need to be repeated 6-8 weeks after the initial application (Newman and Duenas, 2010b). Hussner *et al*. (2017) also proposed that nutrient reductions may at least suppress submerged invasive plants but this has not explicitly been tested.

### 2.5.10 Further research

*Elodea nuttallii* is also a species for which information about basic ecology and reproductive strategies is incomplete. The application of lime has been successful in controlling *E. canadensis* but the effects on *E. nuttallii* have not been tested. There are currently no data to suggest how effective shading can be in controlling *E. nuttallii*.

## 2.6 Common cord-grass *Spartina anglica*

RECOMMENDED CONTROL MEASURES: A combination of cutting, smothering and/or glyphosate although approval is required for the latter. Control measures are only required if the species is considered locally problematic.

### 2.6.1 Species profile

**Description**: *Spartina anglica* is a perennial salt marsh grass.

**Origin:** It originated in the UK as a fertile hybrid of *Spartina maritima* (native to Europe) and the introduced North American *Spartina alterniflora* (Hubbard, 1968; CABI, 2009c) through choromosome doubling of the sterile hybrid *Spartina x townsendii*. Due to the ability of this new species to capture sediment thus helping with land claim projects, it was introduced to over 130 sites around the world between 1924 and 1936 (CABI, 2009c). *Spartina anglica* has has since colonised areas beyond these initial introductions through natural dispersal.

**UK distribution:** First found in Southampton in the 19th Century, *S. anglica* is the most extensive species of cord-grass in the UK (Roberts and Pullin, 2008). McCorry and Ryle (2009a) stated there was little rationale for control at large sites where the likelihood of success was limited. They suggested *S. anglica* swards might now be considered as a pioneer saltmarsh community. Some of the original locations where expansion was rapid are now experiencing 'die-back', so extent can change without intervention.

**Habitat**: *Spartina anglica* is found in estuaries, salt marshes, lagoons and mud flats. It can survive periods of up to 9 hours submergence (Ranwell, 1961). Wave action has been suggested as a factor limiting *S. anglica* establishment (Morley, 1973; Groenendijk, 1986).

**Reproduction**: This species reproduces via seeds but also through rhizomes.

**Impact:** *Spartina anglica* has both positive and negative impacts and these may be site-specific (McCorry *et al.*, 2003). It can alter soil organic matter, porosity and pH (CABI, 2009c). It can also alter the landscape to form badly drained marshes that commonly have steeply sloping seaward edges and deep, steep-sided channels which can result in flooding (McCorry *et al*., 2003). Of particular concern is the potential loss of habitat for wading birds although this has not been quantified (RAFTS, 2006; Roberts and Pullin, 2008; McCorry and Ryle, 2009b). The species outcompetes native vegetation such as *Zostera* but facilitates establishment of other organisms such as some algae and fungi (CABI, 2009c) and creates suitable habitat to support a rich and abundant macroinvertebrate fauna (McCorry and Otte, 2001). There have been ongoing shifts in *S. anglica*-dominated communities but due to lack of detailed monitoring it is unclear if there has been an overall expansion (Lush *et al*., 2016).

**Legislation:** Wildlife and Countryside Act 1981. Wildlife (Northern Ireland) Order 1985. *Spartina anglica* is listed on the IUCN list of problematic alien species.

### 2.6.2 Invasion pathways and techniques to limit spread

| **DELIBERATE: intentional planting** |
|---|
| • Plants should not be used unnecessarily for land reclamation projects (RAFTS, 2006). |
| **HUMAN TRANSPORT: ballast water** |
| • Legislative control of ballast water may limit future spread. |
| **NATURAL: seed dispersal, rhizomes, tides** |
| • No techniques available to limit spread via this mechanism. |

**Further information**

*Spartina anglica* has an extensive rhizome system and for this reason has been deliberately planted to stabilise tidal mudflats and for land reclamation (RAFTS, 2006; CABI, 2009c). Natural dispersal occurs by expansion through the rhizomes and seeds, which can remain dormant for several years (RAFTS, 2006). Tidal conditions can also facilitate spread to new areas (CABI, 2009c). Ballast water in shipping has also been listed as a potential invasion pathway (CABI, 2009c). In some areas in Ireland and England, the species has ceased spreading and there are now positive signs of natural succession to native vegetation communities (McCorry and Ryle, 2009a; Sue Rees, pers. comm.). Before any control measures are considered, it is essential to understand the current situation with *S.anglica* at a site level to assess whether the species is considered a problem. A suggested monitoring method is given in Lush *et al*. (2016). If it is not considered a problem, then control measures are not required.

### 2.6.3 Summary of control measures and evidence of success

| **BIOLOGICAL: co-evolved, host specific herbivores** |
|---|
| ? A controlled, replicated pot experiment showed c.93% mortality of *S. anglica* plants after 5 months when *Prokelisia* leafhoppers were present. |
| **CHEMICAL: herbicides** |
| ? Fluazifop (Fusilade) and Haloxyfop (Gallant) achieve 90% mortality after one application. |
| **PHYSICAL AND MECHANICAL: hand-pulling, burying, burning** |
| ✓ Expert opinion reports hand-pulling as effective for young plants. |
| ✓ A before-and-after trial showed that mechanical disturbance reduced the number of *S. anglica* stems by 50% after 3 years. |
| ✓ Expert opinion cites repeated cutting with a strimmer as being effective on sandy sediments. |
| ✓ Expert opinion reports >90% mortality due to repetitive burying. |
| ✓ Expert opinion reports >90% mortality due to repetitive burning. |
| **CHEMICAL + PHYSICAL: cutting + herbicide** |
| ? A controlled, replicated laboratory experiment found that cutting followed by glyphosate application increased stem density after 1 year. |
| ? Before-and-after field observations reported that cutting followed by glyphosate application reduced *S. anglica* coverage by 71% in high salinity marshes and 10% in low salinity marshes after 4 years. |
| ? Annual cutting combined with 5% glyphosate treatment reduced *S. anglica* by <10% after 1 year, 20-60% after 2 years, 20-80% after 3 years and 100% after 4 years. |
| **ENVIRONMENTAL: smothering** |
| ✓ Expert opinion reports that >90% mortality can be achieved by smothering with plastic sheeting. |
| **PHYSICAL + ENVIRONMENTAL: cutting + smothering** |
| ✓ A controlled, replicated experiment demonstrated more than 90% reduction in the stem density of *S. anglica* when cut and then smothered by black plastic sheeting for 6 months. |

### 2.6.4 Biological control using co-evolved, host specific herbivores

**Key finding**

- A controlled, replicated pot experiment showed c.93% mortality of *S. anglica* plants after 5 months subject to the presence of leafhoppers numbering 2-200 (Wu *et al.*, 1999).

**Further information**

Leaf hoppers (nymphs and adults) of the genus *Prokelisia* typically feed on *Spartina* sp. but had not been recorded on *S. anglica*. An experimental study at Washington State University investigated whether the insects would feed on *S. anglica* and what effect they would have on the plant. High density treatments of each species were provided by adding two insects per plant which reproduced to give c.200 individuals after 5 months. Low density (control treatments) had <1 individual per plant. The results showed c.93% mortality of *S. anglica* plants subject to high densities of either *P. marginata* or *P. dolus* after 5 months. In contrast, mortality in the low density treatment was negligible (<1%) (Wu *et al.*, 1999). Permission for release of any non-native herbivore needs approval from regulatory bodies. See section **1.6 Non-native species for biocontrol**.

### 2.6.5 Chemical control using herbicides

**Key finding**

- Fluazifop (Fusilade) and Haloxyfop (Gallant) both achieve 90% mortality after one application (Global Invasive Species Database, 2016c).

**Further information**

Both dalapon and glyphosate have been considered for controlling *S. anglica* but the latter has been shown in laboratory trials to be ineffective on its own (but see section **2.6.7**). Hammond and Cooper (2003) showed over 95% reduction in stem density during the first year in areas treated with Dalapon applied at a rate of 57 kg $ha^{-1}$ while glyphosate was ineffective, resulting in a similar stem density to untreated controls. In a review, Roberts and Pullin (2008) considered fenuron and aminote-T the most effective herbicides achieving an 88.2% and 75.8% reduction in density respectively, although both results were based on a small data pool. Glyphosate achieved only a 43% reduction in density, although significant results could be achieved with the addition of a wetting agent additive and by carrying out the treatment in July (Roberts and Pullin, 2008). Fluazifop (Fusilade) and Haloxyfop (Gallant) both regularly achieve over 90% mortality after one application (Global Invasive Species Database, 2016c). Complete eradication requires at least two time-separated applications (RAFTS, 2006; Global Invasive Species Database, 2016c). Gallant has been used in New Zealand with near eradication of the plant from estuaries in South Island (K. Crothers, pers. comm. cited in Deithier and Hacker, 2005). Only glyphosate is licensed for aquatic use in the UK (see section **1.5 Use of chemicals**). Chemical control would not be suitable where there are stands of the rare *Spartina maritima*, which is very limited in the UK, only being found in a few locations in England (Garbutt *et al.,* 2015).

### 2.6.6 Physical control by hand-pulling, cutting, burying, burning

**Key findings**

- Hand-pulling is effective especially for very young plants (Cottet *et al.*, 2007; Global Invasive Species Database, 2016c).
- Mechanical disturbance with a tracked vehicle reduced the number of stems by 50% after 3 years (Frid *et al*., 1999).
- Expert opinion cites repeated cutting with a strimmer as being effective on sandy sediments (Mark McCorry, *pers. comm*.).
- Repetitive burying results in over 90% mortality (Global Invasive Species Database, 2016c).
- Repetitive burning results in over 90% mortality (Global Invasive Species Database, 2016c).

**Further information**

There have been widely differing results reported for cutting alone as a control measure, and consequently, it is not recommended except in combination with other methods (e.g. herbicide and/or smothering) (Lush *et al*., 2016). Repeated cutting with a strimmer was effective on sandy sediment (Mark McCorry, *pers. comm.*). Hand-pulling was found to be the most effective treatment in Arcachon Bay, France (Cottet *et al*., 2007). Great care, however, needs to be taken in the transport and storage of vegetation waste (Lush *et al*., 2016). At the same site, an inversion treatment to expose the root systems showed signs of recovery. The age of plants may have some bearing on hand-pulling and it has been deemed effective only for seedlings or very young plants because of the extensive root mass (Hedge *et al.,* 2003; Global Invasive Species Database, 2016c). Mechanical disturbance can be effective but there have been no longer-term studies to monitoring success. On the submerged saltmash at Lindisfarne, UK a tracked vehicle with a Blecavator stone burier which was driven repeatedly over a 50 x 50 m experimental area, dislodging and burying *S. anglica* in the sediment. No plants remained immediately after this process. Three years later the stem density was recorded in 20 0.5 x 0.5 m quadrats. In disturbed plots, stem density was c.40 $ha^{-1}$ compared with c.80 $ha^{-1}$ in the control plots (Frid *et al.*, 1999). In other studies cutting has been found to be unsuccessful and can in fact increase grass growth (Hammond and Cooper, 2003; Hubbard, 1968). Repeated burning reportedly kills over 90% of plants (Global Invasive Species Database, 2016c) but there are no studies to substantiate this claim (Lush *et al*., 2016).

### 2.6.7 Combination chemical and physical control by cutting and herbicide

**Key findings**

- Cutting followed by glyphosate application increased stem density after 1 year (Hammond and Cooper, 2003).
- Cutting followed by glyphosate application reduced *S. anglica* coverage by 71% in high salinity marshes and 10% in low salinity marshes after 4 years (Hacker *et al.*, 2001).
- Annual cutting combined with 5% glyphosate treatment reduced *S. anglica* by <10% after 1 year, 20-60% after 2 years, 20-80% after 3 years and 100% after 4 years (Deithier and Hacker, 2005).
- Annual mowing combined with herbicide treatment reduced cover and tiller numbers by 50-75% after 3 years in a field study (Reeder and Hacker, 2004).

**Further information**

Hammond and Cooper (2003) experimentally cut *S. anglica* plants to a height of 10 cm and sprayed with glyphosate after 6 weeks. The result was an increase in stem density (Hammond and Cooper, 2003). Another study in the United States used infrared aerial photos to investigate the effectiveness of the combined annual treatment of hand mowing and 5% glyphosate combined with 1% of the surfactant R-11 application (Deithier and Hacker, 2005). They found this treatment led to an annual 26% decline in *S. anglica* over 4 years (Hacker *et al.*, 2001). Repeated control over a number of years is essential to successful control (Deithier and Hacker, 2005). However, the success of the treatment was dependent on salinity: 71% decline in high salinity marsh compared with 10% decline in low salinity marsh (Hacker *et al*., 2003). In follow-up experiments it was found that early spraying (July to mid-August) produced more effective results (Dethier and Hacker, 2004). Similarly, Reeder and Hacker (2004) used small-scale mowing with brush cutters and walk-behind mowers with a follow-up herbicide on new growth. Their findings indicated that this method needs to be repeated over several years to be effective. After 3 years' treatment, they observed a 50-75% decline in cover and tiller numbers although there were still signs of recovery (Reeder and Hacker, 2004). See section **1.5 Use of chemicals.**

### 2.6.8 Environmental control by smothering

**Key finding**

- Smothering with plastic sheeting results in >90% mortality (Global Invasive Species Database, 2016c).

**Further information**

Plastic sheeting is reportedly effective against *S. anglica* but due to the costs is only practicable for small areas. Mortality of over 90% is achievable (Global Invasive Species Database, 2016c). This method is currently being employed by RSPB at Skinflats, Aberlady, where sheeting was applied in April 2016 and will be left in place for 2 years.

### 2.6.9 Combined physical and environmental by cutting and smothering

**Key finding**

- Cutting followed by smothering with black plastic sheeting for 6 months resulted in a reduction of over 90% in stem density after 1 year (Hammond and Cooper, 2003).

**Further information**

In a replicated experiment Hammond and Cooper (2003) investigated the effectiveness of the combined treatment of cutting to a sward height of 10 cm followed by smothering with black plastic sheeting for 6 months. The results demonstrated a reduction of over 90% in stem density and more importantly, a decline in dry root weight after 1 year compared with control treatments (Hammond, 2001; Hammond and Cooper, 2003).

#### 2.6.10 Further research

Lush *et al.* (2016) detailed further work recommended for *S. anglica*. This includes developing and improving survey protocols to determine the extent of *S. anglica* communities and its impact at a local scale. For example, the theory that *S. anglica* has a negative impact on wading birds warrants further investigation. Research into the use of habitats containing this species by resident and wintering bird species would be extremely useful in quantifying any negative association with the avian fauna. The history of where and when *Spartina* was planted needs to be established in order to understand distribution patterns and changes over time, and into the future under different climatic scenarios (Lush *et al*., 2016).

## 2.7 Carolina fanwort or watershield *Cabomba caroliniana*

RECOMMENDED CONTROL MEASURES: repeated cutting; benthic matting; floating plastic covers.

#### 2.7.1 Species profile

**Description:** A submerged, rooted perennial macrophyte with flowers that extend above the water surface.

**Origin**: North and South America (Dadds *et al*., 2007; Hussner, 2012).

**UK distribution**: *Cabomba caroliniana* was introduced to the UK as an aquarium plant and first found in the Forth and Clyde canal in 1971 (Dadds *et al.*, 2007; Lansdown, 2015). It has only been discovered at one other UK site in the Basingstoke Canal (NBN Gateway, 2016).

**Habitat**: It grows best at water temperatures between 13-27°C, indeed the Forth and Clyde canal site was heated by water from a nearby factory. However, the Basingstoke Canal is not heated suggesting the plant may be able to survive in UK waters, particularly in a warming climate (Plantlife, 2016a).

**Reproduction:** It disperses mainly by seeds but also has the potential to form new plants from small stem fragments (Plantlife, 2010).

**Impact:** This species has the potential to grow into dense, compact mats which out-compete native vegetation and affect the quality and recreational use of water bodies (Plantlife, 2010).

**Legislation:** Wildlife and Countryside Act 1981. Wildlife (Northern Ireland) Order 1985. *Cabomba caroliniana* is also listed on the IUCN list of problematic alien species. It is banned in the UK under new European Union legislation (EU 2016/1141).

#### 2.7.2 Invasion pathways and techniques to limit spread

**ESCAPE: aquaria**

- Proper disposal of plants/cuttings from aquaria.

**HUMAN TRANSPORT: recreational boats/equipment**

- Good sanitation should be encouraged including removing plant fragments from boat hulls, propellers and the boat trailer. All equipment and wading gear should be thoroughly rinsed (ideally with hot water or salt water) and dried for 5 days before moving to another site.
- Public awareness and education are necessary to prevent spread (CABI, 2008a)

**Further information**

Under European Union regulations (EU 2016/1141), it is now an offence in the UK to keep, cultivate, breed, transport, sell or exchange this species, or release it, intentionally or unintentionally, into the environment (Plantlife, 2016a).

#### 2.7.3 Summary of control measures and evidence of success

**BIOLOGICAL: host-specific, native herbivores**

? The weevil *Hydrotimetes natans* showed promise as a biocontrol agent but further research has been unsuccessful due to insufficient breeding in captivity.

**BIOLOGICAL: non-native herbivores**

? Before-and-after trials in two Florida lakes demonstrated a reduction in *C. caroliniana* from 96 to 62% cover with a stocking density of 61.7 fish ha$^{-1}$, but an increase of 36 to 100% cover with 11.7 carp ha$^{-1}$.

**CHEMICAL: herbicides or lime**

? Fluridone eradicated *C. caroliniana* in a field study.

? In a controlled, replication laboratory study, fluridone at concentrations of 20 µg L$^{-1}$ reduced biomass by >80%.

✓ A controlled, replicated laboratory experiment found that lime applied at 160 µM reduced shoot biomass by ~92%.

**PHYSICAL AND MECHANICAL: cutting, dredging**

✓ Expert opinion cites suction-dredging as an effective control measure.

✓ A study has demonstrated the effectiveness of the Hydro-Venturi ventilation method.

✓ Repeated mechanical cutting reduced stem number by up to 80% in field studies.

**ENVIRONMENTAL: suppression**

✓ A study using benthic matting reduced *C. caroliniana* by 95-100%.

\- A study found plastic sheeting reduced biomass but regrowth occurred.

✓ Floating pool covers providing 99% cover eradicated *C. caroliniana* within 120 days in a controlled, replicated experiment.

**ENVIRONMENTAL: water-level drawdown**

? In a controlled, replicated field experiment, drawdown reduced stem number by up to 80%.

#### 2.7.4 Biological control using co-evolved, host specific herbivores

**Key finding**

- The weevil *Hydrotimetes natans* has shown promise as a biocontrol agent (Schooler and Chan, 2011; Schooler *et al.*, 2012).

**Further information**

In Australia, *Paraponyx disminutalis* and *Paracles sp*. have been assessed as biocontrol agents but neither are host specific, and *P. disminutalis* prefers other species (Hussner *et al*., 2017). Within its native range, the weevil *H. natans* is host-specific in both laboratory and field trials, completing its entire life cycle on the plant (Schooler *et al.*, 2012). At high population densities, this weevil caused severe tip and stem damage (Schooler and Chan, 2011). However, further research into host specificity has been slow because of difficulties maintaining sufficient numbers of the weevil in quarantine (Shon Shooner, *pers. comm.*) and obtaining permits for further imports (Sathyamurthy Raghu, *pers. comm.*). Furthermore, it has not been collected in temperate regions and therefore might not be well suited to conditions in the UK (Cabrera-Walsh *et al*., 2011).

### 2.7.5 Biological control using non-native herbivores

**Key finding**

- In before-and-after trials in Florida, triploid grass carp at a stocking density of 61.7 fish $ha^{-1}$ reduced *C. caroliniana* from 96 to 62% cover in one lake. In another lake, a stocking density of 11.7 fish $ha^{-1}$ increased *C. caroliniana* cover from 36-100% (Hanlon *et al*., 2000).

**Further information**

Hanlon *et al*. (2000) investigated the effectiveness of using triploid grass carp *Ctenopharyngodon idella* to control problematic plant species in 38 lakes in Florida. Of these 38 lakes only two contained *C. caroliniana* and the success of stocking with grass carp was variable. One lake stocked with 61.7 carp $ha^{-1}$ of vegetation led to a reduction in *C. caroliniana* cover from 96% to 62% over 9 years, whilst another lake with 36% *C. caroliniana* cover prior to stocking with 11.9 carp $ha^{-1}$ of vegetation, resulted in 100% *C. caroliniana* cover after 6 years. This suggests the carp stocks were too low in the latter to reduce the *Cabomba* and the authors recommend a density of 25-30 carp $ha^{-1}$ (Hanlon *et al*., 2000). Biocontrol with grass carp would require approval from regulatory bodies. See section **1.6 Non-native species for biocontrol**.

### 2.7.6 Chemical control using herbicides or lime

**Key findings**

- Fluridone eradicated *C. caroliniana* in a field trial but also affected surrounding vegetation (Bugbee and White, 2004).
- In a controlled, replication laboratory study, fluridone at concentration of 20 µg $L^{-1}$ reduced biomass by >80% but also negatively affected other species (Nelson *et al*., 2002).
- Lime applied at 160 µM in a controlled, replicated experiment reduced shoot biomass by ~92% (James, 2011).

**Further information**

Sonar (fluridone) was applied as a spot treatment in a lake in Connecticut in an attempt to demonstrate potential control of *C. caroliniana* in a localised area whilst avoiding damage to non-target plants spread more widely across the lake. Following treatment, *C. caroliniana* disappeared from the area while it continued to thrive in the untreated areas (Bugbee and White, 2001). The aim of the spot treatment was to confine the herbicide to a small area but it was detected up to 300 m away in the control area and effects on other vegetation were observed (Bugbee and White, 2001).

Nelson *et al.* (2002) found that fluridone at concentrations ranging from 5-30 µg $L^{-1}$ reduced shoot dry weight biomass but that 20 µg $L^{-1}$ or above was required to reduce *C. caroliniana* by >80%. These concentrations were detrimental to other plant species. Fluridone is not licensed for aquatic use in the UK.

The application of lime to soft water (pH ~7) to raise the pH to 9-10 has been demonstrated to decrease *C. caroliniana* shoot biomass by reducing the amount of free $CO_2$ in the water and thus limiting photosynthesis (James, 2011). Shoot biomass decreased to 36% and 8% of control means following application of 55 or 160 µM of lime respectively (James, 2011). See section **1.5 Use of chemicals.**

### 2.7.7 Physical removal

**Key findings**

- Expert opinion cites suction-dredging as an effective control measure (Oosterhout, 2009).
- Field application has demonstrated the effectiveness of the Hydro-Venturi ventilation method (van Valkenburg, 2011; Dorenbosch and Bergsma, 2014).
- Repeated mechanical cutting has reduced stem number by up to 80% in field studies (Oosterhout, 2009).

**Further information**

A driver-operated suction dredge which sucks out the root as well as removing the foliage can be used in small areas or as an additional method after other control measures have been implemented (Oosterhout, 2009). Care must be taken to prevent fragments spreading (Oosterhout, 2009). A method that has evolved from this has been used in Ewen Maddock Dam, South East Queensland, Australia, since 1998. The essence of the Hydro-Venturi ventilation method is to wash plants out of the sediment, including their root system and subsequently the plants can be removed as they afloat on the water surface (van Valkenburg, 2011; Dorenbosch and Bergsma, 2014). The number of fragments produced is lower than with conventional methods (Hussner *et al*., 2017). Timing is essential to guarantee successful biomass reduction (Plant Protection Service, 2011; van Valkenburg, 2011).

A 3-year trial of mechanical cutting to remove *C. caroliniana* from Lake Macdonald, South-east Queensland, Australia, showed that the plant is sensitive to repeated cuttings leading to a reduction in biomass (Oosterhout, 2009). Before mechanical harvesting began, plants had up to 60 stems per root ball but after 3 years of harvesting which comprised 4 cuts in summer and 1-3 cuts in winter, this had been reduced to 10-12 stems per root ball and the native vegetation begin to re-establish (Oosterhout, 2009). Additionally, cutting to a depth of 1.2 m restricts light to the remaining plant and reduces the speed of re-growth (Oosterhout, 2009).

### 2.7.8 Environmental control by plant suppression

**Key findings**

- Benthic blankets have resulted in a 95-100% reduction of *C. caroliniana* (Oosterhout, 2009).
- A study found plastic sheeting reduced biomass but regrowth occurred (Schooler and Chan, 2011).
- Floating pool covers providing 99% cover completely eradicated *C. caroliniana* within 120 days in a controlled, replicated field trial (Schooler, 2008).

**Further information**

Benthic matting resulted in a 95-100% reduction of *C. caroliniana* in field studies in the United States with no sign of recolonization 2 months after the matting had been removed (Oosterhout, 2009). Shading with black builders' plastic reduced plant biomass but eradication was not possible because of propagules remaining in the sediment (Schooler and Chan, 2011). Floating pool covers were applied in replicate to a lake in Queensland, Australia to provide shading of 0, 70 and 99%. The 99% cover treatment reduced biomass to zero within 120 days and follow up surveys found no surviving plant fragments (Schooler, 2008).

### 2.7.9 Environmental control by water-level drawdown

**Key finding**

- Drawdown reduced stem number by c.80% in a controlled, replicated field experiment (Dugdale *et al*., 2013).

**Further information**

Dugdale *et al.* (2013) found only c.20% of *C. caroliniana* stems survived when the substrate was fairly dry whilst c.95% of stems survived when the substrate was saturated. The basal part of the plant, however, was unaffected suggesting regrowth could occur.

### 2.7.10 Further research

Biological control of *C. caroliniana* by the weevil *H. natans* holds promise but laboratory testing has been slow. Water-level drawdown has not been fully tested for this species.

# 3.0 Invasive animals

## 3.1 Bloody-red shrimp *Hemimysis anomala*

RECOMMENDED CONTROL MEASURES: None currently available.

### 3.1.1 Species profile

**Description:** A relatively small mysid shrimp.

**Origin**: Native to the freshened parts of the Black Sea (Pothoven *et al*., 2007) within the Ponto-Caspian region.

**UK distribution:** During the 1950s and 1960s, *H. anomala* was successfully introduced into reservoirs in Eastern Europe to boost fish productivity (Gasiunas, 1968; Grigorovich *et al.*, 2002). From there, the species was able to move downstream and access the Baltic Sea and beyond (Gasiunas, 1964). The mysid was first recorded in the UK in the Erewash Canal, Nottingshire, in 2004 (Holdich *et al*., 2006). It has since spread to a few other sites in the English Midlands.

**Habitat:** It is found in brackish and fresh waters. The most rapid population growth is likely to occur in warmer, salt water as salinity increases female size (Ketelaars *et al.*, 1999). It has shown tolerance for salinity concentrations of 0-19 ppt (Bij de Vaate *et al.*, 2002; Borcherding *et al.*, 2006) and prefers water temperatures of 9–20°C (Kipp *et al*., 2016). Lentic or very slow waters are preferred but its otherwise wide tolerance for a range of environmental conditions has allowed it to become established in a variety of habitat types (e.g. coastal waters, lagoons, estuaries, rivers, canals and reservoirs). *Hemimysis anomala* has only a very limited ability to swim against a current (Stubbington, 2006; Wittmann and Ariani, 2009), and this may limit its upstream range extension following an initial introduction. However, its distribution in countries including England indicates that *H. anomala* has some capacity to migrate upstream through slow flowing habitat (Stubbington *et al*., 2008). Factors known to limit distribution are discernible flow, overgrowth of aquatic plants and the accumulation of silt (Ioffe, 1973; cited in Pothoven *et al.,* 2007).

**Reproduction**: The species can only reproduce sexually (Mauchline, 1980), and therefore a female carrying fertilized eggs or a combination of male and female individuals must be introduced for population growth to occur.

**Impact:** *Hemimysis anomala* can reach high population densities in newly invaded habitats (Holdich *et al.*, 2006; Pothoven *et al.*, 2007; Wittmann, 2007) and is omnivorous, thus it can have a significant ecological impact (Ketelaars *et al*., 1999). Anecdotal evidence suggests the mysid may increase macrophyte growth indirectly through the consumption of periphyton (Stubbington *et al.*, 2008). Furthermore, high inputs of faecal pellets affect the physiochemical environment. However, it is known to consume the blue-green algae (cyanobacteria) responsible for toxic algal blooms (Ketelaars *et al.*, 1999).

**Legislation:** Wildlife and Countryside Act 1981. Article 15 (2) of the Wildlife (Northern Ireland) Order 1985.

### 3.1.2 Invasion pathways and techniques to limit spread

**HUMAN TRANSPORT: ballast water**

- Legislative control of ballast water may limit future spread.

**NATURAL: flooding**

- Public awareness and education to encourage submission of sightings is one possible technique.

**Further information**

Further range expansion has been facilitated by boat ballast water, which has enabled transportation over great distances including to North America. Flooding may aid dispersal on a local level (Dumont, 2006; Stubbington *et al.*, 2008). The location of entry to the UK, a recreational rowing lake, suggests invasion via ballast water exchange by vessels from mainland Europe. Previous legislation enacted to prevent these accidental introductions did not appear to be effective, specifically that related to ballast water exchange (Ellis and MacIsaac, 2009). However, this may change after the International Convention for the Control and Management of Ships' Ballast Water and Sediments enters into force in September 2017. This will require that all ships have a ballast water management plan and that procedures concerning water ballast are carried out to a specific standard. Preventative measures are encouraged for boaters travelling between water bodies, including visually inspecting boats, trailers, and equipment for plants, animals, and mud after each use, draining water from the motor, live well, bilge, and transom wells while on land, and rinsing all equipment with high pressure (>250 psi) or hot (>50°) water (Ontario's Invading Species Awareness Program) (Francis and Pyšek, 2012).

### 3.1.3 Summary of control measures and evidence of success

**BIOLOGICAL: native predators**

? Potential for biological control by fish.

**CHEMICAL: salinity**

✓ In a controlled, replicated experiment, increasing water salinity to 30 ppt resulted in 100% mortality of *H. anomala* after 3-5 hours.

**PHYSICAL AND MECHANICAL: radiation**

? Low dose radiation in water treatment facilities and narrow channels may control *H. anomala.*

### 3.1.4 Biological control using native predators

**Key finding**

- Predatory fish could potentially limit population expansion.

**Further information**

Bloody-red mysids are predated by fish such as perch and bullheads, and large invertebrate predators including dragonfly larvae. Adult perch (*Perca fluviatilis*) have been shown to consume vast numbers of *H. anomala* in Europe but this predation pressure is insufficient to have an effect on abundance (Ketelaars *et al*., 1999; Borcherding *et al*., 2006). In North America, high densities of planktivorous fish have been shown to limit population expansion, particularly species such as alewives which have a nocturnal feeding habit (Lantry *et al*., 2010). Research has not yet been carried out to determine the biological control potential of fish on *H. anomala*.

### 3.1.5 Chemical control via altered water quality

**Key finding**

- Increasing salinity of ballast water exchange to 30 ppt resulted in 100% mortality of *H. anomala* after 3-5 hours (Ellis and MacIssac, 2009).

**Further information**

Ellis and MacIsaac (2009) tested salinity tolerance in ballast water exchange (BWE) simulations. They documented 100% mortality for *H. anomala* after 5 hours in a simultaneous BWE treatment, in which salinity was gradually increased from 4-30 ppt, and 100% mortality after 3 hours in a sequential BWE treatment, in which species are immediately exposed to 30 ppt salinity. Alteration of water quality using carbon dioxide, ozone, nitrogen, and/or sodium thiosulphate could be effective in preventing upstream and downstream movement of crustaceans (GLMRIS, 2012). See section **1.5 Use of chemicals**.

### 3.1.6 Physical prevention via electron beam irradiation

**Key finding**

- Electron beam irradiation could be used to control *H. anomala* (GLMRIS, 2012).

**Further information**

Electron beam irradiation is a non-selective control method which exposes water to low doses of radiation using gamma-sterilizers or electron accelerators, breaking down DNA in living organisms while leaving behind no by-products (GLMRIS, 2012). Ultraviolet (UV) light can also effectively control microorganisms including *H. anomala* in water treatment facilities and narrow channels, where UV filters can be used to emit UV light into passing water, penetrating cell walls and rearranging DNA of microorganisms (GLMRIS, 2012).

### 3.1.7 Further research

For *H. anomala,* like many other invasive species, an analysis of invasion pathways would give a better understanding of the mechanisms of introduction. The extent to which different vectors facilitate spread would allow priority to be given to reducing the risks imposed by specific pathways. Quantitative assessment of invasion pathways has already been done for some species (e.g. *Styela clava*) using genetic analysis and shipping patterns (Dupont *et al.*, 2009; Goldstien *et al*., 2010). Human mediated processes have been blamed for the spread of many species, but other dispersal mechanisms need to be investigated. For example, to what degree is *H. anomala* spread by currents? Altered water quality (i.e. in water ballast exchanges) may be an appropriate control method for *H. anomala* but has not been fully tested. Full distribution is not currently known for some species including *H. anomala*, neither is the biology of this species well understood. A greater understanding of factors that control its abundance and distribution are essential in developing control methods. The decision on whether control is needed requires knowing the impact an invasive species has on its receiving ecosystem and associated species. For some species such as *H. anomala*, there are still uncertainties which should be addressed. There are claims, for example, that the shrimp may reduce blue-green algae and encourage macrophyte growth (Stubbington *et al.*, 2008). In some circumstances, therefore, the benefits of having the species present may outweigh any costs to the environment.

## 3.2 Chinese mitten crab *Eriocheir sinensis*

RECOMMENDED CONTROL MEASURES: None currently available.

### 3.2.1 Species profile

**Description:** A large crab up to 56 mm with characteristically dense hairs on the claws. Deemed one of the world's worst invasive species.

**Origin:** Far East; China to Korea (Clark *et al*. 1998).

**UK distribution**: *Eriocheir sinensis* first appeared in European waters in Germany in 1912 (CABI, 2010b). In the UK it has been present in the Thames Basin from the 1930's (Clark *et al*., 1998) but there are now also records from the Medway, Mersey, Tyne and Devon coasts (Herborg *et al*., 2002).

**Habitat:** Females move seaward after breeding in brackish waters, before returning in spring to fresh water to hatch their eggs. Juveniles spend the early part of their lives downstream in brackish waters before returning to fresh water to mature. Adults live in muddy burrows in river banks (Sewell, 2016). The crab appears to have no temperature preference (Marques *et al*., 2015).

**Reproduction:** Mating tends to occur in estuaries.

**Impact**: The species alters aquatic food chains by competing with native species (CABI, 2010b). It can have a severe economic impact by predating species of commercial or recreational fishing interest (Rudnick *et al*., 2005). Burrowing activities increase river bank erosion and it can cause clogging of commercial water intake filters (CABI, 2010b).

**Legislation:** Wildlife and Countryside Act 1981. Article 15 (2) of the Wildlife (Northern Ireland) Order 1985. *Eriocheir sinensis* is also listed on the IUCN and GloBallast lists of problematic alien species.

### 3.2.2 Invasion pathways and techniques to limit spread

| |
|---|
| **DELIBERATE: fisheries** |
| • Current legislation should prevent this. |
| **HUMAN TRANSPORT: ship ballast water, sea chests, aquaculture** |
| • Legislative control of ballast water may limit future spread.<br>• Transfers of oysters should be carefully checked. |
| **NATURAL: migratory behaviour, currents** |
| • Diversion and pitfall trap during downstream migration may have limited success in the long-term.<br>• Public awareness could play a role.<br>• There are no techniques to prevent larval dispersal via currents. |

#### Further information

Long-distance introductions may have been via currents, ballast boat water and in sea chests (Peters, 1933; Herborg *et al*., 2003; Palero *et al*., 2016). The International Convention for the Control and Management of Ships' Ballast Water and Sediments will enter into force in September 2017 which may help prevent further introductions of *E. sinensis* (see section 3.1.2). Herborg *et al.* (2003) speculated that the oyster trade may have facilitated spread along the coast of France. It is possible that crabs have been intentionally released to establish fisheries (CDFW, 2016). The species' migratory behaviour supports rapid spread on a local scale (Leidenberger *et al*., 2015; CABI, 2010b). Dispersal can be overland, as well as in water, but in both cases the preference is for a downhill direction (Marques *et al.*, 2015). Its resistance to desiccation (up to 4.3 days) facilitates overland movement (Fialho *et al.,* 2016). With so few control methods available, prevention is crucial to limiting this species' spread.

### 3.2.3 Summary of control measures and evidence of success

| PHYSICAL AND MECHANICAL: diversion and trapping |
|---|
| ? A diversion and pitfall trap employed during downstream migration caught 85% of crabs within 3 weeks.<br>? Trammel netting provides limited success. |
| **BIOLOGICAL: native predators** |
| ? Predator exist but no experimental evidence of population level effects |

### 3.2.4 Biological control using native predators

#### Key finding

- *Eriocheir sinensis* is predated by many species but there is no evidence of an effect on populations.

#### Further information

*Eriocheir sinensis* is predated by fish, amphibians, birds and mammals including groups which have representatives in the UK including sturgeon (Acipenseridae), frogs (*Rana* spp.), herons (Ardeidae) and mustelids.

### 3.2.5 Physical removal via diversion and pitfall trap

#### Key findings

- A diversion and pitfall trap employed during downstream migration caught 85% of crabs within 3 weeks (NEANS, 2016).
- Trammel netting provides limited success (Wray, 2015).

#### Further information

The "catch as many as you can" strategy showed limited success (Wagley *et al*., 2009; Gollasch, 2011). Artificial substrates and baited traps have been trialled to enhance trapping methods but these have been inefficient (NEANS, 2016). Physical barriers such as grizzly bars and k-rail have been suggested by experts but no trials have been carried out to date (NEANS, 2016). A pilot project in California captured adult crabs via a diversion and pitfall trap during autumn downstream migration. The success of this method was very high, with an estimated 11,000 crabs captured on one small river during a 6-week period, with 85% of the crabs caught in less than 3 weeks (NEANS, 2016). Peak downstream movement in Western Europe is between July and September (Herborg *et al*., 2003). The Dee Chinese mitten crab project reported no success of trapping using modified fyke nets, weirs or from boats or shore. They did find limited success with trammel netting although this is costly (Wray, 2015). However, trapping trials with other crustaceans have raised concerns as to their long-term effectiveness. Trapping may favour the capture of larger individuals, thus causing an unintended increase in growth and earlier maturation of juveniles which can cause the population to increase (Bean, 2015).

### 3.2.6 Further research

Analysis of invasion pathways would give a better understanding of the mechanisms of introduction. Furthermore, identifying the cues related to upstream and downstream migrations would be useful given the most promising potential control measure is reliant on predicting their movements. Such predictive abilities would also help determine years in which directed management efforts may be critically needed to control populations. The Natural History Museum (London) has ongoing research into the biology and behaviour of Chinese mitten crabs aimed at informing decisions about possible control measures (NHM, 2017). However, their proposal for commercial trapping has been actively discouraged by regulatory bodies.

There are many potential control methods for this species which should be investigated as a matter of urgency. Potential control measures for *E. sinensis* which could be tested include crabicides, biotoxins, endocrine disruptors, predation, pathogens, light deterrents, electricity, freezing, and sterilization (Rudnick *et al*., 2005). Combinations of two or more methods are often more successful than the individual methods on their own. Inspired by the problem imposed by *E. sinensis*, Walker *et al*. (2015) developed a modelling approach which allowed for two types of intervention to be assessed simultaneously. Such application of this approach could direct optimal policy.

## 3.3 American slipper limpet *Crepidula fornicata*

RECOMMENDED CONTROL MEASURES: Dredging/manual collection; smothering with sediment.

### 3.3.1 Species profile

**Description:** The American slipper limpet *Crepidula fornicata* is a marine gastropod with a brown shell growing up to 6 cm (CABI, 2009a). It grows into dense stacks several limpets deep which is believed to be an adaptation to avoid it being buried in its self-made environment (Ernhold *et al*., 1998).

**Origin:** Native to the coastal waters of the West Atlantic (Bohn *et al*., 2015).

**UK distribution:** It reached British waters in the 1950s (Cole and Baird, 1953). By the early 1950s it was distributed from Northumberland to Cornwall and South Wales (Orton, 1950; Cole, 1952; Bohn *et al.*, 2015). The slow spread of the species in the UK at least, is most likely due to settlement and post-settlement processes which are implicated in controlling adult abundance.

**Habitat:** It inhabits predominantly shallow estuaries and bays (Loomis and Van Nieuwenhuyze, 1985; Blanchard, 1997) with rocky gravel, sandy or muddy bottoms. The larvae, juveniles and adults are relatively euryhaline and eurythermal enabling the species to survive in a variety of environmental conditions and habitat types (Schubert, 2011).

**Reproduction:** *Crepidula fornicata* is protandric. Juveniles are males and individuals become rapidly hermaphrodites from the second year, and then are females during the rest of their life (CABI, 2009a). Metamorphosis from larvae to juveniles can occur in the absence of growth and/or food (Pechenik *et al*., 1996). Reproduction of adults is strongly regulated by seawater temperature with spawning only occurring in the UK at 7-8°C (Bohn *et al.*, 2015). During the last decade, increases along the French coast have been attributed to warmer seawater which results in an earlier appearance of egg-brooding females and thus an extended breeding season (Valdizan *et al*., 2011). Below seawater temperatures of 12 °C, larval development is slowed and mortality increased (Rigal, 2009). Low winter temperatures may limit populations through adult mortality (Thieltges *et al*., 2004).

**Impact**: The species can form very dense aggregations of up to 10,000 individuals per $m^2$ (Blanchard, 2009) which can have severe and irreversible impacts on the sediment, biodiversity, concentration of suspended matter and biogeochemical cycle (Ragueneau *et al.*, 2004). However, not all their impacts are negative. They can reduce starfish (*Asterias rubens*) predation on blue mussels, for example (Thieltges, 2005).

**Legislation:** Wildlife and Countryside Act 1981. Article 15 (2) of the Wildlife (Northern Ireland) Order 1985. *Crepidula fornicata* is also listed on the IUCN list of problematic alien species.

### 3.3.2 Invasion pathways and techniques to limit spread

**HUMAN TRANSPORT: aquaculture, shipping**

- Legislative control of ballast water may limit future spread.
- Maintenance of ship hulls by cleaning and anti-fouling paint.
- Oysters should be cleaned prior to transport

**NATURAL: floating vegetation/debris, tides**

- There are no techniques to prevent this pathway.

**Further information**

*Crepidula fornicata* was accidentally introduced into European waters in the late 19th century attached to American oysters *Crassostrea virginica* brought in for aquaculture (Bohn *et al.*, 2012; 2015). Further repeated introductions of adults attached to ships, wreckage, shipping containers and transported shellfish species have occurred (Korringa, 1942; 1951; Cole and Baird, 1953; CABI, 2009a). Dredging and trawling of oyster-farming areas has likely contributed to the spread of the species (CABI, 2009a). Transport of the free-swimming larvae with ballast water may also occur during the relatively long pelagic larval phase of c.2-4 weeks (Pechenik, 1980; 1984). This makes new introductions very likely as there is no real control for a marine species capable of larval transport (CABI, 2009a). The International Convention for the Control and Management of Ships' Ballast Water and Sediments that will enter into force in September 2017 may help to some degree (IMO, 2016). Winter temperatures currently prevent population increases in the north of Europe (Thieltges *et al.*, 2004) so global warming could promote further expansion (CABI, 2009a).

### 3.3.3 Summary of control measures and evidence of success

**BIOLOGICAL: native predators**

? Several predators have been identified, but their effects and control potential are unknown.

**BIOLOGICAL: non-native predators**

? The invasive non-native Atlantic oyster drill *Urosalpinx cinerea* is among the non-native predators of *C. fornicata* but interactions between the two species are unknown.

**PHYSICAL AND MECHANICAL: dredging**

✓ Dredging followed by boiling killed 100% limpets in a field study.

✓ Manual collection has yielded 20 kg $h^{-1}$.

✓ Suction dredging has removed 50 kg $hr^{-1}$ or 30,000 t $yr^{-1}$.

**ENVIRONMENTAL: smothering**

✓ Expert observation that smothering with sediment eradicated *C. fornicata*.

### 3.3.4 Biological control using native predators

**Key finding**

- Several predators, native to the UK, have been identified for *C. fornicata* but their effect on populations is unknown.

**Further information**

The starfish, *Asterias rubens,* eats individuals (Orton, 1924). The juveniles are eaten by decapods of the genus *Pagurus* including *P. pollicaris* which occurs in the UK (Shenck, 1986; Pechenik *et al.*, 2010). Larvae are eaten by the oysters (*Ostrea edulis* and *Crassostrea gigas*) and by adult *C. fornicata* (Pechenik *et al.*, 2004). The sponge *Cliona celata* and the gastropod *Ocenebra erinacea* pierce the shells (Orton, 1924). The flatfish *Limanda limanda* (Orton, 1924) and the bass *Dicentrarchus labrax* (Kelley, 1987) eat and scratch large quantities of adult animals. Several carnivorous crabs were observed when limpets are scratched and meat exposed, after dredging for example (Pechenik *et al.*, 2010). It is unlikely that predators are currently a factor limiting population increase (Thieltges *et al.*, 2004; Thieltges, 2005; Beninger *et al.*, 2007; Decottignies *et al.*, 2007).

### 3.3.5 Biological control using non-native predators

**Key finding**

- The invasive non-native Atlantic oyster drill *Urosalpinx cinerea* is a predator and their ranges overlap in the UK.

**Further information**

In the USA, the large whelk *Busicon carita* and the Atlantic oyster drill *Urosalpinx cinerea* (Pratt, 1974; Pechenik *et al.*, 2010) are predators of *C. fornicata* although the latter is also an invasive non-native species in the UK. Permission for release of non-native species needs approval from regulatory bodies. See section **1.6 Non-native species for biocontrol.**

### 3.3.6 Physical removal by dredging

**Key findings**

- Manual collection yields 20 kg $h^{-1}$ (Fitzgerald, 2007).
- Suction dredging removes 50 kg $hr^{-1}$ or 30,000 t $yr^{-1}$ (Fitzgerald, 2007).
- Dredging followed by boiling resulted in 100% mortality in a field study (Blanchard and Thomas, 1998).

**Further information**

Manual collection can yield 20 kg $h^{-1}$ but dredging with a winch and suction dredge can remove 50 kg $hr^{-1}$ (Fitzgerald, 2007). The French ARVAL programme removes ~30,000 t $yr^{-1}$ of slipper limpets by suction dredge (Fitzgerald, 2007). Fitzgerald (2007) gave details of stock storage and destruction following dredging. Blanchard and Thomas (1998) also removed 150 tons of limpets from oyster beds by dredging. Slipper limpets were removed from the seabed via a modified 2 m wide dredge head which removed the surface sediment. These were boiled at 95-98 °C for 2 minutes, and disposed of by dropping into a marine dump. This resulted in 100% mortality (Blanchard and Thomas, 1998). Chain harrowing has also been used in practice. This involves towing chains behind a powered vessel over oyster beds which re-suspends the sediment (Fitzgerald, 2007). There is some concern, however, that this actually promotes dispersal.

### 3.3.7 Environmental control by smothering

**Key finding**

- Smothering with sediment eradicated *C. fornicata* (Holt, 2013).

**Further information**

When *C. fornicata* appeared in the Menai Strait in 2007, it was quickly smothered with sediment. No surviving limpets have been observed (Holt, 2013).

### 3.3.8 Further research

Analysis of invasion pathways would give a better understanding of the mechanisms of introduction.

## 3.4 Asian clubbed tunicate *Styela clava*

RECOMMENDED CONTOL MEASURES: Manual collection; plastic wrapping (with or without sodium hypochorite); acetic acid; acetic/lime/saline sprays or immersions for aquaculture stocks.

### 3.4.1 Species profile

**Description**: The clubbed tunicate or leathery sea-squirt *Styela clava* is a solitary ascidian and fouling species.

**Origin:** The species is native to the Pacific shores of Asia and Russia (Goldstien *et al.*, 2010).

**UK distribution:** This species arrived in the UK in the 1950s and is now distributed along west, south and south-east coasts.

**Habitat:** *Styela clava* is found in coastal and estuarine habitats particularly those with low wave energy but high and fluctuating nutrient levels (e.g. sheltered embayments, harbours and marinas) (Lambert and Lambert, 1995; CABI, 2006; Locke *et al.*, 2007). It is a fouling species commonly found on a wide variety of natural and artificial substrates including: rocks, wood, other organisms, reefs, pylons, concrete, cement, boat hulls, buoys and pontoons (CABI, 2006). Its invasion has been successful due to high tolerance of a range of environmental conditions (Goldstien *et al.,* 2010): it is known to tolerate temperatures ranging from -2 to +23 °C and salinity from 20 to 32 psu (Davis and Davis, 2007).

**Reproduction:** It is a oviparous hermaphrodite and like all ascidians, has a lecithotropic larva that spends only a short time in the water column (24-48 h) before settling on a suitable substrate and metamorphosing into an adult (Darling *et al.*, 2012). It is a prolific breeder (Clarke and Therriault, 2007).

**Impact:** As a highly efficient feeder, it competes with native species for food and space including predation of larvae from the water column (Darling *et al.*, 2012; CABI, 2006). Introduction and increase of *S. clava* in southern England, matched by concurrent decline in the population of a local acidion (Lützen, 1999).

**Legislation:** Wildlife and Countryside Act 1981. Article 15 (2) of the Wildlife (Northern Ireland) Order 1985. *Styela clava* is also listed on the IUCN list of problematic alien species.

### 3.4.2 Invasion pathways and techniques to limit spread

**HUMAN TRANSPORT: aquaculture, shipping**

- Monitoring of water samples can help early detection and response (CABI, 2006).
- Consider management regulations for recreational boaters that incorporate good sanitation practices including when transporting overland.
- Cleaning of marinas and reduction of submerged equipment.
- Ensuring hulls are free of fouling and regularly treated with anti-fouling paint.
- Public awareness to gather distribution data as an early warning system.
- Legislative control of ballast water may limit future spread.
- Immersion for 24 hours in fresh water is recommended before shellfish transfer.

**NATURAL: reduction in predators**

- No evidence of techniques to control this pathway.

**Further information**

This species has naturally poor dispersal, and global introductions have been human assisted via shellfish transfers, shipping vectors such as in ballast water or attached to ship hulls, or on recreational boats and fishing equipment (Minchin and Duggan, 1988; JNCC, 1997; Lützen, 1999; CABI, 2006; Minchin *et al*., 2006; Davis and Davis, 2007; Locke *et al*., 2007; Dupont *et al.*, 2009; Goldstien *et al.*, 2010; Murray *et al*., 2011). The spread of *S. clava* is also facilitated by green crabs (*Carcinus maenas*) which heavily predate a snail which is a predator of *S. clava* (Locke *et al*., 2007). Genetic studies have directly implicated recreational vessel movements in driving regional colonization patterns by *S. clava* in other parts of its non-native range (Dupont *et al*., 2009; Goldstien *et al*., 2010). A key action in preventing the spread of *S. clava* to uninfected localities is therefore the direct removal of tunicates from vectors (e.g. from infested bivalves before processing or transfer, or from boat hulls) (Locke *et al*., 2009). Marinas are pivotal points of transfer for hull fouling organisms (Goldstien *et al*., 2010) as the available large areas of artificial surfaces provide suitable habitat (Locke *et al*., 2007). Transportation can also be overland via towed vessels (Darbyson *et al.,* 2009).

Recreational boating is arguably the largest unregulated vector for the introduction and spread of marine invasive species (Murray *et al*., 2011) as their slow movement compared with commercial ships makes them ideal vectors (Minchin *et al.*, 2006). Recreational boats should be subject to vector management regulations (Murray *et al*., 2011) as current practices appear not to be effective. In particular, users should be encouraged to clean niche areas and frequently renew anti-fouling paint (Floerl *et al.*, 2005; Ashton *et al.*, 2006; Murray *et al.*, 2011). Further, current restrictions on antifouling compounds like tributyl tin (TBT) are likely to increase the rate of invasions (Darbyson *et al.*, 2009). The New Zealand Aquaculture Council recently released a code of practice for preventing the spread of *S. clava* which encouraged the public to look actively for specimens of this species, remove and report their occurrence and to prevent movement from affected areas by ensuring both equipment and vessels were clean before moving to clear areas.

The International Convention for the Control and Management of Ships' Ballast Water and Sediments will enter into force in September 2017. The requirement for all ships to have a ballast water management plan and carry out procedures concerning water ballast to a specific standard may help prevent further introductions of *S. clava* (see section 3.1). Pre-treatment of shellfish is recommended before transferral from infected areas. For example, in a controlled replicated laboratory experiment *S. clava* experienced 100% mortality when immersed in fresh water for 3, 6, 12, 24 hours (Ramsay, 2015) and the author therefore recommended that mussel seed transferred from infected areas be treated with 24 hours freshwater immersion (continuous flow) before transport.

### 3.4.3 Summary of control measures and evidence of success

| |
|---|
| **BIOLOGICAL CONTROL: competition** |
| ? Circumstantial evidence suggests *S. clava* may be outcompeted by barnacles. |
| **CHEMICAL: acetic acid, lime, fresh water, saline** |
| ✓ Spraying or immersion with 4-5% acetic acid was 100% effective in a controlled, replicated trial. |
| ✓ Spraying or immersion with a saturated solution of hydrated line has been employed for many years as a treatment for *S. clava.* |
| ✓ A controlled replicated laboratory experiment showed that immersion in fresh water for ≥ 3 hours, successfully killed *S. clava.* |
| ✓ Expert opinion considers dipping in a saline solution as one of the most effective methods of control. |
| **PHYSICAL AND MECHANICAL: manual collection** |
| ✓ Manual collection can be 100% effective. |
| **ENVIRONMENTAL: water-level drawdown, smothering** |
| ? Expert opinion considers drawdown as a successful control measure. |
| ✓ Plastic wrapping (with or without sodium hypochorite) is considered 100% effective (Coutts and Forrest, 2005). |
| **COMBINED CHEMICAL + ENVIRONMENTAL: saline and air** |
| ✓ One study found that dipping oysters in saline followed by 30 minutes of air exposure caused total mortality of *S. clava***.** |

### 3.4.4 Biological control via competition

**Key finding**

- Circumstantial evidence suggests *S. clava* may be outcompeted by barnacles (Cohen *et al.*, 2005).

**Further information**

On pier pilings in the Yarra River (Australia), *S. clava* was absent when barnacles dominated but present in marine waters nearby (Cohen *et al.*, 2005). This provided circumstantial evidence that native species could offer some form of control by slowing or reducing the impact of *S. clava* (Clarke and Therriault, 2007).

### 3.4.5 Chemical control by acetic acid or lime

**Key findings**

- A controlled, replicated trial reported complete mortality of *S. clava* following 1 min immersion in 4-5% acetic acid (Coutts and Forrest, 2005).
- A study found that spraying or immersion with a saturated solution of hydrated lime to be effective (Locke et al., 2009).
- A controlled replicated laboratory experiment showed that immersion in fresh water for ≥ 3 hours, successfully killed *S. clava* (Ramsay, 2015).
- One study found that dipping oysters in brine for 5 minutes at 14 °C followed by 30 minutes of air exposure caused total mortality of *S. clava* (Minchin and Duggan, 1988).
- Brine dipping is considered one of the most effective methods of control (NIMPIS, 2002).

**Further information**

Chemical treatments with sodium hydroxide, acetic acid, citric acid, formalin, detergents, chlorine bleach and hydrated lime have all been trialled (Locke *et al.* 2009) but these can only be used where *S. clava* is attached to moveable objects (e.g. mussels). Coutts and Forrest (2005) reported that all *S. clava* died after 1 min immersion in 4% acetic acid or 10 min in 1%. Acetic acid is biocidal to some other organisms including mussels (LeBlanc *et al.*, 2007; Locke *et al.*, 2009) but the effects were limited to a short timeframe and area around the treatment site (Locke *et al.*, 2009).

Lime is used either as quicklime (calcium carbonate $CaCO_3$) or hydrated lime ($Ca(OH)_2$). Hydrated lime is less toxic than quicklime. Locke *et al.* (2009) reported that immersion in a trough containing a saturated solution of lime and seawater or low-volume hydrated lime sprayer was effective against *S. clava*. Lime may have additional benefits counteracting acidification of ocean waters and improving water quality in eutrophic systems (Locke *et al.*, 2009). It can increase the pH up to 9 but only in the immediate vicinity (<1 m radius) around the treatment area because of rapid conversion to calcium carbonate (N. MacNair, *pers. comm.*). Juvenile lobsters and flatfish are thought to be particularly vulnerable to the effects of lime and thus Shumway *et al*. (1988) recommended that quicklime is not used when these organisms are present in the water.

A controlled replicated laboratory experiment found that *S. clava* experienced 100% mortality when immersed in fresh water for 3, 6, 12, 24 hours (Ramsay, 2015). Brine dipping is considered one of the cheapest, safest and most effective methods of control (NIMPIS, 2002). The synthetic chemical medetomidine can reduce *S. clava* larval mobility and settlement and may have potential as a management tool to control *S. clava* fouling (Willis and Woods, 2011). See section **1.5 Use of chemicals.**

### 3.4.6 Physical removal

**Key finding**

- Manual can be 100% effective (Gust *et al*., 2008; Jeannine Fischer and Jono Underwood, *pers. comm*.)

**Further information**

Physical treatments against *S. clava* include using air drying, ultraviolet light, steam hot water, electricity, smothering, pressure washing and puncturing (Coutts and Forrest, 2007; LeBlanc *et al.*, 2007). Pressure washing is not particularly effective against *S. clava* because of its tough tunic (Clarke and Therriault, 2007; Locke *et al.*, 2009). Half a ton of *S. clava* physically removed from Pleasant Harbor Marina, Washington, by a group of volunteers failed because the population was too extensive (Droscher, 2006). However, this method can be effective where a stratified, systematic survey method is implemented (Gust *et al*., 2008) and where there is better water clarity (Jono Underwood, *pers. comm*.). The tunicate should be encapsulated in a zip-lock bag and then severed from its anchor and the bag sealed (McClary *et al*., 2005). Manual collection is best done when fertile gametes are not present (i.e. mid-winter or mid-spring) as disturbance can cause gametes to be released and hence increase spread (McClary *et al*., 2005).

### 3.4.7 Environmental control by water-level drawdown

**Key finding**

- Expert opinion considers drawdown as a successful control measure (NIMPIS, 2002; cited in CABI, 2006).

**Further information**

Water-level drawdown has been successfully employed to control *S. clava* with the subsequent freezing or desiccation killing a large proportion of the exposed population (NIMPIS, 2002; cited in CABI, 2006).

### 3.4.8 Environmental control by smothering

**Key finding**

- Expert opinion considers that control on small vessels can be achieved by plastic wrapping with or without the addition of sodium hypochlorite (Jeannine Fischer and Jono Underwood, *pers. comm*.).

**Further information**

*Styela clava* is incredibly resilient to stressors such as freshwater input and sedimentation (Jeannine Fischer, *pers. comm*.). However, encapsulating small vessels with plastic wrappings to create anoxic conditions can be 100% successful (Jeannine Fischer, *pers.comm*.). Large heavy duty plastic sheets can be put in place using divers or boats positioned inside a fabricated floating dock, pumping out the majority of the water to create anoxic environment. The addition of sodium hypochorite (chlorine) granules guarantees successful eradication and has made this a go-to method in New Zealand (Jono Underwood, *pers. comm*.).

### 3.4.9 Combined chemical and environmental: brine and air

**Key finding**

- Dipping oysters in brine for 5 minutes at 14 °C followed by 30 minutes of air exposure caused total mortality of *S. clava* with no observable effect on the oysters (Minchin and Duggan, 1988).

**Further information**

Various combinations of salinity, temperature and exposure to air have proved successful in killing *S. clava* fouled on oysters without harming the oysters (NIMPIS, 2002; cited in CABI, 2006). Minchin and Duggan (1988) recommended a combination of immersion in brine for 5 minutes followed by 30 minutes of air exposure.

### 3.4.10 Further research

Analysis of invasion pathways would give a better understanding of the mechanisms of introduction. There are no data reported on the effectiveness of water-level drawdown for this species.

## 3.5 Atlantic or American oyster drill or whelk-tingle *Urosalpinx cinerea*

RECOMMENDED CONTROL MEASURES: Dredging/manual collection (with or without tile traps).

### 3.5.1 Species profile

**Description:** A sea snail which drills into hard-shelled organisms, notably oysters (CABI, 2009c).

**Origin:** It is native to the east (Atlantic) coast of North America (Abbott, 1974).

**UK distribution**: *Urosalpinx cinerea* probably appeared in the UK prior to 1920, establishing itself in Kent and Essex estuaries (CABI, 2009d). Their range in Essex has extended only 2 miles over a 25 year period.

**Habitat:** Mid and lower intertidal and sublittorial (Cole, 1942). It can tolerate a wide range of temperatures and salinities and survive out of water for up to 8 days (Hancock, 1969; CABI, 2009d).

**Reproduction**: Preferred sites for spawning are the underside of boulders (CABI, 2009c). Young snails develop in egg cases. There is no free-living larval stage (CABI, 2009d). The lifespan is up to 10 years (CABI, 2009d).

**Impact:** Regarded as a pest in mussel and oyster cultures, consuming as much as 70% of 1-year old oysters (Galtsoff *et al.*, 1937). Predation of native species is possible but little studied. Controlled experiments have indicated that temperature is the primary control on feeding, with higher rates of consumption at higher temperatures (Lord and Whitlatch, 2013). This could have implications for future climate change.

**Legislation:** Wildlife and Countryside Act 1981. Article 15 (2) of the Wildlife (Northern Ireland) Order 1985. *Urosalpinx cinerea* is also listed on the IUCN list of problematic alien species.

### 3.5.2 Invasion pathways and techniques to limit spread

**HUMAN TRANSPORT: aquaculture, shipping**

- Importation of shellfish from invaded areas should be avoided.
- Oysters and mussels for consumption may need to be cleaned before sale.
- Juvenile oysters and mussels intended to be re-laid for fattening should be carefully screened for snails and egg cases. Juvenile snails and egg cases may easily escape attention.
- The tarra should not be deposited in on near the marine environment.
- For imports of oysters and mussels to areas where *U. cinerea* is not known to occur it is advisable to select regions of origin where *U. cinerea* has not been reported (CABI 2009c).
- All tingles should be picked out of dredge hauls and taken ashore; all spawn should be noted, collected and dried.

**NATURAL: floating debris, plants**

- There are no techniques available to prevent this pathway.

**Further information**

Most introductions, both long distance and local, are the result of transport on shellfish. Hanks (1957) recommended practices which could help control *U. cinerea*. It can survive transport in humid (but not submerged) conditions at any life stage. The species was severely affected by tributyltin (TBT) pollution (Gibbs *et al*., 1991). The ban on the use of TBT for small boats since 1993 has likely facilitated further introductions (Faasse and Ligthart, 2009). A ban on TBT for large vessels may result in increased populations and/or spread (CABI, 2009d). No free swimming stage so natural dispersal is slow and occurs only on a local scale. Any marked dispersal is likely the result of transportation by humans.

### 3.5.3 Summary of control measures and evidence of success

| |
|---|
| **BIOLOGICAL: non-native predators** |
| ? In a controlled, replicated experiment *Neverita duplicata* consumed 96% *U. cinerea*. |
| **CHEMICAL: saline** |
| ✓ Expert opinion reported that dipping oysters in a saline solution followed by air drying controls *U. cinerea.* |
| **PHYSICAL: manual collection, dredging** |
| ✓ According to expert observation, hand collection reduced numbers. |
| ✓ Drill and suction dredges temporarily reduced numbers according to expert observations. |
| ✓ Expert observation reports tile traps laid down at low-tide allowed substantial collections of *U. cinerea* to be made. |

### 3.5.4 Biological control using native and non-native predators and parasites

**Key finding**

- In a controlled, replicated experiment *Neverita duplicata* consumed 96% *U. cinerea* (Flower, 1954).

**Further information**

Moon snails (family *Naticidae*) may drill and consume *U. cinerea* (Flower, 1954) and in an experiment using the shark eye snail *Neverita duplicata*, 96% *U. cinerea* were predated (Flower, 1954). The starfish *Asterias forbesi* preyed upon oyster drills when bivalves are not obtainable (Carriker, 1955). The flatworms *Parorchis avitus* and *Cercaria sensifera* have been found in *U. cinerea*; the latter species occurs in the UK (Cole, 1942). The ectoparasitic polyclad flatworm *Hoploplana inquilina* has been recorded from the mantle cavity of *U. cinerea* (Carriker, 1955). Other species have been observed but not identified. Permission for release of non-native species needs approval from regulatory bodies. **See 1.6 Non-native species for biocontrol.**

### 3.5.5 Chemical control using saline dips

**Key finding**

- Expert opinion cited saline dips followed by air drying as a control method (Hancock, 1969; Flimlin and Beal, 1993).

**Further information**

The application of chlorinated benzenes killed 66% population with effects shown for up to 2 years (Mackenzie, 1970). A significantly higher percentage of the population were killed in late April and early May rather than later in the summer. Of those that survived, delayed feeding for several months was observed. However, the treatment also killed a small percentage of fish, small clams, crabs and other invertebrates (Mackenzie, 1970). Tributyltin caused imposex in *U. cinerea* but neither this nor chlorinated benzenes are probably advisable as control methods (Global Invasive Species Database, 2016d). See section **1.5 Use of chemicals.**

A control method used successfully has been to dip trays or boxes containing clams or oysters in a saturated solution of rock salt for 1-2 minutes, followed by air drying in the sun (Hancock, 1969; Flimlin and Beal, 1993). Rittschof *et al*. (1983) suggest there is a clear potential for chemical control based upon the mechanism of attraction to prey.

### 3.5.6 Physical removal

**Key findings**

- According to expert observation, hand collection reduced numbers (Carriker, 1955).
- Drill and suction dredges have been used (Galtsoff *et al.*, 1937; Carriker, 1955).
- Tile traps laid down at low-tide resulted in substantial reductions in *U. cinerea* (Hancock, 1969).

**Further information**

Hand collection of snails and egg cases is possible in the littorial zone. Bounties made available in the 1930s in England resulted in greatly reduced numbers (Carriker, 1955). Adults and eggs may be killed in hot water or by leaving them on the shore for more than 8 days (Hancock, 1969). Carriker (1955) stated that there is no evidence that any physical control measures (dredging, trapping and hand-picking) have any significant effect in the long term. Galtsoff *et a*l. (1937) recommended the use of a special drill dredge but this damaged oysters and is therefore only suitable for cleaning once oysters have been harvested (Carriker, 1955). A suction dredge used to prepare a lease site eliminates gastropods, temporarily at least (Carriker, 1955). Cole (1942) described half-sections of large drain-pipes placed on the beach at low water of spring tides. These attracted large numbers of drills. Hancock (1969) described the use of roof tiles for the same purpose.

### 3.5.7 Further research

Analysis of invasion pathways would give benefit understanding of the mechanisms of introduction. There is an absence of quantitative data on the effectiveness of physical and chemical (saline) control measures for *U. cinerea.*

## 3.6 Carpet sea-squirt *Didemnum vexillum*

RECOMMENDED CONTROL MEASURES: Sprays/immersions; manual cleaning; air exposure, smothering with sediment or plastic wrapping.

### 3.6.1 Species profile

**Description:** The taxonomy of *Didemnum* sp. has been disputed until recently where morphologic and genetic studies have shown that the invasive tunicate referred to is *D. vexillum* (Kott, 2002; 2004; Lambert, 2009; Stefaniak *et al*., 2009). This colonial ascidian is commonly known as the carpet sea-squirt.

**Origin:** Thought to have originated from Japan (Lambert, 2009).

**UK distribution:** In the UK it is now distributed around north Wales (Griffith *et al.*, 2008) and Scotland (Beveridge *et al.*, 2011).

**Habitat:** The lecithotrophic larvae spend less than 24 hours in the water column before attaching to a substrate and developing into adults (CABI, 2009b). It is found in coastal and estuarine waters. *Didemnum vexillum* can tolerate a wide range of temperatures

(Carlton, 1989) although optimal growth is believed to occur at 14-18°C, and colonies generally die out when the temperatures are lower than 5 °C (Gittenberger, 2007). It is also tolerant of wide ranging nutrient concentrations (Carman *et al*., 2009) and salinities (Dijkstra *et al*., 2007), although fluctuating salinity reduces growth (Bullard and Whitlatch, 2009).

**Reproduction:** Sexual and asexual reproduction occurs (Holt *et al*., 2009). It is also capable of reproducing while in a fragmented, suspended state (Morris and Carman, 2012).

**Impact:** Can be considered an 'ecosystem engineer' due to its profound alteration of habitats (Lambert, 2009). Growth rates are extremely fast (Valentine *et al*., 2007b) and due to its mat-forming habit, it can quickly cover large areas reducing the substrate available for other organisms or smothering immobile species (CABI, 2009b). A wide range of horizontal and vertical substrates are colonised including gravel, pebble, cobble, boulder, live and dead sea scallops, anemones, sponges, dead shells, other ascidians, barnacles, rock crabs and skate egg cases (York *et al*., 2008). The species attaches to boat hulls and ropes, tyres, cables and keep cages at marina pontoons (Beveridge *et al*., 2011). It also produces an acidic tunic (Bullard *et al*., 2007). Increasing density of *D. vexillum* has been associated with decreases in other shellfish and worms (York *et al.*, 2008).

**Legislation:** Wildlife and Countryside Act 1981. Article 15 (2) of the Wildlife (Northern Ireland) Order 1985. *Didemnum* spp. is listed on the IUCN list of problematic alien species.

### 3.6.2 Invasion pathways and techniques to limit spread

**HUMAN TRANSPORT: hull fouling, ballast water/sea chests, fishing, aquaculture**

- Marina surveys and inspections provide early warning of changes in abundance or new populations of *D. vexillum.*
- Ensure hulls are free of fouling and regularly treated with anti-fouling paint.
- Recreational vessels should be brought ashore for cleaning.
- Debris resulting from cleaning should be allowed to dry/decompose but not returned to the water.

**NATURAL: rafting on debris, fragmentation, currents**

- No techniques available to limit spread via this mechanism.

#### Further information

The specific invasion pathways for this species include hull fouling via international shipping and local boat traffic, marine industries (such as oil, gas and renewables) and transport of aquaculture species (Carlton, 1989; Coutts, 2006; Dijkstra *et al*., 2007; Nimmo *et al*., 2011). From vessels, *D. vexillum* can spread to adjacent moorings, wharf piles and other artificial structures (Pannell and Coutts, 2007). *Didemnum vexillum* has a very short larval stage so the risk of transport in ballast water, although possible, is very low (Carlton and Geller, 1993). Oyster farms and lobster creels are also implicated vectors (Kleeman, 2009). Rafting on broken leaves and other debris is another possible mechanism (Dijkstra *et al*., 2007).

Hull-cleaning successfully removes *D. vexillum* and prevents further spread. Contaminated recreational vessels should be brought ashore and jet-washed or scrubbed clean as in-shore cleaning likely increases the spread of this species (Morris and Carman, 2012). Any debris should be allowed to dry and/or decompose but not be returned to the water (Holt *et al.*, 2009). Prior to import or export, oyster shells can be treated with a 24-hour freshwater immersion followed by 48-hours of air exposure, or for oyster seed, a 0.5% chlorite immersion (Bill Turrell, *pers. comm.*).

### 3.6.3 Summary of control measures and evidence of success

**BIOLOGICAL: native predators**

? In a controlled, replicated study, common periwinkle snails *Littorina littorea* consumed stressed but not healthy *D. vexillum.*

**CHEMICAL: bleach, chloride, acetic acid, fresh water, biocides**

✓ A controlled field study found 0.5 % bleach solution for 30 seconds was 100% effective in killing *D. vexillum*.

✓ In a controlled, replicated experiment, immersion in 4-5% acetic acid was found to be an effective means of control of *D. vexillum*.

✓ Immersion in fresh water killed 87 % *D. vexillum* after 10 minutes.

✓ In controlled, replicated laboratory experiments, freshwater treatments that involved either immersion for 8-hours or a 10-minute spray were 100% effective.

? A study in New Zealand found the biocide 'BioBullet' to be 100% effective.

**PHYSICAL AND MECHANICAL: manual cleaning, exposure**

✓ A study showed that hull cleaning successfully removed *D. vexillum.*

✓ Expert opinion believes air exposure for >6 hours would be 100% effective.

**ENVIRONMENTAL: smothering**

✓ In a study, *D. vexillum* was eradicated from an area of seabed covered with dredge spoil and 178 wharf piles wrapped in black polyethylene.

**COMBINED CHEMICAL and ENVIRONMENTAL: smothering and accelerant**

✓ A before-and-after study found that all *D. vexillum* on two barge hulls subjected to a chloride concentration 200 g $m^3$ were killed.

✓ Plastic wrapping with and without calcium hypochlorite or acetic acid eradicated *D. vexillum* in a 3-year study.

### 3.6.4 Biological control by native predators

#### Key finding

- A controlled and replicated study found that the common periwinkle *Littorina littorea* consumed stressed *D. vexillum* under field conditions and thus should only be used as a supplemental method alongside more reliable control methods (Carman *et al.*, 2009).

#### Further information

*Didemnum vexillum* has few known natural enemies although predation by sea star, sea urchin (*Notechinus albocinctus*), chiton (*Cryptoconchus porosus*) and predatory snails (*Littorina littorea* and *Trivia arctica*) has been reported (Gittenberger, 2007; Valentine *et al*., 2007a; Lambert, 2009). Another snail of the genus *Lamellaria* is believed to be a specialist on *D. vexillum* (Gittenberger, 2007). Osman and Whitlatch (2007) suggested a fish species might be an important predator. Carman *et al.* (2009)

subjected healthy *Didemnum* specimens to zero (control), low, medium and high levels of stress through exposure to air, and then recorded the number of snails (*Littorina littorea*) on them after 3 weeks. No snails were found on unstressed, e.g. healthy, *Didemnum*, but they were found on specimens subjected to low and high stress. Recent studies in New Zealand have shown that the cushion sea star *Patiriella* sp. and sea urchin *Evechinus* sp. are highly effective at removing 'healthy' colonies of *D. vexillum* from the seabed (B. Forrest, *pers. comm*. cited in Nimmo *et al.*, 2011).

### 3.6.5 Chemical control with sprays or immersion

#### Key findings

- Dipping in 0.5 % bleach for 30 seconds resulted in 100 % mortality of *D. vexillum* (Denny, 2008).
- Immersion in 4-5% acetic acid effectively controlled *D. vexillum* (Pannell and Coutts, 2007).
- Freshwater immersion killed 87 % after 10 minutes (Denny, 2008).
- A controlled replicated laboratory experiment demonstrated that either a 8-hour freshwater bath or 10-min freshwater spray was sufficient to kill all *D. vexillum* on blue mussels (Carman *et al*., 2016).
- Biocides result in 100% mortality (Laing *et al*., 2010).

#### Further information

Chemical treatments are non-target specific and affect the surrounding environment, e.g. by altering the water pH (Locke *et al*., 2009), so the benefits of their use need to be carefully considered against any costs. Moreover, they can only effectively be used in situations where the tunicates can be contained (e.g. on shellfish) rather than applied in the wider environment. Control measures for other species of tunicates on shellfish include sprays or immersion in fresh water or hot water (Katayama and Ikeda, 1987), saline solutions (Debrosse and Allen, 1993), acetic acid and calcium hydroxide (Forrest *et al.*, 2007; Locke *et al.*, 2009). Coutts and Forrest (2007) reported partial success of hot water blasting and petrogen torch but ruled these methods out on economic grounds.

In a series of controlled field trials, freshwater immersion was found to be partially effective at killing *D. vexillum* with reported mortality after 2, 5 and 10 minutes of 74, 84 and 87% respectively. At 2% acetic acid concentration, 77% mortality was achieved on average (Denny, 2008). Both these methods also killed high numbers of the mussels on which the tunicates were attached. However, 100% mortality was achieved with either dipping in 0.5% bleach for 30 seconds or 0.25% bleach for 2 minutes (Denny, 2008). Carman *et al*. (2016) found acetic acid, brine and freshwater baths and sprays to be effective to some degree against *D. vexillum* and other colonial tunicates. However, their recommendations were for either an 8-hour freshwater bath or 10-min freshwater spray as these treatments preserve the maximum mussel stocks and do not involve the disposal of chemicals. A meta-analysis of the effectiveness of 13 different bath treatments is currently ongoing (Bill Turrell, *pers. comm*.). In situations where *D. vexillum* infections can be isolated from the wider environment, then a biocide such as 'BioBullet' could be applied. This resulted in 100% mortality in tests in New Zealand (Laing *et al*., 2010). See section **1.5 Use of chemicals**.

### 3.6.6 Physical removal by manual cleaning and/or exposure

#### Key findings

- Hull cleaning successfully removes *D. vexillum* (Coutts and Forrest, 2007).
- Air exposure for >6 hours is believed to be 100% effective (Laing *et al.*, 2010).

#### Further information

*Didemnum vexillum* has been removed from mussel farms where it has become a pest. Numerous manual eradication methods exist but these are labour intensive and expensive (Carman *et al.*, 2009). Techniques include high-pressure sprays and hand-brushing. In New Zealand, 26 fouled recreational vessels and moorings were cleaned and had their anti-fouling paint renewed. These measures completely removed *D. vexillum* (Coutts and Forrest, 2007). Hull cleaning guidelines have been produced by the New Zealand and Australian governments (Australian Government, 2012). If substrates are removable, then air exposure for more than 6 hours should be 100% effective (Laing *et al*., 2010).

### 3.6.7 Environmental control through smothering

#### Key finding

- Smothering with dredge spoil or black polyethylene has been entirely successful in killing *D. vexillum* (Coutts and Forrest, 2007; Pannell and Coutts, 2007).

#### Further information

Smothering techniques work on two principles by restricting water flow to the tunicates to create anoxic conditions and by containing and isolating to prevent larval or fragmented dispersal (Holt and Cordingley, 2011). Uncontaminated dredge spoil, comprising 70% silt/clay, 20% sand and 10% cobble was dumped on an area of the seabed (80 x 40 m) in the Marlborough Sounds, New Zealand to a depth of 100 mm (Coutts and Forrest, 2007). This method was completely successful in eliminating *D. vexillum* (Coutts, 2006). Divers wrapped 178 wharf piles in black polyethylene (1 m wide x 50 μm thick), ensuring an overlap of c.400 mm on each successive wrap. This was secured in place with PVC tape. This method was completely effective at killing *D. vexillum* except where materials had become loose (Pannell and Coutts, 2007). Wrapping in plastic can be applied to pontoons, anchor chains and boat hulls (Kleeman, 2009).

### 3.6.8 Combined chemical and environmental control via smothering and accelerant

#### Key findings

- Chlorine concentration of 200 g $m^3$ applied to two barge hulls was effectively in killing *D. vexillum* (Coutts and Forrest, 2007).
- Plastic wrapping with and without calcium hypochlorite or acetic acid eradicated *D. vexillum* in a 3-year study (Holt, 2013).

#### Further information

Complete removal was achieved from two barges in New Zealand. The hulls were wrapped in polyethylene and then granulised chlorine added to give a chlorine concentration of 200 g $m^{-3}$ (Coutts and Forrest, 2007). The chlorine acts as an accelerant to speed up the process. At Holyhead, Wales, plastic wrapping with or without calcium hypochlorite or acetic acid (5% working solution) was applied to all structures for 3 years (Kleeman, 2009; Holt, 2013). This involved designing specific plastic bags and wrappings to cover all surfaces (Holt and Cordingley, 2011). After this period, no *D. vexillum* was found (Holt, 2013).

### 3.6.9 Further research

Analysis of invasion pathways would give a better understanding of the mechanisms of introduction. More information is also needed about the ecology of *D. vexillum*, in particular its physical tolerances, life history characteristics and interactions with other species in order to continue to develop and improve methods to control or eradicate it. Osman and Whitlatch (2007) observed fragmentation of *D. vexillum* colonies, in particular, the loss of the oldest parts of the colony at some sites, but they were unable to establish the environmental conditions causing this. Such an insight could identify particular sites or situations in which spread is more likely and thus prioritising areas where action may have the biggest effect in controlling species at a local or broader scale. This may be particularly important for a species such as *D. vexillum* for which the cost of control/eradication is relatively high.

## 3.7 Japanese or Asian oyster drill *Ocenebra inornata*

RECOMMENDED CONTROL MEASURES: Manual collection.

### 3.7.1 Species profile

**Description:** The Asian oyster drill *Ocenebra inornata* is a predatory marine snail (Fofonoff *et al.*, 2003). In recent literature it has been referred to by several of its synonyms: *Ceratostoma inornata, Ceratostoma inornatum, Ocinebrellus inornatus* and *Pteropurpura* (Appeltans, 2003; Global Invasive Species Database, 2016b).

**Origin:** Native to the Northwest Pacific, *O. inornata* has been introduced to the Pacific coast of North America and the Atlantic coast of Europe from France to Denmark (Martel *et al.*, 2004; Lützen *et al.*, 2012).

**UK distribution:** South and southeast coast (NBN Gateway, 2016).

**Habitat:** It can be found in intertidal and subtidal zones in gravel, mud and shell substrates, usually in oyster beds (Buhle *et al*., 2009; Lützen *et al*., 2012). *Ocenebra inornata* can tolerate winter temperatures as low as -1°C (Faasse and Ligthart, 2009) and salinity as low as 23 PSU (Lützen *et al.*, 2011). In Willapa Bay, Washington, it was most abundant in the more saline regions of the bay (Buhle *et al*., 2009).

**Reproduction:** Gonochoric. Juveniles are not planktonic and hatch from egg capsules, growing rapidly to reach reproductive age within a year (Buhle *et al.*, 2005; Global Invasive Species Database, 2016b). Reproduction appears to be controlled by water temperature (Martel *et al.*, 2004).

**Impact:** It is carnivorous, feeding on a variety of shelled invertebrates including mussels, clams, barnacles and other gastropods (Chew and Eisler, 1958; Duckwall, 2009; Faasse and Ligthart, 2009; Lützen *et al.*, 2012). However, its main ecological and economic impacts are due to its predation of oysters, and particularly young 'seed oysters' (Buhle *et al.*, 2009; Lützen *et al.*, 2012). It competes with native carnivorous snails and drills (e.g. in France with *O. erinacea* (Martel *et al*., 2004)).

**Legislation:** Wildlife and Countryside Act 1981. Article 15 (2) of the Wildlife (Northern Ireland) Order 1985. *Ocenebra inornata* is also listed on the IUCN list of problematic alien species.

### 3.7.2 Invasion pathways and techniques to limit spread

**HUMAN TRANSPORT: aquaculture**

- Importation of shellfish from invaded areas should be avoided.
- Oysters and mussels for consumption may need to be cleaned before sale.
- Juvenile oysters and mussels intended to be re-laid for fattening should be carefully screened for snails and egg cases. Juvenile snails and egg cases may easily escape attention.
- The tarra should not be deposited in on near the marine environment.
- For imports of oysters and mussels to areas where *O. inornata* is not known to occur it is advisable to select regions of origin where *O. inornata* has not been reported.
- All tingles are picked out of dredge hauls and taken ashore; all spawn noted is collected and dried.

#### Further information

Introduction has been via oyster transportation (Fofonoff *et al.*, 2003). The high shellfish health status of the UK prevents the import of many species from many other countries (Laing *et al*., 2010). It can be controlled by quarantine because juveniles are not planktonic (Buhle *et al.*, 2005). Drill damage in an infested oysterbed can be controlled by tilling the substrate, removing debris, and planting older oysters, which are less likely to be eaten (Fofonoff *et al.*, 2003). Coordination between growers on adjacent grounds is essential for effective control (Quayle, 1969).

### 3.7.3 Summary of control measures and evidence of success

**PHYSICAL AND MECHANICAL: manual removal**

✓ Manual collection or pot fishing for adults, burning eggs and freshwater immersions for juveniles have all been reported as effective.

### 3.7.4 Physical removal

#### Key finding

- Manual collection or pot fishing for adults, burning eggs and freshwater immersions for juveniles have all been reported as effective (Mueller and Hoffmann, 1996; Stiger-Pouvreau and Thouzeau, 2015; Global Invasive Species Database, 2016b).

#### Further information

Physical removal is the only control measure currently available but there is only anecdotal evidence of effectiveness. Drill infestations can be prevented by inspection and removal of drills on seed oysters, and inspection and regulation of oyster transfers and culture equipment (Fofonoff *et al.*, 2003). Control of drills on infested oyster beds can be achieved through the time-consuming and labour-intensive task of combing through the cultivated oysters a few times in early spring and manually removing snails and egg casings (Chris Eardley, *pers. comm.*). Removing debris from oyster beds and planting older oysters (which are less likely to be eaten) can also help (Quayle, 1969). Dragging dredges over the the bottom to bury oysterdrills is reportedly effective if there is coordination between adjacent growers (Quayle, 1969). Incentive harvest operations in the intertidal zone and pot fishing using oyster meat like bait have all been unsuccessful in eradicating the species in North America (Stiger-Pouvreau and Thouzeau, 2015). On the Skokomish tidelands (Oregon, USA) experiments have been conducted using natural and artificial surfaces to act as breeding aggregation sites from which snails can then be easy collected en masse (NWIFC, 2016). Cinder blocks attracted *O. inornata* but no more so than other hard vertical surfaces, although they might be more effective in habitats where these are lacking (Chris Eardley, *pers. comm.*). Bags of seed-on-cultch appear to be more effective at attracting snails but at the cost of losing spat (Chris Eardley, *pers. comm.*). Several sources (e.g. Global Invasive Species Database, 2016b) have reported that destroying the eggs of the drills by burning effectively controlled their numbers but the reference cited does not mention this. Larvae can be killed by freshwater immersion (Mueller and Hoffmann, 1996).

### 3.7.5 Further research

Analysis of invasion pathways would give a better understanding of the mechanisms of introduction. Pheromones are not a current control method for any of the species in this report but should be considered for *O. inornata*. The snails release a pheromone to attract others to egg-laying sites. Isolation and synthetic production of these pheromones could improve the efficiency of already used manual collection methods. The lack of basic reporting and published data on the effectiveness of methods is a hindrance to a rapid response to new introductions and long-term control of established populations. Practitioners should be encouraged, where possible, to report on the success (or failure) or methods in the medium-long term as well as any immediate effects. The timing of control methods as well as site-specific conditions should be reported in addition to efficiency. In this regard, *O. inornata* is a case in point.

## 4.0 References

Abbott, R.T. 1974. American seashells; the marine Mollusca of the Atlantic and Pacific coasts of North America. Van Nostrand Reinhold, New York.

Abernethy, V.J., Sabbatini, M.R., and Murphy, K.J. 1996. Response of *Elodea canadensis* Michx. and *Myriophyllum spicatum* L. to shade, cutting and competition in experimental culture. In Management and Ecology of Freshwater Plants (pp. 219-224). Springer Netherlands.

Alaska DNR. 2016. http://dnr.alaska.gov/ag/akpmc/invasives/elodea.htm [accessed 20.11.16].

Aldridge, D.C., Aldridge, S.L., Mead, A., Scales, H., Smith, R.K., Zieritz, A. and Sutherland, W.J. 2015. Control of freshwater invasive species: global evidence for the effects of selected interventions. The University of Cambridge, UK.

Andersen, T., Bello-González, O.C., Baars, J-R. and Earle, W. 2015. A new invasive weed-feeding species of *Polypedilum* (*Pentapedilum*) Kieffer from South Africa (Diptera: Chironomidae, Chironominae). Zootaxa 4000: 559-570.

Anderson, L.G., Dunn, A.M., Rosewarne, P.J., and Stebbing, P.D. 2015. Invaders in hot water: a simple decontamination method to prevent the accidental spread of aquatic invasive non-native species. Biological invasions 17: 2287-2297.

Angling Trust. 2016. www.anglingtrust.net/core/core_picker/download.asp?id=1782 [Accessed 18/9/16].

Appeltans, C.M.L. 2003. World Registry of Marine Species. http://www.marinespecies.org/index.php [accessed 4 Oct 2016].

Ashton, G., Boos, K., Shucksmith, R. and Cook, E. 2006. Risk assessment of hull fouling as a vector for marine non-natives in Scotland. Aquatic Invasions 1: 214-218.

Australian Government: Department of Agriculture, Fisheries and Forestry and Department Sustainability, Environment, Water, Population and Communities and New Zealand Ministry for Primary Industries. 2012. Anti-fouling and in-water cleaning guidelines, Department of Agriculture, Fisheries and Forestry, Canberra.

Baars, J.-M. 2011. Classical biological control for the management of alien invasive species in Ireland. Biology and Environment: Proceedings of the Royal Irish Academy 111B: 1-10.

Baars, J.R., Coetzee, J.A., Martin, G., Hill, M.P., and Caffrey, J.M. 2010. Natural enemies from South Africa for biological control of *Lagarosiphon major* (Ridl.) Moss ex Wager (Hydrocharitaceae) in Europe. Hydrobiologia 656: 149-158.

Bailey, J.E. and Calhoun, A.J.K. 2008. Comparison of three physical management techniques for controlling variable-leaf milfoil in Maine Lakes. Journal of Aquatic Plant Management 46: 163-167.

Barrat-Segretain, M.H. and Cellot, B. 2007. Response of invasive macrophyte species to drawdown: The case of *Elodea* sp.. Aquatic Botany 87: 255-261.

Bean, C. 2015. American Signal Crayfish (Trapping). Report to Scottish Parliament Petitions Committee. Available online at: http://www.parliament.scot/GettingInvolved/Petitions/americansignalcrayfish

Beninger, P.G., Decottignies, P., Guiheneuf, F., Barillé, L. and Rincé, Y. 2007. Comparison of particle processing by two introduced suspension feeders: selection in *Crepidula fornicata* and *Crassostrea gigas*. Marine Ecology Process Series 334: 165–177.

Beveridge, C., Cook, E.J., Brunner, L., MacLeod, A., Black, K. Brown, C. and Manson,F.J. 2011. Initial reponse to the invasive carpet sea squirt, *Didemnum vexillum*, in Scotland. Scottish Natural Heritage Commissioned Report No. 413.

Bij de Vaate, A., Jazdzewski, K., Ketelaars, H.A.M., Gollasch, S. and Van der Velde, G. 2002. Geographical patterns in range extension of Ponto-Caspian macroinvertebrate species in Europe. Canadian Journal of Fisheries and Aquatic Sciences 59: 1159-1174.

Blanchard, M. and Thomas, G. 1998. Suivi des opérations de nettoyage des bancs de crépidules (*Crepidula fornicata)* sur le littoral de Fouras (Charente-Maritime). Report/DEL 98/06.

Blanchard, M. 1997. Spread of the slipper limpet (*Crepidula fornicata*) in Europe, current state and consequences. Scientia Marina 61(2 supp.): 109-118.

Blanchard, M. 2009. Recent expansion of the slipper limpet population (*Crepidula fornicata*) in the Bay of Mont-Saint-Michel (Western Channel, France). Aquatic Living Resources 22:11-19.

Bohn, K., Richardson, C. and Jenkins, S. 2012. The invasive gastropod *Crepidula fornicata*: reproduction and recruitment in the intertidal at its northernmost range in Wales, UK, and implications for its secondary spread. Marine Biology 159: 2091-2103.

Bohn, K., Richardson, C. and Jenkins, S. 2015. The distribution of the invasive non-native gastropod *Crepidula fornicata* in the

Milford Haven Waterway, its northernmost population along the west coast of Britain. Helgoland Marine Research 69: 313-325.

Borcherding, J., Murawski, S. and Arndt, H. 2006. Population ecology, vertical migration and feeding of the Ponto-Caspian invader *Hemimysis anomala* in a gravel-pit lake connected to the River Rhine. Freshwater Biology 51: 2376-2387.

Browmer, K.H., Jacobs, S.W.L., and Sainty, G.R. 1995. Identification, biology and management of *Elodea canadensis*, Hydrocharitaceae. Journal of Aquatic Plant Management 33: 13-19.

Boylen, C.W., Eichler, L.W. and Sutherland, J.W. 1996. Physical control of Eurasian watermilfoil in an oligotrophic lake. Hydrobiologia 340: 213-218.

Bowmer, K.H. 1982. Aggregates of particulate matter and aufwuchs on *Elodea canadensis* in irrigation waters, and inactivation of diquat. Marine and Freshwater Research 33: 589-593.

Bugbee, G.J. and White, J.C. 2004. Control of *Cabomba* and Eurasian Milfoil in Lake Quonnipaug with Fluridone and 2,4-D. The Connecticut Agricultural Experiment Station, New Haven, CT. Bulletin.

Buhle, E.R., Margolis, M. and Ruesink, J.L. 2005. Bang for buck: cost-effective control of invasive species with different life histories. Ecological Economics 52: 355-366.

Bullard, S.G., Lambert, G., Carman, M.R., Byrnes, J., Whitlatch, R.B., Ruiz, G.M., Miller, R.J., Harris, L.G., Valentine, P.C., Collie, J.S., Pederson, J., McNaught, D.C., Cohen, A.N., Asch, R.G., Dijkstra, J. and Heinonen, K. 2007. The Invasive colonial ascidian *Didemnum* sp.: current distribution, basic biology, and potential threat to marine communities of the northeast and west coasts of the United States. Journal of Experimental Marine Biology and Ecology 342: 99-108.

Bullard, S.G. and Whitlatch, R.B. 2009. In situ growth of the colonial ascidian *Didemnum vexillum* under different environmental conditions. Aquatic Invasions 4: 275-278.

CABI. 2006. Invasive Species Compendium: Datasheet report for *Styela clava*. Datasheet no. 62274. Available online at: http://www.cabi.org/isc/datasheet/62274 [accessed 31 August 2016].

CABI. 2007. Invasive species compendium: Datasheet for *Myriophyllum aquaticm* (parrot's feather). Datasheet no. 34939. Available online at: http://www.cabi.org/isc/datasheet/34939 [accessed 12/9/2016]

CABI. 2008a. Invasive species compendium: Datasheet for *Cabomba caroliniana* (Carolina fanwort). Datasheet no. 107743. Available online at: http://www.cabi.org/isc/datasheet/107743 [accessed 23 May 2016].

CABI. 2008b. Invasive species compendium: Datasheet for *Lagarosiphon major* (African elodea). Datasheet no. 30548. Available online at: http://www.cabi.org/isc/datasheet/30548 [accessed 23 May 2016].

CABI. 2009a. Invasive Species Compendium: Datasheet report for *Crepidula fornicata*. Datasheet no. 108234. Available online at: http://www.cabi.org/isc/datasheet/108234 [accessed 16.07.16].

CABI. 2009b. Invasive Species Compendium: Datasheet report for *Didemnum vexillum*. Datasheet no. 107996. Available online at http://www.cabi.org/isc/datasheet/107996 [accessed 31 August 2016].

CABI (2009c) Invasive Species Compendium Datasheet report for *Spartina anglica* (common cordgrass). http://www.cabi.org/isc/datasheet/107739 [accessed 13.09.16].

CABI. 2009d. Invasive Species Compendium: Datasheet report for *Urosalpinx cinerea*. Datasheet no. 10687. Available online at: http://www.cabi.org/isc/datasheet/60187 [accessed 31 August 2016].

CABI. 2010a. Invasive species compendium: Datasheet for *Elodea nuttallii* (Nuttall's waterweed). Datasheet no. 20761. Available online at: http://www.cabi.org/isc/datasheet/20761 [accessed 23 May 2016].

CABI. 2010b. Invasive species compendium: Datasheet for *Eriocheir sinensis* (Chinese mitten crab). Datasheet no. 84140. Available online at: http://www.cabi.org/isc/datasheet/84120 [accessed 29 September 2016].

CABI. 2014. Invasive species compendium: Datasheet for *Azolla filiculoides* (water fern). Datasheet no. 8119. Available online at: http://www.cabi.org/isc/datasheet/8119 [accessed 23 May 2016].

Cabrera-Walsh, G., Schooler, S. and Julien, M. 2011. Biology and preliminary host range of *Hydrotimetes natans* Kolbe (Coleoptera: Curculionidae), a natural enemy candidate for biological control of *Cabomba caroliniana* Gray (Cabombaceae) in Australia. Austral Entomology 50: 200-206.

Caffrey, J. M., Millane, M., Evers, S., Moron, H. and Butler, M. 2010. A novel approach to aquatic weed control and habitat restoration using biodegradable jute matting. Aquatic Invasions 5: 123-129.

Carlton, J.T. 1989. Man's role in changing the face of the ocean: Biological invasions and implications for conservation of near-shore environments. Conservation Biology 3: 265-273.

Carlton, J.T. and Geller, J. 1993. Ecological roulette: the global transport of non-indigenous marine organisms. Science 261: 78–82.

Carman, M.R., Allen, H,M. and Tyrrell, M.C. 2009. Limited value of the common periwinkle snail *Littorina ittorea* as a biological control for the invasive tunicate *Didemnum vexillum*. Aquatic Invasions 4: 291-294.

Carman, M.R., Lindell, S., Green-Beach, E. and Starczak, V.R. 2016. Treatments to eradictate invasive tunicate fouling from blue mussel seed and aquaculture socks. Management of Biological Invasions 7: 101-110.

Carriker, M.R. 1955. Critical review of biology and control of oyster drills *Urosalpinx* and *Eupleura*. US Department of the Interior, Fish and Wildlife Service. Special Scientific Report - Fisheries 148:1-150.

CDFW. 2016. Chinese mitten crab, *Eriocheir sinensis*. Invasive species fact sheet, California Department of Fish and Wildlife. Available online at: https://www.wildlife.ca.gov/Conservation/Invasives/Species/Mitten-Crab [accessed 21.10.16].

CEH. 2004. Information Sheet *Myriophyllum aquaticum* Parrot's Feather. Available online at: https://secure.fera.defra.gov.uk/nonnativespecies/downloadDocument.cfm?id=1085 [accessed 23 May 2016].

Champion, P.D. and Clayton, J.S. 2001. Border control for potential aquatic weeds. Stage 2. Weed risk assessment. Science for Conservation 165. Department of Conservation, New Zealand, 30pp.

Chew, K.K. and Eisler, R. 1958. A preliminary study of the feeding habits of the Japanese oyster drill, *Ocienebra japonica*. Journal of the Fisheries Research Board of Canada 15: 529–535.

Cilliers, C. J. 1999. *Lysathia* n. sp. (Coleoptera: Chrysomelidae), a host-specific beetle for the control of the aquatic weed *Myriophyllum aquaticum* (Haloragaceae) in South Africa. In Biology, Ecology and Management of Aquatic Plants (pp. 271-276). Springer, Netherlands.

Cilliers, C. and Mabulu, L. 2002. *Lysathia* (Lysathia n.sp.); a natural enemy of parrot's feather (*Myriophyllym aquaticum*) in South Africa. Dossiers on biological control agents available to aid alien plant control, Agriculture Research Council, South Africa.

Clark, P.F., Rainbow, P.S., Robbins, R.S., Smith, B., Yeomans, W.E., Thomas, M. and Dobson, G. 1998. The alien Chinese mitten crab, *Eriocheir sinensis* (Crustacea: Decapoda: Brachyura), in the Thames catchment. Journal of the Marine Biological Association of the United Kingdom 78: 1215-1221.

Clarke, C.L. and Therriault, T.W. 2007. Biological Synopsis of the Invasive Tunicate *Styela clava* (Herdman 1881). Canadian Manuscript Report of Fisheries and Aquatic Sciences 2807.

Clayton, J.S. 1996. Aquatic weeds and their control in New Zealand lakes. Lake and Reservoir Management 12: 477-486.

Cohen, A.N. 2005. *Styela clava* Herdman, 1881. Guide to the Exotic Species of San Francisco Bay. Oakland, CA, San Francisco Estuary Institute. Available online at: http://www.exoticsguide.org/ [accessed 30.09.16].

Cole, H.A. 1942. The American whelk tingle, *Urosalpinx cinerea* (Say), on British oyster beds. Journal of the Marine Biological Association of the United Kingdom 25:477-508.

Cole, H.A. 1952. The American slipper limpet (*Crepidula fornicata*) on Cornish beds. Fishery Investigations Series 2, 17: 1-13.

Cole, H.A. and Baird, R.H. 1953. The American slipper limpet (*Crepidula fomicata*) in Milford Haven. Nature, 172: 687

Cottet, M., de Montaudouin, X., Blanchet, H. and Lebleu, P. 2007. *Spartina anglica* eradication experiment and *in situ* monitoring assess structuring strength of habitat complexity on marine macrofauna at high tidal level. Estuarine, Coastal and Shelf Science 71: 629–640.

Coutts, A.D.M. 2006. An evaluation of incursion response tools for invasive species: a case study of *Didemnum vexillum* in the Marlborough Sounds. Cawthron Report, vol. 1093. Cawthron Institute, Nelson, New Zealand. February 2006, 81pp.

Coutts, A.D.M. and Forrest, B.M. 2005. Evaluation of eradication tools for the clubbed tunicate, *Styela clava*. Cawthron Rep 1110. Cawthron Institute, Nelson, New Zealand.

Coutts, A.D.M. and Forrest, B.M. 2007. Development and application of tools for incursion response: Lessons learned from the management of the fouling pest *Didemnum vexillum*. Journal of Experimental Marine Biology and Ecology 342: 154-162.

Cronk, Q.C.B. and Fuller, J.L. 1995. Plant invaders: the threat to natural ecosystems. London, UK; Chapman and Hall Ltd, xiv + 241 pp.

Dadds, N., Bell, S. and Wilson, S. 2007. Invasive non-native plants associated with fresh waters: A guide to their identification. Produced by SNH as part of the Species Action Framework [accessed online 23.05.16].

Darbyson, E.A., Hanson, J.M., Locke, A. and Willison, J.H.M. 2009. Settlement and potential for transport of clubbed tunicate (*Styela clava*) on boat hulls. Aquatic Invasions [Proceedings of the 2nd International Invasive Sea Squirt Conference, Prince Edward Island, Canada, 2-4 October 2007.] 4: 95-103.

Darling, J.A., Herborg, L-M. and Davidson, I.C. 2012. Intracoastal shipping drives patterns of regional population expansion by an invasive marine invertebrate. Ecology and Evolution 2: 2552-2561.

Davis, M.H. and Davis, M.E. 2007. The distribution of *Styela clava* (Tunicata, Ascidiacea) in European waters. Journal of Experimental Marine Biology and Ecology 342: 182–184.

Debrosse, G.A. and Allen, S.K. 1993. Control of overset on cultured oysters using brine solutions. Journal of Shellfish Research 12: 29-33.

Decottignies, P., Beninger, P.G., Rince, Y. and Riera, P. 2007. Trophic interactions between two introduced suspension-feeders, *Crepidula fornicata* and *Crassostrea gigas*, are influenced by seasonal effects and qualitative selection capacity. Journal of Experimental Marine Biology and Ecology 342: 231–241.

Denny, C.M. 2008. Development of a method to reduce the spread of the ascidian *Didemnum vexillum* with aquaculture transfers. ICES Journal of Marine Science 65: 805-810.

Department of Ecology State of Washington. 2016. Non-native, invasive, freshwater plants: Brazilian *Elodea* (*Egeria densa*). Available online at: http://www.ecy.wa.gov/programs/wq/plants/weeds/aqua002.html [accessed 18.08.16].

Dethier, M.N. and Hacker, S.D. 2005. Physical factors vs. biotic resistance in controlling the invasion of an estuarine marsh grass. Ecological Applications 15: 1273-1283.

Dijkstra, J., Harris, L.G. and Westerman, E. 2007. Distribution and long-term temporal patterns of four invasive colonial ascidians in the Gulf of Maine. Journal of Experimental Marine Biology and Ecology 342: 61-68.

Di Nino, F., Thiébaut, G. and Muller, S. 2005. Response of *Elodea nuttallii* (Planch.) H. St. John to manual harvesting in the North-East of France. Hydrobiologia 551: 147-157.

Dorenbosch, M. and Bergsma, J.H. 2014. Bestrijding van waterwaaier in Hardinxveld met hydro-venturi. Evaluatie onderzoek en beknopte literatuur vergelijking. Bureau Waardenburg, Culemborg.

Droscher, T. 2006. Volunteer divers tackle tough tunicates. Sound Waves: Puget Sound Action Team. 21: 8.

Duckwall, L. 2009. Pacific Northwest Aquatic Invasive Species Profile: Japanese Oyster Drill *Ocinebrellus inornatus*. University of Washington.

Dugdale, T.M., Butler, K.L, Clements, D. and Hunt, T.D. 2013. Survival of *Cabomba caroliniana* during lake drawdown within mounds of stranded vegetation. Lake and Reservoir Management 29: 61-67.

Dumont, S. 2006. A new invasive species in the north-east of France, *Hemimysis anomala* G. Sars, 1907 (Mysidacea). Crustaceana 79: 1269-1274.

Dupont, L., Viard, F., Dowell, M.J., Wood, C. and Bishop, J.D.D. 2009. Fine- and regional-scale genetic structure of the exotic ascidian *Styela clava* (Tunicata) in southwest England, 50 years after its introduction. Molecular Ecology 18: 442–453.

EA. 2010. Managing invasive non-native plants. Leaflet produced by The Environment Agency, Bristol. 29pp.

Earle, W., Mangan, R., O'Brien, M. and Baars, J.-R. 2013. Biology of *Polypedilum* n. sp. (Diptera: Chironomidae), a promising candidate agent for the biological control of the aquatic weed *Lagarosiphon major* (Hydrocharitaceae) in Ireland. Biocontrol Science and Technology 23: 1267–1283.

Ellis, S. and MacIsaac, H.J. 2009. Salinity tolerance of Great Lakes invaders. Freshwater Biology 54: 77-89.

Emerine, S.E., Richardson, R.J., True, S.L., West, A.M. and Roten, R.L. 2010. Greenhouse response of six aquatic invasive weeds to imazamox. Journal of Aquatic Plant Management 48:105-111.

Ernhold, A., Blanchard, M. Auffret, J-P. and Garlan, T. 1998. The role of *Crepidula* proliferation in the modification of the sedimentary tidal environment in Mont-Saint-Michel Bay (The Channel, France). Earth and Planetary Sciences 327: 583-588.

Faasse, M. and Ligthart, M. 2009. American (*Urosalpinx cinerea*) and Japanese oyster drill (*Ocinebrellus inornatus*) (Gastropod: Muricidae) flourish near shellfish in the Netherlands. Aquatic Invasions 4: 321-326.

Fialho, C., Banha, F. and Anastácio, P.M. 2016. Factors determining active dispersal capacity of adult Chinese mitten crab *Eriocheir sinensis* (Decapoda, Varunidae). Hydrobiologia 767: 321-331.

Fitzgerald, A. 2007. Slipper limpet utilisation and management. Final report, Port of Truro Oyster Management Group. Available online at: http://www.shellfish.org.uk/files/Literature/Projects-Reports/0701-Slipper_Limpet_Report_Final_Small.pdf [accessed 27.11.16].

Flimlin, G. and Beal, B.F. 1993. Major predators of cultured shellfish. Factsheet Northeastern Regional Aquaculture Center. NRAC Bulletin 180: 1-6.

Floerl, O., Inglis, G.J. and Hayden, B.J. 2005. A risk-based predictive tool to prevent accidental introductions of nonindigenous marine species. Environmental Management 35: 765-778.

Flower, F.B. 1954. A new enemy of the oyster drill. Science, 120: 231-232.

Fofonoff, P.W., Ruiz, G.M., Steves, B. and Carlton, J.A. 2003. California Non-native Estuarine and Marine Organisms (Cal-NEMO) System. http://invasions.si.edu/nemesis/ [accessed 04.10.16].

Forrest B.M., Hopkins, G.A., Dodgshun, T.J. and Gardner, J.P.A. 2007. Efficacy of acetic acid treatments in the management of marine biofouling. Aquaculture 262: 319-332.

Fowler, M.C. 1984. The present status of grass carp (*Ctenopharyngodon idella*) for the control of aquatic weeds in England and Wales. In: Delfosse, E.S. (Ed). Proceedings of the VI International Symposium on Biological Control of Weeds, 19-25 August 1984, Vancouver, pp.537-542. Canadian Government Publishing Centre.

Francis, R.A. and Pyšek, P. 2012. Management of freshwater invasive alien species. In Francis, R.A. (ed). A handbook of global freshwater invasive species. Earthscan.

Frid, C.L.J., Chandrasekera, L.W.H.U., and Davey, P. 1999. The restoration of mud flats invaded by common cord-grass (*Spartina anglica*, CE Hubbard) using mechanical disturbance and its effects on the macrobenthic fauna. Aquatic Conservation: Marine and Freshwater Ecosystems 9: 47-61.

Galtsoff, P.S., Prytherch, H.F., Engle, J.B. 1937. Natural history and methods of controlling the common oyster drills (*Urosalpinx cinerea* Say and *Eupleura caudata* Say). U.S. Bureau Fisheries, Circular no. 25. pp.1-24.

Garbutt, A., Burden, A., Maskell, L., Smart, S., Hughes, S., Norrism D. and Cooper, M. 2015. The status of Habitats Directive Annex I saltmarsh habitats, transition zones and *Spartina* species in England. Natural England Commissioned Report, NECR185.

Garcia, R.P. 1986. Survey of mycoflora associated with *Azolla* spp. Phillippine Agriculturist 69: 529-534.

Garner, A. B., Kwak, T. J., Manuel, K. L., and Barwick, D. H. 2013. High-density grass carp stocking effects on a reservoir invasive plant and water quality. Journal of Aquatic Plant Management 51: 27-33.

Gasiunas, I.I. 1964. Acclimatization of forage crustaceans into the Kaunas hydropower plant reservoir and possibility of their migration into other waters of Lithuania. Trudy Akademii Nauk Litovskoi SSR, Seriya B 1: 79-85.

Gasiunas, I.I. 1968. Akklimatizatsiya mizidii *Hemimysis anomala* Sars v vodokhranilishche Kaunasskoi GES). Trudy Akademii Nauk Litovskoi SSR,Seriya B 3: 71-73.

Gassman, A., Cock, M.J.W., Shaw, R. and Evans, H.C. 2006. The potential for biological control of invasive alien aquatic weeds in Europe: a review. Hydrobiologia 570: 217-222.

Gibbs, P.E., Spencer, B.E., and Pascoe, P.L. 1991. The American oyster drill *Urosalpinx cinerea* (Gastropoda): evidence of decline in an imposex-affected population (R. Blackwater, Essex). Journal of the Marine Biological Association of the United Kingdom 71: 827-838.

Gittenberger, A. 2007. Recent population expansions of non-native ascidians in The Netherlands. Journal of Experimental Marine Biology and Ecology [Proceedings of the 1st International Invasive Sea Squirt Conference, Woods Hole, Massachusetts, USA, April 21-22, 2005.], 342(1):122-126.

GLMRIS (Great Lakes and Mississippi river interbasin study). 2012. Electron beam irradiation. Available online at http://glmris.anl.gov/documents/docs/anscontrol/ElectronBeamIrradiation.pdf [accessed 20.09.16]

Global Invasive Species Database. 2016a. Species profile: Myriophyllum aquaticum. Downloaded from http://www.iucngisd.org/gisd/species.php?sc=401 on 12-11-2016.

Global Invasive Species Database. 2016b. Species profile: *Ocenebra inornata*. Downloaded from http://www.gbif.org/species/4364689 on 31-01-2017.

Global Invasive Species Database. 2016c. Species profile: *Spartina anglica*. Downloaded from http://www.iucngisd.org/gisd/species.php?sc=76 on 26-11-2016.

Global Invasive Species Database. 2016d. Species profile: *Urosalpinx cinerea*. Available online at: http://www.iucngisd.org/gisd/species.php?sc=1383 [accessed 28.11.16].

Glomski, L. A., Skogerboe, J. G., and Getsinger, K. D. 2005. Comparative efficacy of diquat for control of two members of the Hydrocharitaceae: *Elodea* and *Hydrilla*. Journal of Aquatic Plant Management 43: 103-105.

Goldstien, S.J., Schiel, D.R. and Gemmell, N.J. 2010. Regional connectivity and coastal expansion: differentiating pre-border and post-border vectors for the invasive tunicate *Styela clava*. Molecular Ecology 19: 874-885.

Gollasch, S. 2011. NOBANIS – Invasive Alien Species Fact Sheet – *Eriocheir sinensis*. – From: Online Database of the European Network on Invasive Alien Species – NOBANIS www.nobanis.org [accessed 29.09.16].

Griffith, K., Mowat, S., Holt, R.H.F., Ramsay, K., Bishop, J.D.D., Lambert, G. and Jenkins, S.R. 2008. First records in Great Britain of the invasive colonial ascidian *Didemnum vexillum* Kott, 2002. Aquatic Invasions 4: 581-590.

Grigorovich, I.A., MacIsaac, H.J., Shadrin, N.V. and Mills, E.L. 2002. Patterns and mechanisms of aquatic invertebrate introductions in the Ponto-Caspian region. Canadian Journal of Fisheries and Aquatic Science 59: 1189-1208.

Groenendijk, A.M. 1986. Establishment of a *Spartina anglica* population on a tidal mudflat: a field experiment. Journal of Environmental Management 22: 1-12.

Gust, N., Inglis, G., Floerl, O., Peacock, L., Denny, C. and Forrest, B. 2008. Assessment of population management options for Styela clava. MAF Biosecurity New Zealand Technical Paper No: 2009/04.

Haberland, M. 2014. Parrot feather (*Myriophyllum aquaticum*): A non-native aquatic plant in New Jersey waterways. Fact Sheet FS1232. Rutgers, The State University of New Jersey.

Hacker, S.D., Heimer, D., Hellquist, C.E., Reeder, T.G., Reeves, B., Riordan, T.J. and Dethier, M.N. 2001. A marine plant (*Spartina anglica*) invades widely varying habitats: potential mechanisms of invasion and control. Biological Invasions 3: 211-217.

Hammond, M.E.R. 2001. The experimental control of *Spartina anglica* and *Spartina* x *townsendii* in estuarine salt marsh. University of Ulster.

Hammond, M.E.R, and Cooper, A. 2003. *Spartina anglica* eradication and inter-tidal recovery in Northern Ireland estuaries. Turning the tide: Proceedings of the International Conference on Eradication of Island Invasives.

Hancock DA, 1969. Oyster pests and their control. Laboratory Leaflet (new series) no. 19. Oyster pests and their control. Laboratory Leaflet (new series) no. 19. Burnham on Crouch, Essex, UK: Fisheries laboratory, Ministry of Agriculture, Fisheries and Food, unpaginated.

Hanks, J.E. 1957. The rate of feeding of the common oyster drill, *Urosalpinx cinerea* (Say), at controlled water temperatures. Biological Bulletin 112: 330-335.

Hanlon, S. G., Hoyer, M. V., Cichra, C. E., and Canfield, D. E. 2000. Evaluation of macrophyte control in 38 Florida lakes using triploid grass carp. Journal of Aquatic Plant Management 38: 48-54.

Hedge, P., Kriwoken, L. K., and Patten, K. 2003. A review of *Spartina* management in Washington State, US. Journal of Aquatic Plant Management 41, 82-90.

Herborg, L.M., Bentley, M.G. and Clare, A.S. 2002. First confirmed record of the Chinese mitten crab (*Eriocheir sinensis*) from the River Tyne, United Kingdom. Journal of the Marine Biological Association of the United Kingdom 82: 921-922.

Herborg, L.-M., Rushton, S.P., Clare, A.S. and Bentley, M.G., 2003. Spread of the Chinese mitten crab (*Eriocheir sinensis* H. Milne Edwards) in Continental Europe: analysis of a historical data set. Hydrobiologica 503: 21–28.

Hill, M.P. 1998. Life history and laboratory host range of *Stenopelmus rufinasus*, a natural enemy for *Azolla filiculoides* in South Africa. BioControl 43: 215-224.

Hill, M.P. 1999. The world's worst aquatic weed. Pesticide Outlook 10: 58-61.

Hill, M.P. and Cilliers, C.J. 1999. *Azolla filiculoides* Lamarck (Pteridophyta: Azollaceae), its status in South Africa and control. Hydrobiologia 415: 203-206.

Hill, M.P., McConnachie, A.J. and Byrne, M.J. 2008. *Azolla filiculoides* Lamark (Pteridophyta: Azollaceae) control in South Africa: a 10-year review. Proceedings of the XII International Symposium on Biological Control of Weeds (eds M.H. Julien, R. Sforza, M.C. Bon, H.C. Evans, P.E. Hatcher), La Grande Motte, France, 22-27 April 2007.

Hoffmann, M. A., González, A. B., Raeder, U., and Melzer, A. 2013. Experimental weed control of *Najas marina* ssp. intermedia and *Elodea nuttallii* in lakes using biodegradable jute matting. Journal of Limnology 72: 39.

Hofstra, D.E., Champion, P.D. and Dugdale, T.M. 2006. Herbicide trials for the control of parrotsfeather. Journal of Aquatic Plant Managament 44: 13-18.

Hofstra, D. E., and Clayton, J. S. 2001. Evaluation of selected herbicides for the control of exotic submerged weeds in New Zealand: I. The use of endothall, triclopyr and dichlobenil. Journal of Aquatic Plant Management, 39: 20-24.

Holdich, D., Gallagher, S., Rippon, L., Harding, P. and Stubbington, R. 2006. The invasive Ponto-Caspian mysid, *Hemimysis anomala*, reaches the UK. Aquatic Invasions, 1:4-6.

Holm, L.G., Weldon, L.W. and Blackburn, R.D. 1969. Aquatic weeds. Science 166: 699-709.

Holt, R. 2013. The carpet seasquirt (*Didemnum vexillum*) eradication programme. Progress to April 2013. Natural Resources Wales. Available online at: http://invasivespeciesireland.com/wp-content/uploads/2013/03/Rohan-Holt.pdf [accessed 21.08.16]

Holt, R.H.F., Ramsay, K., Mowat, S., Kent. F.E.A. and Griffith, K. 2009. Survey of a non-native ascidian (sea squirt) *Didemnum vexillum* in Holyhead Harbour. CCW Marine Monitoring Report No: 67.

Holt, R.H.F. and Cordingley, A.P. 2011. Eradication of the non-native carpet ascidian (sea squirt) *Didemnum vexillum* in Holyhead Harbour: Progress, methods and results to spring 2011. CCW Marine Monitoring. Countryside Council for Wales: 112.

Howard-Williams, C., Schwarz, A. M., and Reid, V. 1996. Patterns of aquatic weed regrowth following mechanical harvesting in New Zealand hydro-lakes. In Management and Ecology of Freshwater Plants Springer Netherlands. pp. 229-234.

Hubbard, C.E., 1968. Grasses. (2nd edition). Pelican.

Hussner, A. 2012. Alien aquatic plants in European countries. Weed Research 52: 397-406.

Hussner, A. and Champion, P.D. 2011. *Myriophyllum aquaticum* (Vell.) verdcourt (parrot feather). In: Francis, R.A. (Ed), A

Handbook of Global Freshwater Invasive Species. Earthscan Publisher, New York, pp.103-112.

Hussner, A., Stiers, I., Verhofstad, M.J.J.M., Bakker, E.S., Grutters, B.M.C., Haury, J., van Valkenburg, J.L.C.H., Brundu, G., Newman, J., Clayton, J.S., Anderson, L.W.J. and Hofstra, D. 2017. Management and control methods of invasive alien freshwater aquatic plants: A review. Aquatic Botany 136:112-137.

IMO (International Maritime Organisation). 2016. International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM). Available online at http://www.imo.org/ [accessed 20.09.16].

James, W.F. 2008. Effects of lime-induced inorganic carbon reduction on the growth of three aquatic macrophyte species. Aquatic Botany 88: 99-104.

James, W.F. 2011. Effects of lime addition on the growth of fanwort in softwater systems. Journal of Aquatic Plant Management 49: 28-32.

Jerde, C.L., Barnes, M.A., DeBuysser, E.K., Noveroske, A., Chadderton, W.L. and Lodge, D.M. 2012. Eurasian watermilfoil fitness loss and invasion potential following desiccation during simulated overland transport. Aquatic Invasions 7: 135–142.

JNCC (Joint Nature Conservation Committee). 1997. Non-native marine species in British waters: a review and directory. Editors: N. Clare Eno, Robin A. Clark and William G. Sanderson. Available online at http://www.jncc.gov.uk/page-1722 [accessed 20.09.16].

Katayama, K. and Ikeda, Z. 1987. Tolerance of fresh water, hot water, and sun-drying by *Didemnum moseleyi*, fouling organisms attached to culture oyster. Bulletin of the Fisheries Experiment Station, Okayama Prefecture 2: 104-106

Kelly, A. 2006. Removal of invasive floating pennywort *Hydrocotyle ranunculoides* from Gillingham marshes, Suffolk, England. Conservation Evidence 3: 52-53.

Kelley D.F. 1987. Food of bass in UK waters. Journal of the Marine Biological Association UK 67: 275-286.

Kelly, J., and Maguire, C.M. 2009. *Azolla filiculoides* Invasive Species Action Plan. Prepared for NIEA and NPWS as part of Invasive Species Ireland.

Ketelaars, H.A.M., Lambregts-van de Clundert, F.E., Carpentier, C.J., Wagenvoort, A.J. and Hoogenboezem, W. 1999. Ecological effects of the mass occurrence of the Ponto-Caspian invader, *Hemimysis anomala* G.O. Sars, 1907 (Crustacea: Mysidacea), in a freshwater storage reservoir in the Netherlands, with notes on its autecology and new records. Hydrobiologia 394: 233-248.

Kipp, R.M., Ricciardi, A., Larson, J. Fusaro, A. and Makled, T. 2016. *Hemimysis anomala*. USGS Nonindigenous Aquatic Species Database, Gainesville, FL.
Available online at: http://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=2627 Revision Date: 05.31.2013 [accessed 14.09.16]

Kleeman, S.N. 2009. *Didemnum vexillum* – Feasibility of Eradication and/or Control. CCW Contract Science report no, 875.

Kornijów, R., Kuoppamäki, K., Horppila, J., Luokkanen, E. and Kairesalo, T. 2004. Impacts of a submerged plant (*Elodea canadensis*) on interactions between roach (*Rutilus rutilus*) and its invertebrate prey communities in a lake littorial zone. Freshwater Biology 50: 262-276.

Korringa, P. 1942. *Crepidula fornicata*'s invasion in Europe. Basteria 7: 12–23.

Korringa, P. 1951. *Crepidula fornicata* as an oyster pest. Conseil Permanent International Pour L'Exploration de la Mer Rapports Proces-Verbaux des Reunions 128: 55–59.

Kott, P. 2002. A complex didemnid ascidian from Whangamata, New Zealand. Journal of Marine Biology Association of the United Kingdom, 82: 625-628.

Kott, P. 2004. A new species of *Didemnum* (Ascidiacea, Tunicata) from the Atlantic coast of North America. Zootaxa 732: 1-10.

Laing, I., Bussell, J. and Somerwill, K. 2010. Assessment of the impacts of *Didemnum vexillum* and options for the management of the species in England. Fera, CEFAS and Natural England: 62.

Lambert, G., 2009, Adventures of a sea squirt sleuth: unraveling the identity of *Didemnum vexillum*, a global ascidian invader. Aquatic Invasions 4: 5-28.

Lambert G. and Lambert, C.C. 1995. Nonindigenous sea squirts in California Harbors. Aquatic Nuisance Species Digest 1: 17-20.

Lansdown, R.V. 2015. Carolina Water-shield, *Cabomba caroliniana* factsheet. Available online at: http://www.nonnativespecies.org/factsheet/downloadFactsheet.cfm?speciesId=596 [accessed 22.08.16]

Lantry, B.F., Walsh, M.G., Johnson, J.H. and McKenna, J.E. 2010. Occurrence of the Great Lake's most recent invader, *Hemimysis anomala*, in the diet of fishes in southeastern Lake Ontario. Journal of Great Lakes Research 36: 179-183.

Laranjeira, C.M. and Nadais, G. 2008. *Eichhornia crassipes* control in the largest Portuguese natural freshwater lagoon. EPPO Bulletin 38: 487-495.

LeBlanc, N., Davidson, J., Tremblay, R., McNiven, M., Laudry, T. 2007. The effect of anti-fouling treatments for the clubbed tunicate on the blue mussel, *Mytilus edulis*. Aquaculture 264: 205-213.

Leidenberger, S., Obst, M., Kulawik, R., Stelzer, K., Heyer, K., Hardisty, A. and Bourlat, S.J. 2015. Evaluating the potential of ecological niche modelling as a component in marine non-indigenous species risk assessments. Marine Pollution Bulletin 97: 470-487.

LeYi, N. 1999. Effects of apex cutting on growth of *Elodea canadensis* St. John. Acta Hydrobiologica Sinica 23: 297-303.

Locke, A., Doe, K.G., Fairchild, W.L., Jackman, P.M. and Reese, E.J. 2009. Preliminary evaluation of effects of invasive tunicate management with acetic acid and calcium hydroxide on non-target marine organisms in Prince Edward Island, Canada. Aquatic Invasions 4: 221-236.

Locke, A., Hanson, J.M., Ellis, K.M., Thompson, J. and Rochette, R. 2007. Invasion of the southern Gulf of St. Lawrence by the clubbed tunicate (*Styela clava* Herdman): Potential mechanisms for invasions of Price Edward Island estuaries. Journal of Experimental Marine Biology and Ecology 342: 69-77.

Loomis, S.H. and Van Nieuwenhuyze, W. 1985. Sediment correlates to density of *Crepidula fornicata* Linnaeus in the Pataguanset River, Connecticut. Veliger 27: 266–272.

Lord, J. and Whitlatch, R. 2013. Impact of temperature and prey shell thickness on feeding of the oyster drill U*rosalpinx cinerea*

Say. Journal of Experimental Marine Biology and Ecology 448: 321-326.

Lumpkin, T.A. and Plucknett, D.L. 1982. *Azolla* as a green manure: use and management in crop production. Westview Press Boulder, Colorado, 230pp.

Lush, M.J., Haynes, T.A. and Lush, C.E. 2016. *Spartina anglica* and its management in estuarine Natura 2000 sites: an update of its status and monitoring future change in England. Published by Natural England as part of the Improvement Programme for England's Natura 2000 sites (IPENS).

Lützen, J. 1999. *Styela clava* Herdman (Urochordata, Ascidiacea), a successful immigrant to North West Europe: ecology, propagation and chronology of spread. Helgol. Meeresunters 52: 383-391.

Lützen, J., Faasse, M., Gittenberger, A., Glenner, H. and Hoffmann, E. 2012. The Japanese oyster drill *Ocinebrellus inornatus* (Récluz, 1851) (Mollusca, Gastropoda, Muricidae), introduced to the Limfjord, Denmark. Aquatic Invasions 7: 181-191.

Maceina, M.J., Cichra, M.F., Betsill, R.K. and Bettoli, P.W. 1992. Limnological changes in a large reservoir following vegetation removal by grasscarp. Freshwater Ecology 7: 81-95.

Machado, C. and Rocha, F. 1998. Control of *Myriophyllum aquaticum* in drainage and irrigated channels of the Mondego river valley, Portugal. In Management and ecology of aquatic plants. Proceedings of the 10th EWRS International Symposium on Aquatic Weeds, Lisbon, Portugal, 21-25 September 1998. (pp. 373-375). European Weed Research Society.

Mackenzie, C. L. 1970. Control of oyster drills, *Eupleura caudata* and *Urosalpinx cinerea*, with the chemical Polystream. Fishery Bulletin 68: 285-297.

Madeira, P.T., Center, T.D., Coetzee, J.A., Pemberton, R.W., Purcell, M.F. and Hill, MP. 2013. Identity and origins of introduced and native *Azolla* species in Florida. Aquatic Botany 111: 9-15.

Madeira, P.T., Hill, M.P., Dray, F.A. Jr, Coetzee, J.A., Paterson, I.D. and Tipping, P.W. 2016. Molecular identification of *Azolla* invasions in Africa: the *Azolla* specialist, *Stenopelmus rufinasus* proves to be an excellent taxonomist. South African Journal of Botany 105: 299-305.

Mangan, R. and Baars, J. 2011. Pre-release Efficacy Assessments of the Leaf-mining Fly *Hydrellia lagarosiphon*, a Candidate Biological Control Agent of the Submerged Weed *Lagarosiphon major* Session 1 Pre-Release Testing of Weed Biological Control Agents. XIII International Symposium on Biological Control of Weeds 2011.

Mangan, R. and Baars, J. 2013. Use of life table statistics and degree day values to predict the colonisation success of *Hydrellia lagarosiphon* Deeming (Diptera: Ephydridae), a leaf mining fly of *Lagarosiphon major* (Ridley) Moss (Hydrocharitaceae), in Ireland and the rest of Europe. Biological Control, 64: 143-151.

Mangan, R. and Baars, J. 2016. Can leaf-mining flies generate damage with significant impact on the submerged weed *Lagarosiphon major*? BioControl 61: 803-813.

Marques, M., Banha, F., Áquas, M. and Anastácio, P. 2015. Environmental cues during overland dispersal by three freshwater invaders: *Eriocheir sinensis*, *Pacifastacus leniusculus*, and *Procambarus clarkia* (Crustacea, Decapoda). Hydrobiologia 742: 81-93.

Martel, C., Guarini, J.M., Blanchard, G., Sauriau, P.G., Trichet, C., Robert, S. and Garcia-Meunier, P. 2004. Invasion by the marine gastropod *Ocinebrellus inornatus* in France. III. Comparison of biological traits with the resident species *Ocenebra erinacea*. Marine Biology 146: 93-102.

Mauchline J, 1980. The biology of mysids. Advances in Marine Biology, 18:1-369.

McClary, D., Phipps, C. and Hinni, S. 2005. Reproductive behaviour of the Clubbed Tunicate, *Styela clava*, in northern New Zealand waters. MAF Biosecurity New Zealand Technical Paper No: 2009/01.

McConnachie, A.J., Hill, M.P. and Byrne, M.J. 2004. Field assessment of a frond-feeding weevil, a successful biological control agent of red waterfern, *Azolla filiculoides*, in southern Africa. Biological Control 29: 326-331.

McConnachie, A.J., Wit, M.P., Hill, M.P. and Byrne, M.J. 2003. Economic evaluation of the successful biological control of *Azolla filicuolides* in South Africa. Biological Control 28: 25-32.

McCorry, M, Curtis, T.G.F. and Otte, M.L. 2003. *Spartina* in Ireland. In Wetlands of Ireland, distribution, ecology, uses and economic value. Otte, M.L. (ed.) University College Press Dublin, 44-50.

McCorry, M. J. and Otte, M. L. 2001. Ecological effects of *Spartina anglica* on the macro-invertebrate infauna of the mud flats at Bull Island, Dublin Bay, Ireland. Web Ecology 2: 71-73.

McCorry, M. and Ryle, T. 2009a. Saltmarsh monitoring project 2007-2008. Volume 1. Final report for Research Branch, National Parks and Wildlife Service, Ref: D/C/227.

McCorry, M. and Ryle, T. 2009b. A management plan for North Bull Island. Dublin City Parks and Landscape Services. Available online at http://www.dublincity.ie/sites/default/files/content/RecreationandCulture/DublinCityParks/VisitaPark/Documents/North%20Bull%20Island%20Management%20Plan%20Final.pdf [accessed 28.11.16].

McGregor, P.G. and Gourlay, H. 2002. Assessing the prospects for biological control of lagarosiphon (*Lagarosiphon major* (Hydrocharitaceae)). DOC Science Internal Series 57. Department of Conservation, Wellington, 14pp.

Mielecki, M., and Pieczynska, E. 2005. The influence of fragmentation on the growth of *Elodea canadensis* Michx. in different light conditions. Polish Journal of Ecology 53: 155-164.

Minchin, D., and C. B. Duggan. 1988. The distribution of the exotic ascidian, *Styela clava* Herdman, in Cork Harbour. Irish Naturalist 22: 388–393.

Minchin, D., Floerl, O., Savini, D. and Occhipinti-Ambrogi, A. 2006. Small craft and the spread of exotic species. Environmental Pollution 10: 99–118.

Mitzner, L. 1978. Evaluation of biological control of nuisance aquatic vegetation by grass carp. Transactions of the American Fisheries Society 107: 135-145.

Morley, J.V. 1973. Tidal immersion of *Spartina* marsh at Bridgewater Bay, Somerset. Ecology 61: 383-386.

Morris Jr., J.A. and Carman, M.R. 2012. Fragment reattachment, reproductive status, and health indicators of the invasive colonial tunicate *Didemnum vexillum* with implications for dispersal. Biological Invasions 14: 2133-2140.

Mueller, W. and Hoffmann, A. 1996. Effect of freshwater immersion on attachment in the Japanese oyster drill, *Ceratostoma inornatum*: Implications for shellfish transfers in Washington State: Journal of Shellfish Research 15, 788.

Murray, C.C, Pakhomov, E.A and Therriaut, T.W. 2011. Recreational boating; a large unregulated vector transporting marine mucsile species. Diversity and Distribution 17: 1161-1172.

NBN Gateway. 2016. Available online at: http://www.nbn.org.uk [accessed 13.11.16].

NEANS. 2016. Northeast aquatic nuisance species panel: Aquatic nuisance species control methods. Available online at: www.northeastans.org [accessed 01 October 2016].

Negrisoli, E., Tofoli, G. R., Velini, E. D., Martins, D., and Cavenaghi, A. L. 2003. Chemical control of *Myriophyllum aquaticum*. Planta Daninha, 21: 89-92.

Nelson, L.S., Stewart. A.B. and Getsinger, K.D. 2002. Fluridone Effects on Fanwort and Water Marigold. Journal of Aquatic Plant management 40: 58-63

Newman, J. 2004a. CEH Information Sheet 22: *Azolla filiculoides*. Centre for Ecology and Hydrology, Wallingford, Oxon. Available online at: http://www.nonnativespecies.org/downloadDocument.cfm?id=1067 [accessed 19.08.16].

Newman, J.R. 2004b. CEH Information Sheet 23: *Lagarosiphon major*. Centre for Ecology and Hydrology, Wallingford, Oxon.

Newman, J.R. and Duenas, M.A. 2010a. Information Sheet 7: *Elodea canadensis* (Canadian Waterweed). Centre for Ecology and Hydrology, Oxon. Available online at: http://nora.nerc.ac.uk/10424/3/N010424_leaflet.pdf [accessed 19.08.16].

Newman, J.R. and Duenas, M.A. 2010b. Information Sheet 25: Elodea nuttallii, Nuttall's pondweed. Centre for Ecology and Hydrology. New Zealand Aquaculture Council 2005.

NHM (Natural History Musem). 2017. Chinese mitten crab research. Available online at: http://www.nhm.ac.uk/research-curation/life-sciences/invertebrates/research/crustacea/mitten-crab/index.html [accessed 31.01.17].

Nimmo, F., Cook, E., Moxey, A.P., Hambrey, J., Black, K. 2011. Cost-benefit analysis of management options for *Didemnum vexillum* (carpet sea squirt) in Scotland. Report by Hambrey Consulting in association with the Scottish Association for Marine Science and Poseidon Aquatic Resource Management to the Scottish Government.

NIMPIS (National Introduced Marine Pest Information System). 2002. Available online at: https://www.sciencebase.gov/catalog/item/505795bde4b01ad7e0284549 [accessed 31.01.17].

NWIFC (Northwest Indian Fisheries Commission). 2016. Available online at: http://nwifc.org/ [accessed 31.01.17].

Oduro, C., Hatcher, P.E. and Newman, J. 2005. Controlling *Azolla filiculoides* using *Artemisia dracunculus* and *A. vulgaris* leaf extracts. Paper presented at the International Symosium on Intractable Weeds and Plant Invaders, Ponta Degada, Azores, Portugal, Programme Abstracts, p.34.

Oosterhout, E. V. 2009. *Cabomba* control manual: current management and control options for *cabomba* (Cabomba caroliniana) in Australia. NSW Department of Primary Industries.

Orton, J.H. 1924. English enemies of the American slipper limpet *Crepidula fornicata*. Nature 2861: 312.

Orton, J.H. 1950. The recent extension in the distribution of the American slipper limpet, *Crepidula fornicata*, into Lyme Bay in the English Channel. Proceedings of the Malacological Society of London. 28: 168–184

Osman, R.W. and Whitlatch, R.B. 2007. Variation in the ability of *Didemnum* sp. to invade established communities. Journal of Experimental Marine Biology and Ecology 342: 40–53.

Palero, F., Mateu, I.F., Wray, B., Hughes, R., Morritt, D., Lepage, M., Van der Meer, M., Tate, M. and Clark, P.F. 2016. Pathways of invasion: the genetic structure of the Chinese mitten crab in Europe. Frontiers Marine Science Conference Abstract: XIX Iberian Symposium on Marine Biology Studies. doi: 10.3389/conf.FMARS.2016.05.00183.

Pannell, A. and Coutts, A.D.M. 2007. Treatment methods used to manage *Didemnum vexillum* in New Zealand. New Zealand Farming Association Inc. Prepared for Biosecurity New Zealand.

Pechenik, J.A. 1980. Growth and energy-balance during the larval lives of 3 prosobranch gastropods. Journal of Experimental Marine Biology and Ecology 44: 1–28.

Pechenik, J.A. 1984. The relationship between temperature, growth rate, and duration of planktonic life for larvae of the gastropod *Crepidula fornicata* (L). Journal of Experimental Marine Biology and Ecology 74: 241–257.

Pechenik, J.A., Ambrogio, O.V. and Untersee, S. 2010. Predation on juveniles of *Crepidula fornicata* by two crustaceans and two gastropods. Journal of Experimental Marine Biology and Ecology 384: 91-98.

Pechenik, J.A., Blanchard, M. and Rotjan, R. 2004. Susceptibility of larval *Crepidula fornicata* to predation by suspension-feeding adults. Journal of Experimental Marine Biology and Ecology 306: 75-94.

Pechenik, J.A., Hammer, K., Weise, C. 1996. The effect of starvation on acquisition of competence and post-metamorphic performance in the marine prosobranch gastropod *Crepidula fornicata* (L). Journal of Experimental Marine Biology and Ecology 199: 137-152.

Peters, N. 1933. Lebenskundlicher Teil. In: Peters, N., Panning, A. and Schnakenbeck, W. (Eds). Die chinesische Wollhandkrabbe (Eriocheir sinensis) H.Milne-Edwards) in Deutschland. Zoologischer Anzeiger (Leipzig): 59-155.

Plantlife. 2010. Fanwort. Available online at: http://www.plantlife.org.uk/wild_plants/plant_species/fanwort [accessed 22.08.16].

Plantlife. 2016a. Plants banned by the European Union in 2016. Available online at http://www.plantlife.org.uk/uploads/documents/Banned_Plants_2016.pdf [accessed 26.11.16].

Plantlife. 2016b. Available online at: http://plantlife.org.uk/wild_plants/plant_species/parrots-feather [accessed 12.09.16].

Plant Protection Service. 2011. Aquatic Ecology and Water Quality Management Group WUR, Centre for Ecology and Ecology and Hydrology Wallingford, 2011. *Cabomba caroliana* Gray. EUPHRESCO DeCLAIM final report.A state-of-the-art June 2011. Available online at: http://www.q-bank.eu/Plants/Controlsheets/Cabomba.State-of-the-Art.pdf [accessed 22.08.16].

Pothoven, S.A., Grigorovich, I.A., Fahnenstiel, G.L. and Balcer, M.D. 2007. Introduction of the Ponto-Caspian bloody-red mysid

*Hemimysis anomala* into the Lake Michigan basin. Journal of Great Lakes Research, 33:285-292.

Pratt, C.F., Shaw, R.H., Tanner, R.A., Djeddour, D.H. and Vos, J.G.M. 2013. Biological control of invasive non-native weeds: An opportunity not to be ignored. Entomologische Berichten 73: 144-154.

Pratt, C., Wood, S. and Shaw, D. 2014. Advances in the biocontrol of invasive non-native weeds. Presentation to the RINSE: Bridging the Gap Conference, 23 Sept 2014, Norwich. Available online at: http://www.rinse-europe.eu/assets/__files/rinse-closing-conference-corin-pratt_2014_09_23_final.pdf [accessed 23.05.16].

Pratt, D.M. 1974. Behavioural defense of *Crepidula fornicata* against attack by *Urosalpinx cinerea*. Marine Biology, 27:47-49.

Quayle, D.B. 1969. Pacific oyster culture in British Columbia. Fisheries Research Board of Canada Bulletin 169: 192 pp.

RAFTS. 2006. Invasive Species and Biosecurity Programme: Common Cord-grass (*Spartina anglica*). Available online at: http://www.invasivespeciesscotland.org.uk/common-cord-grass-spartina-anglica/ [accessed 13.09.16]

Ragueneau, O., Chauvaud, L., Moriceau, B., Leynaert, A., Thouzeau, G., Donval, A., Le Loc'H, F. and Jean, F. 2004. Biodeposition by an invasive suspension feeder impacts the biogeochemical cycle of Si in a coastal ecosystem (Bay of Brest, France). Biogeochemistry 75: 19-41.

Ramsay, A. 2015. Freshwater immersion to control the clubbed tunicate *Styela clava*. Aqua Info: Aquaculture Notes, PEI Canada, Fisheries, Aquaculture and Rural Development.

Ranwell, D.S. 1961. *Spartina* salt marshes in southern England: I. The effects of sheep grazing at the upper limites of Spartina marsh in Bridgwater Bay. Ecology 49: 325-340.

Reeder, T. and Hacker, S. 2004. Factors contributing to the removal of a marine grass invader (*Spartina anglica*) and subsequent potential for habitat restoration. Estuaries 27: 244–252.

Rigal, F. 2009. Etude de la dynamique spatio-temporelle du nuage larvaire du gasteropode introduit *Crepidula fornicata* dans une baie megatidale, la baie de Morlaix. Doctoral Thesis, University Pierre et Marie Curie-Paris 6.

Rittschof, D., Williams, L.G., Brown, B., Carriker, M.R. 1983. Chemical attraction of newly hatched oyster drills. Biological Bulletin 164: 493-505.

Roberts, P. D., and Pullin, A. S. 2008. The effectiveness of management interventions for the control of *Spartina* species: a systematic review and meta□analysis. Aquatic Conservation: Marine and Freshwater Ecosystems, 18: 592-618.

Rudnick, D., Veldhuizen, T., Tullis, R., Culver, C., Hieb, K. and Tsukimura, B. 2005. A life history model for the San Francisco Estuary population of the Chinese mitten crab, *Eriocheir sinensis* (Decapoda: Grapsoidea). Biological Invasions 7: 333-350.

Schooler, S. 2008. Shade as a management tool for the invasive submerged macrophyte, *Cabomba caroliniana*. Journal of Aquatic Plant Managament 46: 168-171.

Schooler, S. and Chan, R. 2011. Biological control and ecology of *Cabomba* and Alligator weed. Rural Industries Research and Development Corporation, Canberra.

Schooler, S., Julien, M., and Walsh, G. C. 2012. *Cabomba carolinana* Gray – *cabomba*. In: Julien, M., McFayden, R., Cullen, J. (Eds). Biological control of weeds in Australia. CSIRO Publishing, Collingwood, Victoria, Australia, pp. 108-117.

Schooler, S.S. 2008. Shade as a Management Tool for the Invasive Submerged Macrophyte, *Cabomba caroliniana*. Journal of Aquatic Plant Management. 46: 168-171.

Schubert, S. 2011. Stress response of native and invasive populations of intertidal invertebrates from the North Atlantic: an intraspecific comparison. Diplomarbeit, Universität Bremen.

Scott Wilson, 2009. Control of invasive non-native species in priority mesotrophic lochs R80014PUR Final Report.

Sewell, J. (2016) Chinese mitten crab, *Eriocheir sinensis*. NNSS factsheet. Available online at: http://www.nonnativespecies.org/factsheet/downloadFactsheet.cfm?speciesId=1379 [accessed 20.10.16].

Shenck, M.A. 1986. Ecological determinants of *Crepidula* sp. distributions. USA: University of Delaware, 92 pp.

Shumway, S.E., Card, D., Getchell, R. and Newell, C. 1988. Effects of calcium oxide (quicklime) on non-target organisms in mussel beds. Bulletin of Environmental Contamination and Toxicology. 40: 503-509.

Stefaniak, L., Lambert, G., Gittenberger, A., Zhang, H., Lin, S., and Whiltlatch, R.B. 2009. Genetic conspecificity of the worldwide populations of *Didemnum vexillum* Kott 2002. Aquatic Invasions 4: 29-44.

Stiger-Pouvreau, V. and Thouzeau, G. 2015. Marine Species Introduced on the French Channel-Atlantic Coasts: A Review of Main. Open Journal of Ecology 5: 227-257.

Stubbington R, 2006. Factors affecting the distribution of a new invasive species, the Ponto-Caspian *Hemimysis anomala* G. Sars, 1907 (Crustacea: Mysidacea). Nottingham, UK: Nottingham Trent University.

Stubbington, R., Terrell-Nield, C. and Harding, P. 2008. The first occurrence of the Ponto-Caspian invader, *Hemimysis anomala* G. Sars, 1907 (Mysidacea) in the U.K. Crustaceana, 81((1)):43-55.

Thieltges, D.W. 2005. Benefit from an invader: American slipper limpet *Crepidula fornicata* reduces star fish predation on basibiont European mussels. Hydrobiologia, 541:241–244.

Thieltges, D.W., Strasser, M., Van Beusekom, J.E.E. and Reise, K. 2004. Too cold to prosper: winter mortality prevents population increase of the introduced American slipper limpet *Crepidula fornicata* in northern Europe. Journal of Experimental Marine Biology and Ecology, 311:375–391.

UKTAG (2015) Revised classification of aquatic alien species according to their level of impact. Guidance Paper version 7.6. Available online at: https://www.wfduk.org/sites/default/files/Media/Assessing%20the%20status%20of%20the%20water%20environment/UKTAG%20classification%20of%20alien%20species%20working%20paper%20v7.6.pdf [accessed 13.01.17].

Valdizan, A., Beninger, P.G., Decottignies, P., Chantrel, M. and Cognie, B. 2011. Evidence that rising coastal seawater temperatures increase reproductive output of the invasive gastropod *Crepidula fornicata*. Marine Ecology Prog Ser 438:153–165.

Valentine, P.C., Carman, M.R., Blackwood, D.S. and Heffron, E.J. 2007a. Ecological observations on the colonial ascidian *Didemnum* sp. in a New England tide pool habitat. Journal of Experimental Marine Biology and Ecology 342: 109-121.

Valentine, P.C., Collie, J.S., Reid, R.N., Asch, R.G., Guida, V.G. and Blackwood, D.S. 2007b. The occurrence of the colonial ascidian Didemnum sp. on Georges Bank gravel habitat: Ecological observations and potential effects on groundfish and scallop fisheries. Journal of Experimental Marine Biology and Ecology 342: 179-181.

van de Haterd, R. J. W., and Ter Heerdt, G. N. J. 2007. Potential for the development of submerged macrophytes in eutrophicated shallow peaty lakes after restoration measures. Hydrobiologia 584: 277-290.

Van De Wiel., C.C.M., Van Der Schoot, J., Van Valkenburg, J.L.C.H., Duistermaat, H. and Smulders, M.J.M. 2009. DNA barcoding discriminates the noxious invasive plant species, floating pennywort (*Hydrocotyle ranunculoides* Lf), from non-invasive relatives. Molecular Ecology Resources 9: 1086–1091.

Van Donk, E., and Otte, A. 1996. Effects of grazing by fish and waterfowl on the biomass and species composition of submerged macrophytes. In Management and Ecology of Freshwater Plants (pp. 285-290). Springer Netherlands.

van Valkenburg, J. 2011. *Cabomba caroliniana* and *Myriophyllum heterophyllum* a nightmare combination. Robson Meeting February 2011. Available online at: www.robsonmeeting.org/valkenburg.pdf [accessed 31.01.17].

Wagley, S., Koofhethile, K. and Rangdale, R. 2009. Prevalace and potential pathogenicity of vibrio parahaemolyticus in Chinese mitten crabs (Eriocheir Sinensis) harvested from the River thames estuary England. Food Protection 72: 60-66

Walker, A.N., Poos, J-J. and Groeneveld, R.A. 2015. Invasive species control in a one-dimentional metapopulation network. Ecological Modelling 316: 176-184.

Wells, R. D., and Champion, P. D. 2010. Endothall for aquatic weed control in New Zealand. In 17th Australasian Weeds Conference, New Zealand Plant Protection Society, Christchurch, New Zealand, pp307–310.

Wersal, R. M., Cheshier, J. C., Madsen, J. D., and Gerard, P. D. 2011. Phenology, starch allocation, and environmental effects on *Myriophyllum aquaticum*. Aquatic Botany 95: 194-199.

Wersal, R.M. and Madsen, J.D. 2007. Comparison of imazapyr and imazamox for control of parrotfeather (*Myriophyllum aquaticum* (Vell.) Verdc). Journal of Aquatic Plant Management 45: 132-136.

Wersal, R. M., Madsen, J. D., and Gerard, P. D. 2013. Survival of parrotfeather following simulated drawdown events. Journal of Aquatic Plant Management 51: 22-26.

Willby, N.J., Casas Mulet, R. and Perfect, C. 2011. The Scottish Beaver Trial: Monitoring and further baseline survey of the aquatic and semi-aquatic macrophytes of the lochs 2009. Scottish Natural Heritage Commissioned Report No. 455.

Willis, K.J. and Woods, C.M.C. 2011. Managing invasive *Styela clava* populations: inhibiting larval recruitment with medetomidine. Aquatic Invasions [Proceedings of the 3rd International Invasive Sea Squirt Conference, Woods Hole, USA, 26-28 April 2010.]. 6:511-514.

Wittmann, K.J. 2007. Continued massive invasion of *Mysidae* in the Rhine and Danube river systems, with first records of the Mysidacea (Crustacea: Malacostraca: Pericarida) for Switzerland. Revue Suisse de Zoologie, 114:65-86.

Wittmann, K.J. and Ariani, A.P. 2009. Reappraisal and range extension of non-indigenous *Mysidae* (Crustacea, Mysida) in continental and coastal waters of eastern France. Biological Invasions 11: 401-407. http://www.springerlink.com/content/

Wray, B. 2015. Control and management of marine non-native species. Presentation to Marine Pathways Project Conference, 2015. Available online at: http://www.nonnativespecies.org/downloadDocument.cfm?id=1220 [accessed 31.01.17].

Wu, M. Y., Hacker, S., Ayres, D., and Strong, D. R. 1999. Potential of *Prokelisia* spp. as biological control agents of English cordgrass, *Spartina anglica*. Biological Control, 16(3), 267-273.

York, A., Gallager, S., Taylor, R., Vine, N. and Lerner, S. 2008. Using a towed optical habitat mapping system to monitor the invasive tunicate species *Didemnum* sp. along Georges Bank. Journal of Shellfish Research, 27: 1066-1067.

Zehnsdorf, A., Hussner, A., Eismann, F., Rönicke, H., and Melzer, A. 2015. Management options of invasive *Elodea nuttallii* and *Elodea canadensis*. Limnologica-Ecology and Management of Inland Waters, 51, 110-117.

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