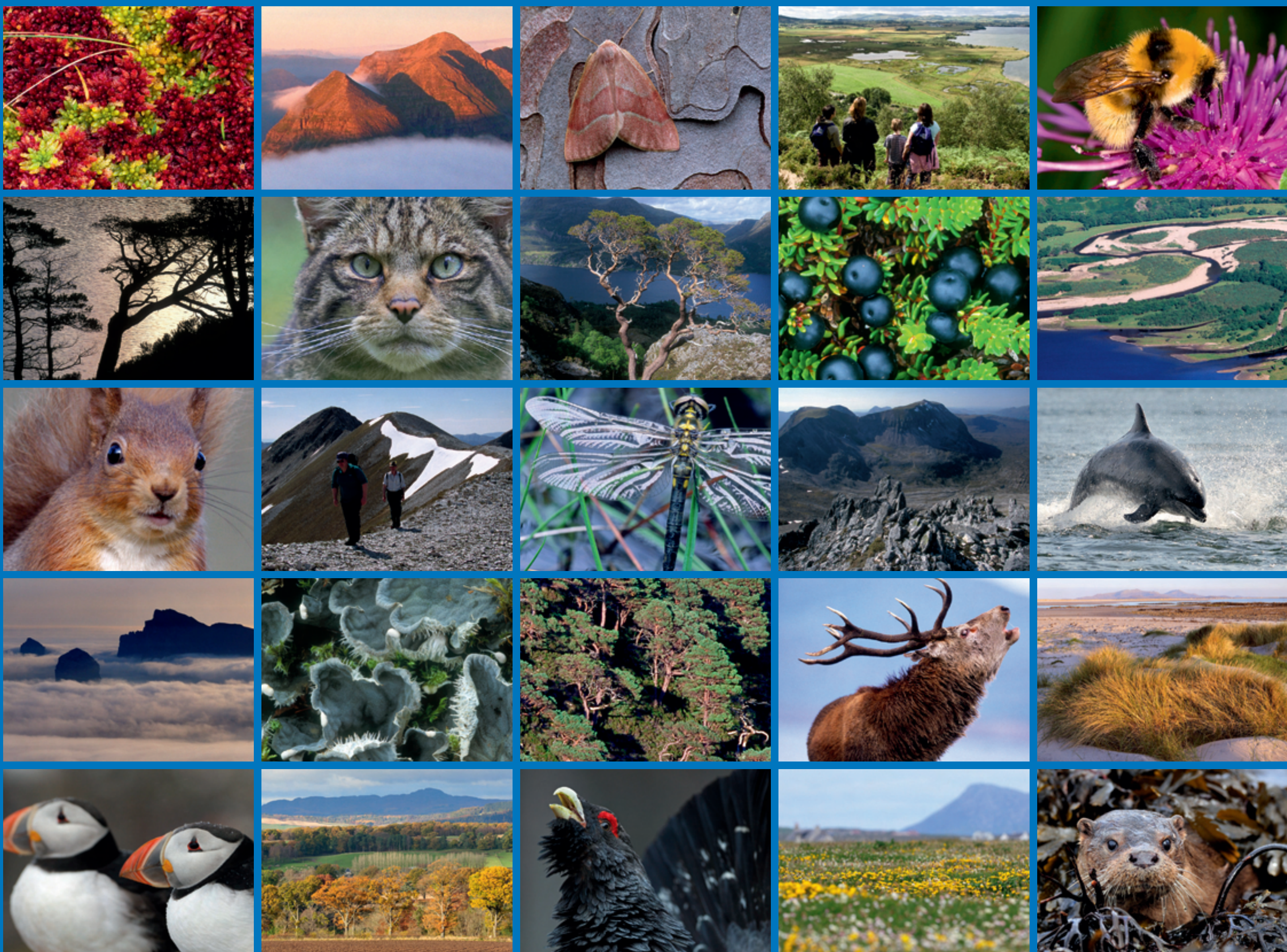
Scottish Natural Heritage
Commissioned Report No. 433

Literature review on methods of control and eradication of Canadian pondweed and Nuttall's pondweed in standing waters



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COMMISSIONED REPORT

Summary

Literature review on methods of control and eradication of Canadian pondweed and Nuttall's pondweed in standing waters

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Contractor: Penny Anderson Associates
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Background

Invasive non-native species are one of the main causes of biodiversity loss world-wide, and cost the British economy an estimated excess of £2 billion pounds per year. The cost of controlling freshwater invasive species has been estimated at £25 million per year for the British economy, of which a large part is due to Canadian pondweed *Elodea canadensis* control. The majority of the standing waters in the United Kingdom (UK) are in Scotland, and invasive species problems are one of the most common reasons for standing water SSSIs being classed as in unfavourable condition.

E. canadensis and Nuttall's pondweed *Elodea nuttallii* are North American natives that have naturalised in the UK and become problematic invasive species. Both species are commonly sold as oxygenators for the horticultural trade, and can escape into the wild if disposed of irresponsibly. There are many available control and eradication methods for invasive aquatic plants and for *Elodea* in particular. However, detailed information on these is only available through a wide range of disparate resources, many of which are difficult for site managers to access. In addition, there are some avenues of research into control methods that have not been explored to their full potential. This report aims to describe the ecology of *E. canadensis* and *E. nuttallii*, to consolidate the research undertaken to date, to identify knowledge gaps, and to make informed suggestions as to the most useful lines of research to pursue in order to improve our knowledge and understanding of *Elodea* control and eradication.

Main findings

There is no effective control for invasive *Elodea* available in the UK at the present time which is compatible with maintaining the condition of existing aquatic floras of nature conservation value. This literature review found:

- the use of fish as a biological control has been recommended in the past, but is no longer considered suitable. Reasons for this include fish being generalist herbivores, and that the recommended species, grass carp *Ctenopharyngodon idella*, is a non-native in the UK. Fish as biological control agents offer little potential for further research, particularly not for sites where existing aquatic floras are of nature conservation value;

- invertebrates have been used successfully for other species control, and offer an as-yet unexplored opportunity for biological control of *Elodea*. This requires knowledge of *Elodea*'s pests in its natural habitat, which may represent a significant and useful advancement in knowledge;

- fungal bio-controls have been used for other invasive aquatic species, and as yet are little-researched for *Elodea*. Fungal pathogens offer another opportunity to further our knowledge of *Elodea* control, as they are species-specific and of low impact to the surrounding habitat;

- herbicides have been used successfully for *Elodea* control in the past, but appear to have fallen out of favour in recent years. There are now no herbicides available in the UK that are permissible for aquatic weeds. However, herbicides offer good potential for control and have already been well-researched. Recent innovations in hydrogel applications improve herbicide targeting and minimise adverse effects;

- physical control of *Elodea* by harvesting is well-used as a control method, and many machines are commercially available. However, there is some disagreement as to its efficacy, since physical damage may increase branching and growth rate, and creates more fragments which can survive and grow. There is therefore some controversy as to the long-term effects of conventional physical control methods. Turion removal offers perhaps the best opportunity for further research into improving physical control methods for *Elodea*;

- controlling *Elodea* by increasing shading has been recommended as a suitable technique; however results to date are inconclusive as to its efficacy. Surface shading material is aesthetically unpleasant, may be problematic to attach, and takes a long time to have an effect. Using benthic shading materials has been little-researched, but potentially offers an opportunity for *Elodea* control that addresses some of the negative aspects of surface water shading;

- draw-down has been reviewed as a control method, and is unlikely to be suitable for widespread use on *Elodea*, since it may conflict with other site objectives and may not be possible in the majority of sites which lack a draw-down mechanism;

- combinations of control methods have been researched, but have been little explored for *Elodea* to date. However, particular combinations that have been used for other aquatic species offer great potential for improving our ability to control *Elodea*. In particular, if knowledge of *Elodea* pathogens and pests can be developed, combinations of a) herbicide plus fungal pathogen, and b) insect pest plus fungal pathogen, could present opportunities for effective *Elodea* control;

- a number of case studies in Scotland have been examined in this review. It was found that, although *Elodea* is a significant problem at many sites, knowledge of suitable control methods was largely lacking, and in many cases nothing had been attempted.

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1 INTRODUCTION

1.1 Background

Canadian waterweed *Elodea canadensis* and Nuttall's waterweed *Elodea nuttallii* comprise two of the three species of waterweeds (*Elodea*) found within the United Kingdom (UK) (Simpson, 1986). Along with the third species, South American waterweed *Elodea callitrichoides*, this genus is entirely non-native to the UK. Waterweeds are also commonly known as pondweeds, although this name is more correctly used for the genus *Potamogeton*. Waterweeds are members of the Hydrocharitaceae or frogbit family which, within the UK, also includes the non-native species large-flowered waterweed *Egeria densa* and curly waterweed *Lagarosiphon major*, and the native species water soldier *Stratiotes aloides* and Esthwaite waterweed *Hydrilla verticillata* (Stace, 2010).

Both *E. canadensis* and *E. nuttallii* are native to North America (Stace, 2010) and fully naturalised within the UK, being problematic invasive species. *E. canadensis* was the first to arrive, having been introduced to Ireland in 1836, probably as a fragment on an imported log from Canada, and spreading rapidly thereafter (Newman & Duenas, 2010), although there is evidence that it may have been present in England since as early as 1817 (Simpson, 1984). *E. nuttallii* was a more recent arrival to Europe in 1939 and was first found in Britain in 1966 (CEH, 2004). Only a few genotypes of each species are found within the UK (Simpson 1988). This suggests that only a few separate invasions have taken place, resulting in a small number of widespread clonal groups.

Both species are highly invasive and have colonised many sites within the UK. *E. canadensis* is now common throughout the UK except in the extreme north and north-west Scotland (Stace, 2010), being widespread in lowland Scotland and present in parts of the Highlands and Islands (Dadds & Bell, undated). *E. nuttallii* is locally common in England but scattered in Wales, Scotland, Ireland and Jersey, although is rapidly spreading (Stace, 2010) and replacing *E. canadensis* at many sites (CEH, 2004). In Scotland, it is mainly recorded from the Central Belt, although may be under-recorded (Dadds & Bell, undated). Both species are commonly sold as oxygenating plants for ponds and aquaria, and can easily escape into the wild if unwanted plants are thrown into lakes or canals (Dadds & Bell, undated). Their problematic nature has been highlighted by their April 2010 inclusion within the Wildlife and Countryside Act's Schedule 9 list of plants, which makes it an offence to "plant or otherwise cause to grow in the wild" any listed species (Environment Agency, 2003; Defra, 2009). However, this does nothing to tackle the existing UK distribution of *Elodea*; hence the need for control and eradication methods.

There are many available control and eradication methods for invasive aquatic plants in general, and for *Elodea* in particular. However, detailed information on these is currently only available through a wide range of disparate resources, both UK-based and worldwide, and dating from recent research to much older sources. This makes it difficult for site managers to access relevant information that may help tailor a suitable control programme for a particular site.

1.2 Aim and Objectives

1.2.1 Aim

The aim of this report is to assess the available information on methods of control and eradication of *E. canadensis* and *E. nuttallii.*

1.2.2 Objectives

- To gather and discuss information on the ecological preferences of *E. canadensis* and *E. nuttallii*.
- To identify and evaluate the available information worldwide on methods of control and eradication of *E. canadensis* and *E. nuttallii*.
- To identify knowledge gaps and research requirements in relation to control and eradication techniques.

1.3 Structure of This Report

The report will begin by discussing the ecology of *E. canadensis* and *E. nuttallii*, including their similarities and differences, and the ecology of similar related species. It will highlight the problems that these species can cause and the need for effective control and eradication methods. The actual methods of control will then be examined in detail, including biological, chemical, physical and environmental techniques and combinations thereof, including the limitations and restrictions placed upon each technique. Several Scottish case studies will be discussed that highlight current problems in control and eradication. This will lead in to a discussion of the existing knowledge gaps and how these can be addressed by targeted research recommendations. A final conclusion will summarise the main findings.

2 METHODS

A desk-based literature review was undertaken, accumulating both web-based and printed resources relating to the biology and control of *E. canadensis* and *E. nuttallii*. Where possible, discussions with key individuals and organisations were undertaken to take advantage of the relevant experience and expertise in control and management of these aquatic weeds in the standing waters of Britain.

The first step in the process was a systematic literature search of the subject utilising internet sources and online search engines. A literature search was initially undertaken utilising search engines and databases such as Google Scholar and Web of Knowledge, to access worldwide literature and public documents. This was followed by a targeted search of databases managed by statutory and non-statutory nature conservation organisations that might be involved in the management and control of pondweed species. The literature search also included a review of available material from other key organisations such as the GB Non-native Species Secretariat (NNSS), the Centre for Ecology and Hydrology (CEH) and Global Invasive Species Database.

Penny Anderson Associates Ltd possesses a library which has been compiled over more than 30 years of work in ecology. A search of relevant documents catalogued within this library as well as documents stored electronically was undertaken to provide further supporting material.

Key words were used to search for relevant material on *Elodea* and its management. All relevant sources of information were reviewed including journals, books, educational material, and information databases. Information was not limited to British work but encompassed worldwide research and experience. All relevant results were extracted and reviewed. As research progressed, the list of key words evolved and became ever more specific as new channels of enquiry developed through the project, allowing a more extensive review to be undertaken. A list of search terms and databases accessed during the literature search are presented in Appendix I. Where key words yielded no relevant results, these were recorded to illustrate gaps in current research.

An end point for the literature search was established, that is when further searches yielded no new information or references. When this point was reached, accumulated information was reviewed and any further searches were conducted in response to references identified in reviewed papers. Search for specific papers was achieved by direct access to journals, the Web of Knowledge and Liverpool University electronic library.

Additional collation of information was achieved by directly contacting key individuals in organisations such as Scottish Natural Heritage (SNH) and Universities, to tap into staff experience in managing *Elodea* and to further access literature and management documents.

Initially, information sources and papers were organised into broad categories along the following themes:

- general biology and ecological preferences;
- methods of control (divided into herbicide, mechanical, environmental manipulation, etc) in standing waters.

As the literature search evolved, information was further sub-divided into more specific categories enabling the correct management of information sources but also allowing one to identify gaps in current research. Table 1 lists the categories into which relevant documents were organised. This formed the basis for the structure of the results section.

Table 1 - Categories of literature search

Category	Primary Sub Category	Secondary Sub Category
Legislation/Legal Information		
General Biology	Ecology of Elodea Impact of Elodea Slender naiad	
Control methods	Techniques overview	
	Biological	Pathogens Fish Invertebrates
	Chemical	Herbicides Nutrient Control Agents Liming
	Environmental	Shade Cutting Competition Drawdown Manual harvesting
	Prevention	

Case studies were based upon telephone conversations with relevant site officers at SNH and information provided by them and available on SNH's Sitelink website. Case studies were not sought from nature conservation organisations outside Scotland. Scotland supports the majority of the UK's standing waters and most sites which are notified for their botanical interest also lie in Scotland. However, it is possible that there may be more experience to draw upon e.g. from Natural England, Countryside Council for Wales etc.

3 RESULTS

3.1 Publication Trends

To detect trends in publication, all documents reviewed and referenced were classified according to publication type, publication date, and country of origin. The results are presented graphically for visual interpretation. This information is useful in interpreting the available literature and evaluating the opportunities for further research.

3.1.1 Publication Type

All documents reviewed and referenced were divided into broad categories based on literature type. Literature was split into seven categories:

- **scientific research**: papers based on new research that has been peer reviewed. Often presented in scientific journals;
- **review articles**: review of research conducted in the area of study. Often present in primary scientific or review journals;
- **miscellaneous**: includes newspaper articles, general information databases and identification guides;
- **commissioned reports**: published research reports by statutory and non statutory organisations;
- **abstracts and conference proceedings**;
- **technical documents/guidance**; includes documents printed by statutory and non statutory organisations relating to legislation, policy and management guidance;
- **books**.

The literature types were evaluated and the results are presented in Figure 1. Of the 127 documents reviewed, 42% were scientific papers based on primary research and 17% were scientific reviews published in academic journals.

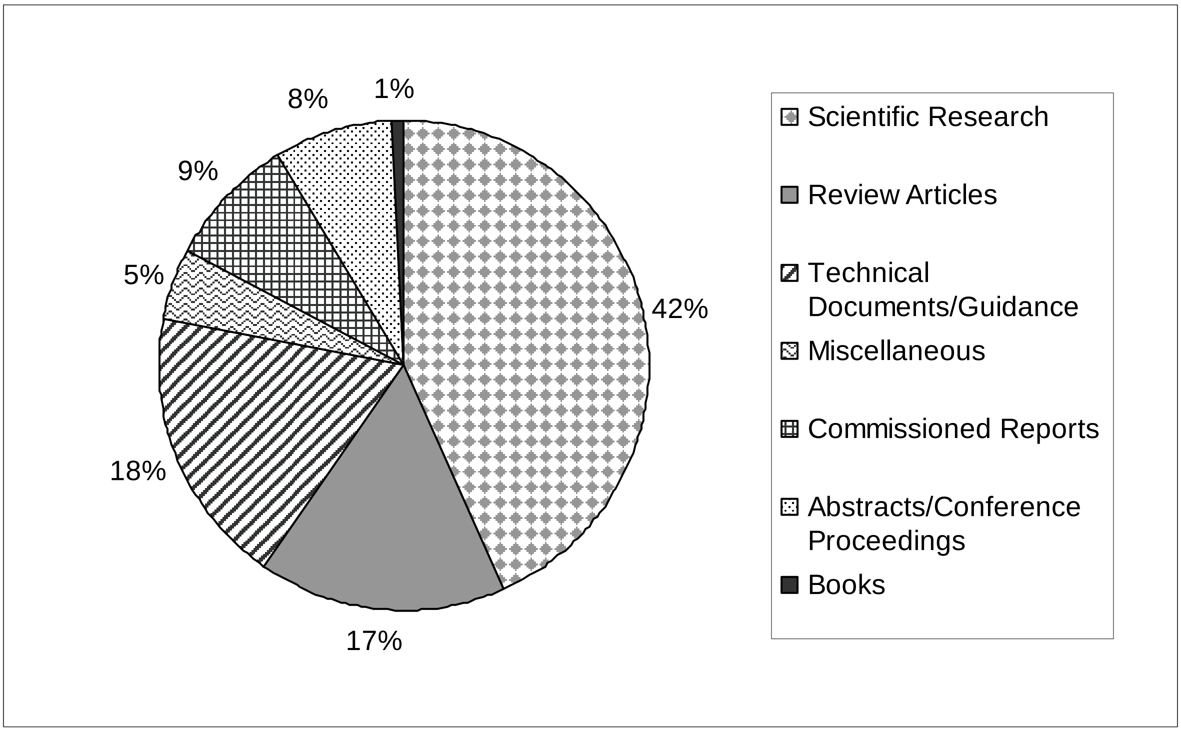

Figure 1: Literature type (%)

3.1.2 Publication Date

Of the 59% of documents that were based on scientific research (53 articles in total), the year in which the article was published was noted and the total number of articles produced in any one decade assessed. Figure 2 presents the total number of research papers published in each decade. The amount of research conducted on waterweed species has increased since the 1960s. In the past ten years, more research has been undertaken than in any previous decade.

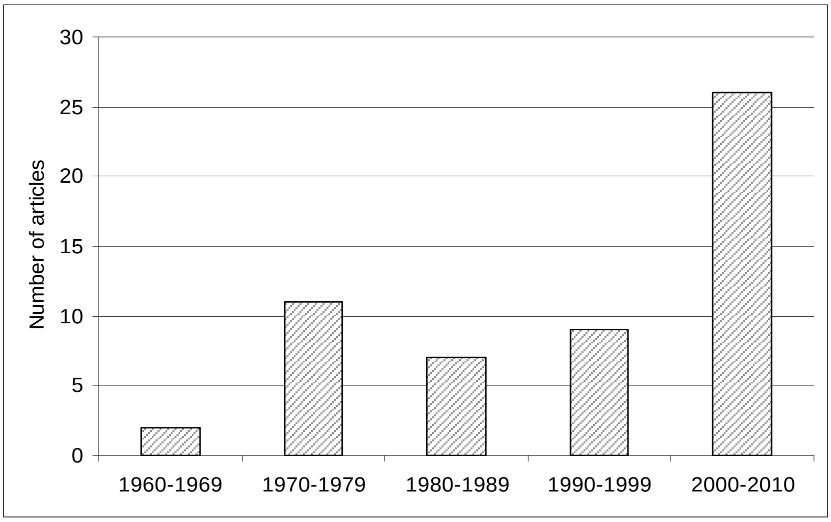

Figure 1: Number of reviewed scientific research papers published each decade between 1960 and 2010.

3.1.3 Country of Origin

Of the scientific research reviewed (primary research and review articles), 45% of documents were based on research conducted in the United States. Only 22% of papers were based on research conducted in the UK (Figure 3).

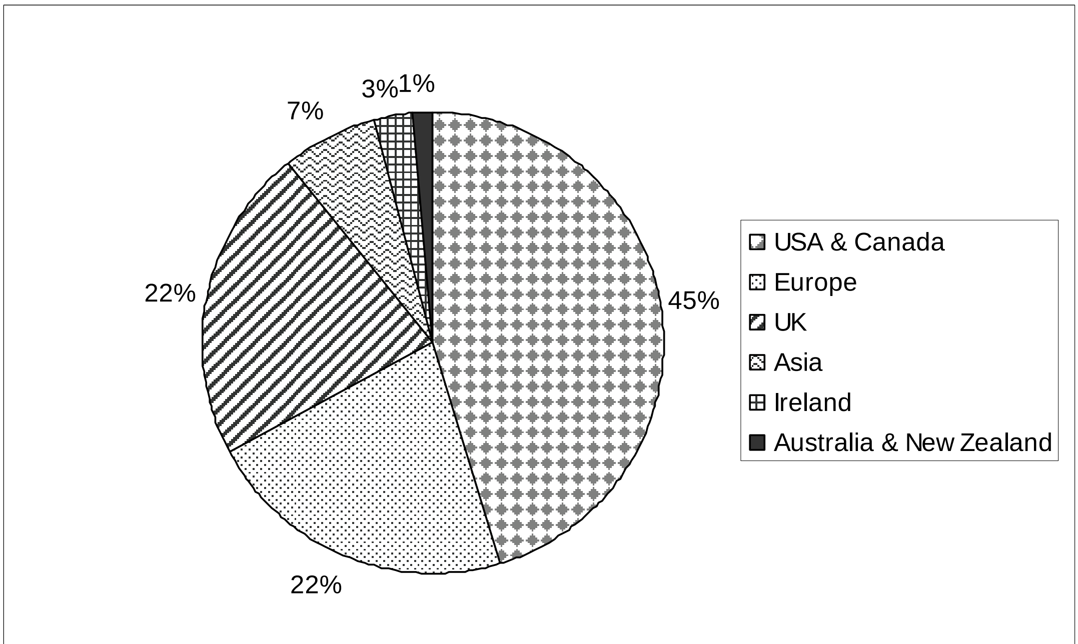

Figure 2: Country of origin for scientific research reviewed.

3.2 The Ecology of *Elodea*

E. canadensis ecology tends to be more researched than *E. nuttallii*. This is due to its much earlier appearance as a non-native invading species (Simpson, 1986), and its well documented invasion of habitats (Bowmer *et al*, 1995). By comparison, not as much is known about the biology of *E. nuttallii* (Bowmer *et al*, 1995). For this reason, some of this section focuses on *E. canadensis*. However, more recent studies focus on *E. nuttallii*, in particular its physiology (e.g. Jones *et al*, 2000; Jones, 2005). Many later studies have also documented the apparent displacement of *E. canadensis* by *E. nuttallii* and this sheds some light on their similarities and differences (e.g. Simpson, 1990; Barrat-Segretain & Elger, 2004; James *et al.*, 2006). This is also discussed below.

3.2.1 <u>Structure and appearance</u>

Elodea is a genus of dioecious freshwater aquatic perennials with submerged leaves and floating flowers (Stace, 2010; Bowmer *et al*, 1995). The structure of *Elodea* is described in detail in Simpson (1986), and the identification of *E. canadensis* and *E. nuttallii* is dealt with in Newman and Duenas (2010) and CEH (2004) respectively. *Elodea* has a comparatively simple vegetative structure, consisting of axillary, branched stems with narrow, sessile and minutely serrated leaves in whorls of three, featuring a midrib and no other venation. Adventitious roots are produced at the nodes, one per node, coinciding with the growth of a new stem. Root hairs develop when the root reaches the sediment. *E. canadensis* has flat leaves with blunt or rounded tips (Newman & Duenas, 2010), unlike *E. nuttallii* which has narrower folded leaves with pointed tips (CEH, 2004). *E. nuttalii* is also said to have paler green leaves than *E. canadensis* (CEH, 2004); although it has been suggested that colour is determined by light intensity and/or nutrient availability rather than species differences (Simpson, 1988).

Much taxonomic confusion has existed between the two species due, in part, to their considerable morphological plasticity caused by environmental differences, in common with many aquatic macrophytes (Simpson, 1986). Additionally, misidentifications may have taken place due to inadequate knowledge of the characters separating the two species (Simpson, 1988). This may explain the potential under-recording of *E. nuttallii* in Scotland (Dadds & Bell, undated).

3.2.2 <u>Habitat Requirements</u>

Within the UK, only female plants of both species occur (Stace, 2010). This is likely to be a chance occurrence, since elsewhere only male plants may be found. These male plants are still invasive, for example male *E. nuttallii* in Japan (Kunii, 1981) and male *E. canadensis* in an Albertan lake (Haag & Gorman, 1977). *Elodea* is found in standing or slow-flowing freshwaters such as lakes, ponds and canals (Newman & Duenas, 2010). During most of the annual growth cycle, plants are weakly rooted into the mud (Madsen & Adams, 1989), and it has been suggested that a silty rather than a sandy substrate is preferred (Bowmer *et al.*, 1995). Madsen and Adams (1989) found that *E. canadensis* biomass was significantly greater in silt compared to gravel (moderate biomass) and sand (low biomass), and that biomass was significantly correlated to organic matter levels in the substrate. Nichols and Shaw (1986) suggest that sediment organic matter in the range of 10 to 25% promotes best growth. This may be the reason that low current velocities are preferred, as these conditions create a substrate suitable for rooting (Madsen & Adams, 1989). One study of *Elodea* in streams found that 50% coverage was found at a mean water flow rate of 0.1 ms^{-1} (Nichols & Shaw, 1986). *Elodea* grows in a wide range of water depths, with an optimum depth of 4 to 8 m and a maximum reported depth of 12 m. It does not thrive in shallow waters of less than 0.5 m (Nichols & Shaw, 1986).

3.2.3 Life Cycle

The main growth season of *Elodea* in the UK is between mid-April and mid-September, with little or no growth at other times (Simpson, 1986). The plant over-winters by means of short unbranched stems (Simpson, 1986). *Elodea* also develops turions; vegetative buds produced in leaf axils during early autumn for the purposes of over-wintering, which either remain on the stem or drop off, to germinate the following spring (Simpson, 1986; CEH, 2004). The life cycle of *E. nuttallii* in Japan, where it is an invasive non-native species, is described in detail by Kunii (1981; 1984). Here, a water temperature of 10^{o}C was found to be a key determinant of annual growth pattern. Shoot elongation from over-wintering stems at the bottom of the water column began when the bottom water temperature reached 10^{o}C in late March. Stems elongated until they reached the pond surface, when vigorous branching occurred from June to September, with peak flowering occurring at peak root density in June. From July onwards, the roots gradually thinned, breaking from the bottom in September to form a free-floating mat of short shoots. By September, a dense matted canopy had formed, with over half of the total biomass in the top 30 cm of water. When the water temperature dropped below 10^{o}C in December, the mat suddenly sank to the bottom, where it over-wintered. This supports the results of a laboratory study that found the critical temperature for active growth of *E. nuttallii* was between 8.2 and 12^{o}C (Kunii, 1982).

This pattern of seasonal growth can be strongly linked to *Elodea*'s capacity for invasiveness. Firstly, root loss during September leaves the remaining plant in a mobile form, which can easily spread by drift. Evidence suggests that at this time of year, stems become more brittle which, again, would promote vegetative spread by enabling further fragmentation (Kunii, 1981). In favourable conditions, *Elodea* can achieve a high net assimilation rate with an abundant production of vegetative propagules during seasons with large standing crops (Haag & Gorham, 1977). Secondly, the ability to survive the winter in an active growth form rather than a dormant condition allows the plant to exploit rapidly the increase in water temperature in spring, long before seed germination of annuals or foliage production by rhizomes (Kunii, 1984). *Elodea* has even been found surviving in the green leafy condition under ice (Haag & Gorham, 1977; Nichols & Shaw, 1986). Vegetative fragments have also been found to survive and regenerate under a wide range of light conditions (Mielecki & Pieczyńska, 2005). These factors mean that *Elodea* is capable of rapid growth and spread which gives it a competitive advantage, and of rapid vegetative reproduction in the absence of any sexual reproduction, since only female plants are found in the UK (Simpson, 1986). A further point is that *Elodea* has been found to secrete allelopathic chemicals which have the effect of suppressing the growth of surrounding algae and cyanobacteria, with which it would otherwise be competing for light and carbon dioxide (Erhard & Gross, 2006). The same chemicals have been found to inhibit the growth of aquatic herbivorous larvae, which would provide some defence against herbivory, and that allelopathic chemical production is negatively correlated with temperature, which would give *Elodea* a competitive advantage at lower temperatures (Erhard & Gross, 2005).

3.2.4 Morphological and Physiological Plasticity

A wide range of morphological variation with *Elodea* has been observed within the UK, which is entirely due to phenotypic plasticity. This means that the plants vary according to environmental conditions rather than underlying genetic variation, of which there is little if any (Simpson, 1988). It has been suggested that a high level of phenotypic plasticity is a key ingredient of aquatic plant invasiveness, since plastic responses to new environments enhance plant performance (Thiébaut & Di Nino, 2009). The structural features that exhibit variation, and the environmental causes for this, are explained in detail in Simpson (1988).

Phenotypic plasticity in both species is seen in the vegetative parts rather than floral structure. Features that vary include leaf shape, leaf size, leaf posture (i.e. extent of curvature), internode length, and plant colour. In general, *E. nuttallii* is more variable than *E. canadensis* in the UK for all features except leaf shape, although leaf colour is probably related to environmental rather than species differences. It has even been suggested in the past that *E. nuttallii* is merely a phenotype of *E. canadensis*. However, close examination of phenotypic variation presents a clear morphological distinction that supports their treatment as two distinct species, particularly given that the lack of sexual reproduction in UK populations of *Elodea* prohibits the production of hybrids (Simpson, 1988).

Light intensity and temperature have the strongest influence on *Elodea* morphology (Simpson, 1988). As light intensity decreases, leaves become longer, thinner and paler, and internode length increases. Light intensity is strongly correlated with water depth, meaning that the shorter, broader leaved, darker green phenotype typically occurs at or near the surface. *Elodea* is considered to be highly tolerant of low light conditions (Mielecki & Pieczyńska, 2005), which may be explained by its ability to adapt readily to such conditions. Water temperature is also higher nearer the water surface, meaning that the effects of light intensity and temperature are difficult to separate, and probably have an interactive effect on morphology. In contrast, substrate type and water nutrient availability have a relatively small effect on phenotype (Simpson, 1988).

In terms of physiological plasticity, the main feature of importance is the ability of *Elodea* to switch from the use of dissolved CO_2 as a carbon source for photosynthesis, to the use of bicarbonate (HCO_3^-). Bicarbonate levels are related to water pH, and increase with increasing alkalinity of the water. This adaptation allows *Elodea* to maintain carbon fixation at conditions of high pH and/or low CO_2, which would usually cause a reduction in aquatic plant growth rate (Jones *et al.*, 1993). Although CO_2 uptake is by passive diffusion and bicarbonate uptake is by active transport, therefore requiring energy (Jones *et al.*, 1993), experiments have shown that growth of *E. nuttallii* was not significantly affected by carbon source type (Jones, 2005). The ability to utilise bicarbonate as an alternative dissolved carbon source allows *Elodea* to adapt to short-term changes in the water body over the pH range encountered in UK standing waters, and allows growth to continue in conditions of low CO_2 and/or high pH, for example during hot, calm weather or algal blooms (Jones *et al.*, 1993).

3.2.5 Differences between E. canadensis and E. nuttallii

It is generally accepted that *E. nuttallii* prefers more eutrophic conditions than *E. canadensis* (CEH, 2004; Newman & Duenas, 2010; NNSS undated). A study of habitat preferences in France found that *E. canadensis* occurred in oligo-mesotrophic habitats, with low water phosphate and ammonium levels, a wide range of nitrate levels, and a stable, generally low water temperature. *E. nuttallii* was encountered in meso- to eutrophic sites with a wider range of generally warmer water temperature (Greulich & Trémolières, 2006).

However, comparative habitat preferences between the two species are currently unclear, as illustrated by the many studies relating to the competitive interactions between *E. canadensis* and *E. nuttallii* (e.g. Simpson, 1990; Barrat-Segretain *et al.*, 2002; James *et al.*, 2006). It has been observed that *E. canadensis* has been displaced by the arrival of *E. nuttallii* at some eutrophic inland standing waters (James *et al.*, 2006). This displacement has taken place over a relatively short period of time, approximately one to two years at sites where *E. canadensis* was formerly very abundant (Simpson, 1990). It is difficult to explain this phenomenon in terms of comparative physiology. James *et al.* (1999; 2006) examined species' responses to nutrient enrichment and found that this did not explain the displacement of *E. canadensis* by *E. nuttallii*, since the conditions created and tolerated by the two species were largely very similar. Eugelink (1998) found that root uptake of phosphorus did not differ between the two species, but that shoot phosphorus uptake was greater in *E. canadensis* than *E. nuttallii*, which would suggest a competitive advantage to *E. canadensis* rather than to *E. nuttallii*. Jones *et al.* (2000) found that both species showed a reduction in photosynthesis above pH 7, but that more acidic conditions (below pH 6) favoured the growth of *E. canadensis*, which again would give this species a competitive advantage. Other studies have shown that the species differ in terms of competitive interactions, with *E. canadensis* being more sensitive to intraspecific competition than *E. nuttallii*, which was indifferent to the presence of neighbours (Barrat-Segretain & Elger, 2004).

In spite of these somewhat contradictory findings, *E. nuttallii* is capable of a higher relative growth rate than *E. canadensis* regardless of nutrient supply (James *et al.*, 2006). *E. nuttallii* forms taller growing canopies, which may suppress *E. canadensis* by shading (Simpson, 1990). The invasion pattern of *E. canadensis*, which has been present for a much longer period of time in the UK than *E. nuttallii*, has been to increase rapidly at first, then to suffer a steady decline in abundance over time after a residence of approximately 50 years (Simpson, 1984). In contrast, *E. nuttallii* has only been resident in the UK since 1966 and is therefore still (albeit only just) within its initial period of vigorous spread, if we assume a similar invasion pattern. The reason for the ability of *E. nuttallii* to outcompete *E. canadensis* may therefore be intrinsically linked to the fact that its arrival in the UK is of much more recent origin. The reasons some non-native species become invasive and some do not is poorly understood, but may be linked to the initial lack of predators and the subsequent build-up of predators and pathogens after arrival (Williamson & Fitter, 1996). It may be the case that *E. canadensis* populations are now being kept in check by such agents, whereas *E. nuttallii* is experiencing a relative lack of predators and pathogens.

3.2.6 Closely Related Invasive Species

As mentioned in Section 1.1, *Elodea* has a close relative in the UK, the native species known as Esthwaite waterweed *Hydrilla verticillata*. *H. verticillata* is very similar in appearance to both *E. nuttallii* and *E. canadensis* and has previously been classed within the *Elodea* genus, although it has leaves in whorls of four or five rather than three (ANHP, 2006; Stace, 2010). Interestingly, although *H. verticillata* is extremely rare in mainland Britain, known only from Esthwaite Water in the Lake District, it is an invasive non-native species in the United States of America (USA). In the USA, *H. verticillata* is commonly known as hydrilla, Florida elodea or water thyme, has been declared a Federal Noxious Weed due to its aggressive invasion of waterbodies in 21 states since its discovery in 1960 (Chadwell & Engelhardt, 2008), and is now the most economically damaging weed in the USA (Richardson, 2008). *H. verticillata* has very similar ecology to *Elodea*, as would be expected from its close taxonomic relationship. It has a high growth rate and can quickly form extensive mats on the surface of waterbodies, can grow in a range of water chemistry conditions, is adapted to growth in low light conditions (Bowes *et al*, 1977), and can switch to bicarbonate utilisation where conditions favour its use (Langeland, 1996). Control and eradication of *H. verticillata* is therefore likely to utilise a range of techniques that can be equally applied to *Elodea*, with the added advantage of being extensively researched in the USA. For these reasons, *H. verticillata* control in the USA is included in Section 3.6 where control and eradication methods are discussed.

3.2.7 Summary of Reasons for Invasiveness

A sound understanding of the reasons *Elodea* is such a successful invader of standing waters in the UK is essential to the development of effective means of control and eradication. The reasons for its invasiveness can be summarised as follows:

- general factors relating to all successful invading species: release from population control by predators and pathogens only present in the native environment;
- high relative growth rate;
- ability to over-winter in an active growth form; allows for rapid growth in spring;
- produces abundant vegetative propagules in the form of mobile shoot fragments, which can easily spread;
- ability to suppress competing algae and cyanobacteria by allelopathy;
- phenotypic plasticity; enables morphological adaptation to a range of conditions;
- can utilise a range of light intensities, particularly low levels;
- can use an alternative carbon source in the form of bicarbonate; allows continued photosynthesis during short-term environmental changes.

3.3 Ecological Impacts of *Elodea*

3.3.1 Detrimental Effects

Both *E. canadensis* and *E. nuttallii* have been classified as 'high impact' in terms of their impact on native habitats and biota, and these impacts are well-documented (UKTAG, 2008). The detrimental effects of *Elodea* are compounded by a lack of public and corporate understanding of legislation with respect to invasive plants and their potential for adverse environmental effects (Defra, 2003). *E. canadensis* and *E. nuttallii* were raised a number of times in interviews with a range of organisations involved in managing alien species (ADAS, 2008). *E. canadensis* was considered a problem in the context of Water Framework Directive objectives in clear water lakes with low nutrients and specifically in lochs with slender naiad *Najas flexilis.*

Although *Elodea* only grows in slow-flowing or standing waters, extensive surface matting in slow-flowing waters such as rivers, drainage ditches and canals can further impede or prevent flow taking place. This can increase the risk of flooding (POST, 2008; NNSS, undated). In all waters with an *Elodea* infestation, dense matting near the surface intercepts sunlight and creates conditions of heavy shade below the canopy (ANHP, 2006). This can have knock-on biological impacts, for example the displacement of submerged native plant species by shading, and decreased population sizes of native plants due to reduced seed production and competition for nutrients (Madsen *et al*, 1991; Newman & Duenas, 2010; NNSS, undated). This in turn can lead to a general reduction of biodiversity in and around the infested site (POST, 2008). For example, it has been found that *Elodea* has a negative impact on native fish populations (ANHP, 2006) and reduces native crayfish populations (Hessen *et al.*, 2004), by replacing native plant species as the primary producers in the food chain. Extensive infestation can interfere with recreational activities such as boating and fishing by inhibiting access (NNSS, undated). Although not an ecological impact as such, these sorts of activities are often the reason for the survival and management of the habitat, and a cessation of recreational activity could lead to habitat deterioration through neglect.

3.4 Conflicts with Protected Species: The Example of Slender Naiad

One issue in dealing with the control and eradication of invasive species is how to undertake this without having a negative impact on co-existing populations of rare native species. This section deals exclusively with the aquatic macrophyte slender naiad *Najas flexilis*, as this species is present at several Scottish sites with *Elodea* infestations. A 2004 survey of 42 Scottish lochs found that 10 sites with *E. canadensis* and/or *E. nuttallii* also had *N. flexilis*, compared to only six sites with *Elodea* but without *N. flexilis* (Wingfield *et al.*, 2004).

3.4.1 Ecology of Slender Naiad

The ecology of *N. flexilis* has been the subject of a PhD thesis (Wingfield, 2002), and is described in detail in a SNH Commissioned Report based on the same findings (Wingfield *et al.*, 2004).

N. flexilis is a slender submerged rooted macrophyte found in some lochs. It is shorter than *Elodea*, growing only to 30 cm, and has several features which are unusual for an aquatic macrophyte. Unlike *Elodea,* it does not grow to the water surface, and lives out its entire lifecycle entirely submerged. It is an obligate hydrophile, meaning that it is incapable of vegetative spread, and pollination takes place under water. It is also an annual, relying entirely on seed production for reproduction and dispersal (Wingfield, 2004). *N. flexilis* utilises the sediment as a primary nutrient source (Fairchild, 2006), unlike *Elodea*, which relies mainly on aquatic nutrients (Eugelink, 1998). *N. flexilis* also relies entirely on dissolved CO_2 for photosynthesis (Wingfield, 2004), unlike *Elodea* which can switch to bicarbonate use if conditions dictate (Jones, 2005). *N. flexilis* is native to North America, Europe and Asia, and within Scotland is found in the Outer and Inner Hebrides, Perthshire, and a few other scattered locations (Wingfield, 2004).

N. flexilis is a European Protected Species, a UK Biodiversity Action Plan Priority Species, and is listed on the Scottish Biodiversity List. This gives it protection under domestic and international legislation via the Conservation (Natural Habitats, &c.) Regulations 1994 as amended, and the Nature Conservation (Scotland) Act 2004. *N. flexilis* is threatened by eutrophication (which prevents photosynthesis by a lack of dissolved CO_2), acidification (which appears to prevent seed formation), and the presence of *E. canadensis* and *E. nuttallii*. Although *Elodea* and *N. flexilis* sometimes co-exist, they may outcompete *N. flexilis* (Wingfield, 2004).

3.4.2 <u>Examples within Scotland</u>

Out of a survey of 42 Scottish lochs, 10 sites had populations of both *Elodea* and *N. flexilis* (Wingfield, 2004). These were the following:

E. canadensis and *N. flexilis*

- Loch Clunie (mainland);
- Loch nam Faoileann (Outer Isles);
- Loch Fada (Inner Isles and Kintyre);
- Loch nan Gad (Inner Isles and Kintyre);
- Tangy Loch (Inner Isles and Kintyre).
-

E. nuttallii and *N. flexilis*

- Loch of Butterstone (mainland);
- Loch Grogary (Outer Isles);
- Loch Scarie (Outer Isles).
-

E. canadensis, *E. nuttallii* and *N. flexilis*

- Lake of Menteith (mainland);
- Loch of Lowes (mainland).

SNH (2007) describes the results of a detailed snorkel survey of three of these lochs: Loch Clunie, Loch of Butterstone, and Loch of Lowes (two other sites were also included which are not listed above). These are all mainland sites and represent *N. flexilis*' stronghold in mainland Scotland, being collectively designated as a Special Areas of Conservation primarily for the presence of *N. flexilis*. The findings for two of these lochs, chosen for their contrasting results, are summarised below.

3.4.2.1 Loch of Lowes

A healthy population of *N. flexilis* was found in Loch of Lowes in 2007. This population was substantially more widespread than a previous survey in 2004. In some locations, a population density of up to 7 plants per m^2 was recorded. Reproductive health appeared to be very good, with seeds present on 97% of plants. *Elodea* was reported as being present in Loch of Lowes, but within a narrow zone in places, and generally not overlapping with populations of *N. flexilis* (SNH, 2007).

3.4.2.2 Loch of Butterstone

Loch of Butterstone had low levels of *N. flexilis* recorded from an earlier survey in 2004, and the 2007 survey found no plants at all, despite an intense survey effort, particularly in the vicinity of previous records. In contrast to Loch of Lowes, Loch of Butterstone had experienced 'rampant' growth of *E. canadensis*, with large *Elodea* beds having been observed. Nutrient enrichment may have contributed to the differences. The report suggests that a future increase in *Elodea* growth is likely to pose a significant threat to *N. flexilis* in the remaining lochs within the system, including Loch of Lowes, which had a healthy population of *N. flexilis* at the time of the survey in 2007, but only a small population of *Elodea* (SNH, 2007).

However, although these results show a negative correlation between *Elodea* density and *N. flexilis* density, it is not clear whether an increase in *Elodea* has a direct impact on *N. flexilis* via competition, or whether both population changes occurred as a result of other variables. This could, for example, be an environmental change such as an increase in nutrient levels, which favours preferential growth of *Elodea*, or increasing pH levels which would reduce the ability of *N. flexilis* to photosynthesise, but allow *Elodea* to utilise bicarbonate (SEPA, 2009).

3.5 Legislation and Policy Issues

3.5.1 Legislation

Invasive non-native species are dealt with by several pieces of legislation, both national and international. The most important are listed below:

- the Convention on Biological Diversity 1992, updated by the Conservation of Habitats and Species Regulations 2010, calls for the prevention of introduction, control and eradication of species which threaten ecosystems, habitats and species. Implementation is left to signatory countries, with a precautionary approach advised (SWT, 2007);
- the Wildlife and Countryside Act 1981 makes it an offence to introduce certain plant species into the wild. These species are listed on Schedule 9. Schedule 9 was updated in April 2010 to include several more invasive non-native aquatic species, including *E. canadensis* and *E. nuttallii*. In fact, the legislation covers the entire *Elodea* genus, accounting for the possibility of future problems with other *Elodea* species such as *E. callitrichoides;*
- in Scotland, the Wildlife and Countryside Act 1981 was updated by the Nature Conservation Act (Scotland) (2004). This includes provision for ministers to prohibit the sale of invasive non-native species and issue guidance in relation to invasive non-native species (SWT, 2007). Legislation will be further strengthened to prevent release of invasive non-native species, and provide powers to control them, by the Wildlife and Natural Environment (WANE) Bill, which is currently undergoing consultation (The Scottish Government, 2009);

- a list of 'high impact' invasive non-native species has been compiled by the UK Technical Advisory Group (UKTAG) for use in implementing the Water Framework Directive (WFD) in the UK.

3.5.2 Policy

Several policies within various organisations seek to support and enhance the legislation controlling invasive non-native species. Examples include the following:

- in May 2008, Defra, the Scottish Government and the Welsh Assembly Government launched the GB Invasive Non-Native Species Framework Strategy. This strategy is based on a preventative approach, aiming to prevent entry of invasive non-native species, early eradication, and control and containment of already established populations, and is co-ordinated by the GB Non-native Species Secretariat (Scottish Parliament 2010). One strategy implemented to date is the publicity campaign 'Be Plant Wise', which aims to educate the public about invasive species (Booy, 2010);
- a Scottish Working Group on Invasive Non-Native Species co-ordinates the response of public-sector bodies in Scotland to the challenges presented by invasive non-native species, and supports the efficacy of wider action at the GB level;
- the Scottish Wildlife Trust has its own policy document, dealing with the control and eradication of invasive non-native species including *E. canadensis* and *E. nuttallii* (SWT, 2007);
- the presence of alien species is included as a relevant habitat feature in the Common Standards Monitoring Guidance for Standing Waters, the standard methodology for assessing the condition of designated sites such as SSSIs (JNCC, 2005). In particular, the percentage cover of *E. canadensis* and *E. nuttallii* are included as quantitative assessments of habitat quality;
- the potential for waterbodies to fail their environmental objectives under the WFD due to the presence of invasive non-native species has been addressed in ADAS (2008), which discusses ways of tackling alien species in Scotland and developing strategies to manage them;
- The Scottish Environment Protection Agency (SEPA) is currently drafting an invasive non-native species supplementary plan for the Scotland river basin district.

3.6 Methods of Control and Eradication

3.6.1 Overview of Control Techniques

Responsibility for dealing with invasive non-native species rests with individual land owners, and there is currently no power to require individuals to control invasive non-native species on their land, or to provide access to other bodies undertaking control programmes. Additionally, there is no requirement in Section 14 of the 1981 Wildlife and Countryside Act to deal with invasive non-native species, and no government organisation has responsibility for addressing invasions when they arise. These are perceived as failings in the current invasive species policy in Scotland which the new Wildlife and Natural Environment Act will seek to address (The Scottish Government, 2009). Co-ordinated action involving a wide range of agencies and stakeholders is recognised as the most effective way forward in tackling the problems (RPS Ecoscope Applied Ecologists, 2005). It is also recognised that full-scale eradication is only possible or cost-effective in a minority of cases, and that control and reduction is a much more realistic objective. Action taken should be cost-effective, proportional to the level of threat, and take account of the effect of treatment on native species (Defra, 2008). It is also advisable not to make generalisations about any methods of control, as it is likely that different approaches need to be tailored to individual sites, and also take into account any uses of the site, for example, fisheries or reservoirs (Barko *et al.*, 1986).

Types of control techniques for aquatic weeds in general have been reviewed in many publications, for example Bowmer *et al.* (1995), Langeland (1996) and SEPA (2009). There are also numerous research papers dealing with each technique in depth. The various strategies can be grouped into four main categories as follows:

- **biological control**: introducing another species which will graze or infect the offending plant;
- **chemical control**: using chemicals such as herbicides;
- **physical control**: using mechanical removal techniques;
- **environmental control**: manipulating the plant's environment to reduce its suitability (SEPA, 2009).

The following sections of the report will discuss individual techniques in each category in depth, going back to both review articles and primary literature to ensure as complete coverage of each as can be undertaken with the information available. It has been suggested that management-outcome driven invasive species research in Europe is lagging behind other countries, including North America, Australia and New Zealand. This may be because the impacts of invasive species have been much more evident in these countries (Sheppard *et al.*, 2006). This report has looked for relevant research in all countries, and there is much to be learnt from other parts of the world that is applicable to Scotland.

3.6.2 *Biological Control*

Biological control means the importation and release of an organism outside its natural range for the purpose of controlling a pest species (Howarth, 1991). The control agent reduces the vigour and/or kills off the problem species, by feeding on it, or acting as a parasite or pathogen. Biological control of invasive species appears to have a poor reputation as a suitable means of controlling aquatic weeds, judging by phrases such as "despite the biological control tag" (Newman, 2009) which occasionally crop up in the literature. This is probably due to the many examples of disastrous attempts at biological control, where the control agent has done more damage than the original problem species. A classic example of failed biological control is the introduction of the cane toad *Bufo marinus* into Queensland, Australia in 1935 in an attempt to control cane beetles. The toad has since spread widely and impacted on native herpetofauna, mammals and fish, due to its prodigious and indiscriminate appetite, and is now the subject of research into more biological control – to control the biological control (Hyatt & Humphrey, 1995).

Since these early attempts at biological control, efforts have been made to give a more thorough assessment to the suitability of control agents prior to release. It has been stated that biological control is "the only low risk and viable, if not always reliable, long-term ecological solution…the only means for permanent ecological and economical management of introduced invasive alien species" (Sheppard *et al.*, 2006). The ideal biological control agent is one that is specific to the problem species, does not affect any non-target species, and is able to effect adequate management of the problem species (SEPA, 2009). Is there such a species that can control *Elodea* effectively, but have no effect on any other species? A variety of biological control agents have been trialled on *Elodea* and other aquatic weeds, with a range of outcomes. These are discussed below.

3.6.2.1 Fish

Control of aquatic weeds using fish features regularly in papers and reviews, and appears to be one of the earliest techniques implemented, with references dating from the 1960s (Avault, 1965). Use of fish is mentioned as being suitable when herbicide use is prohibited

(Mehta & Sharma, 1972). The grass carp (white amur) is the most frequently mentioned, with one reference found to silver carp *Hypophthalmichthys molitrix* (Opuszyński, 1972). Grass carp are native to large rivers in China, and have a natural diet of aquatic vegetation (Avault, 1965).

An early experimental study, (Avault, 1965) showed that grass carp were effective in eliminating 12 species of weeds from experimental ponds, but that the softer species such as naiad were eaten in preference to *Elodea*. Sills (1970) reports that grass carp do feed on *Elodea* but this was when placed in a tank with *Elodea* as the only available food. In natural habitats they apparently will feed on whatever is available (Sills, 1970), and this conclusion is backed up by other experimental studies (Mehta & Sharma, 1972). Mitzner (1978) found that in an American lake, grass carp effectively controlled both *Elodea* and *Najas* species.

The size of fish used is a consideration, as it has been found that only larger individuals feed on *Elodea* (Mehta & Sharma, 1972). Avault (1965) reports that the failure of grass carp to breed outside its natural range is a disadvantage to its use as a biological control. It seems that grass carp do not breed in the UK, but may establish breeding populations in the USA (Langeland, 1996; SEPA, 2009). Other studies generally recognise this as an advantage, as it prevents a population explosion that could have a negative effect on the habitat (SEPA, 2009), which has happened for carp *Cyprinus* sp. when trialled for biological control (Sills, 1970). Since the 1980s, triploid grass carp have been available which, although sterile, can be long-lived (Jordan, 2003). In the USA these are available for use by permit in some states for the control of hydrilla, and have been reported to be effective and highly recommended for situations where total removal of vegetation is acceptable (Langeland, 1996). However, an adequate method of recapture has not been developed, and appropriate stocking rates have not been ascertained (Langeland, 1996). Grass carp are voracious eaters and may also disturb sediment, compete for food with native crayfish and invertebrates, and cause eutrophication (Jordan, 2003). For these reasons they are actually banned from use in some American states (Jordan, 2003).

In summary, there are many problems associated with the use of grass carp as biological control. Firstly, they feed on any available vegetation, and may prefer softer species to *Elodea*, which would be undesirable in a loch with *N. flexilis*. Indeed, it has been stated that grass carp cannot be considered as biological control since they are indiscriminate generalist feeders (Gassmann *et al*., 2006). They may upset trophic relationships in the food web and cause environmental problems such as turbidity and eutrophication. If not carefully contained they can escape to neighbouring waterways, even through fish barriers, and can transmit diseases to native fish (Jordan, 2003). With careful evaluation of risks on a case by case basis, it has been suggested that grass carp may be an effective supplement to other techniques when a lower stocking density can be used (Opuszyński, 1972). However, given all the constraints, it would seem unlikely that grass carp would be recommended as a suitable technique for use in Scottish lochs.

3.6.2.2 Invertebrates

Invertebrates present a potentially better solution for more closely targeted biological control of *Elodea*, since many invertebrate species have preferential or even obligate host plants. An essential pre-requisite for developing effective bio-control is a thorough knowledge of the problem plant's complex of natural enemies, and to date this information is largely lacking for *Elodea* (Gassmann *et al.*, 2006). Submerged aquatic species seem to be more problematic to control using biological control when compared to floating and emergent weeds (Gassmann *et al.*, 2006). However, there are several potential avenues of biological control using invertebrates that have been trialled on other aquatic weeds that could shed some light on the potential for similar techniques applicable to *Elodea*.

The most researched example is the use of weevils in the control of hydrilla in the USA. Two species of weevil have been found that offer promising results, these being *Bagous hydrillae* and *Bagous affinis* (both introduced) (Wheeler & Center, 2007). Adults of both species feed on hydrilla leaves and stems. Larvae of *B. hydrillae* feed on leaves, stems and tubers whereas larvae of *B. affinis* feed only on tubers; underground storage organs that allow the population to survive unfavourable conditions (Wheeler & Center, 2007). An experimental study found that both *B. hydrillae* and *B. affinis* were host specific, but that *B. hydrillae* provided better hydrilla control since damage to tubers by developing larvae was sufficient to reduce fecundity of the hydrilla population (Wheeler & Center, 2007). It is promising for *Elodea* control that a similar species in America can be controlled by a non-native weevil pest. However, the direct applicability to *Elodea* control may be limited since *Elodea* are not known to produce tubers, and even for hydrilla the tubers need to be exposed at the water's edge to be used as oviposition sites by the weevils (Wheeler & Center, 2007). Use of *Bagous* sp. for hydrilla control may only be suitable in combination with lake draw-down or intermittently wet shorelines (Langeland, 1996). Another intensive study of *B. hydrillae* for hydrilla control in Australia found that adult *B. hydrillae* caused extensive damage to hydrilla mats floating on the surface, with limited damage potential for native vegetation. It was suggested that although hydrilla is biologically similar to *E. canadensis*, *B. hydrillae* is not suitable for control of *E. canadensis* since it is has a warmer climatic range and would not survive the cold winters characteristic of *Elodea* habitats (Buckingham & Balciunas, 1994). The non-native weevil *Stenopelmus rufinasus* has been trialled for the control of water fern *Azolla filiculoides* in the UK. This species is showing promising results in trials by British Waterways in the Leeds and Liverpool Canal using captive-bred weevils released onto problem sites (British Waterways, 2004; SEPA, 2009; British Waterways, 2010). These results suggest the possibility of finding a similar weevil species which feeds on *Elodea* in its native habitats that could be utilised as a biological control in a similar way. Weevils seem to offer the most promising results out of all biological control of submerged aquatic species to date (Gassmann *et al.*, 2006).

A leaf-mining fly, *Hydrellia balciunasi*, has also been shown to provide effective control for hydrilla in the USA. The larvae of this species feed preferentially on hydrilla, and are highly mobile underwater. *H. balciunasi* are native to Australia, and were licensed for use as hydrilla biocontrol in the USA in 1989 (Buckingham *et al.*, 1991). Since then another leaf-mining fly has been used for hydrilla control in the USA: *H. pakistanae*. Both species were rigorously assessed for host plant specificity prior to use (Flanders, 2003). It is essential to the success of any biological control schemes that potential negative impacts on native vegetation are well assessed before use (Howarth, 1991). An aquatic moth, *Acentropus niveus*, was also suggested as potential hydrilla control from an early study (Batra, 1977), but later references to this species were not found.

The only example of an experimental study into biological control of *Elodea* species (as opposed to other aquatic weeds) using invertebrates found in the literature search was that of Barrat-Segretain and Lemoine (2007), which investigated the use of the snail *Lymaea stagnalis.* It was found that *L. stagnalis*, a generalist herbivore, was able to influence the competitive interactions between *E. canadensis* and *E. nuttallii*. However, it was not an effective biological control agent. This was because snails cause fragmentation of *Elodea* plants, which would increase its invasive potential, and it was thought that in the field *L. stagnalis* would feed preferentially on more palatable species. It was found that *E. nuttallii* was preferred to *E. canadensis*, which would suggest that *E. nuttallii* may be a more promising species on which to focus research, as it is more palatable to herbivores (Barrat-Segretain *et al.*, 2002; Barrat-Segretain & Lemoine, 2007).

3.6.2.3 Microorganisms

The number of insects with potential to control invasive aquatic weeds is limited because most aquatic insects are carnivorous or detritivorous (Zettler & Freeman, 1972). Plant pathogens offer a much larger reservoir of potential biocontrol due to the large number of plant diseases that exist from which to select, although these are much more poorly known for submersed species. A study in 1972 found no known diseases affecting *Elodea* (Zettler & Freeman, 1972). Micro-organisms such as fungi may be used to control aquatic weeds via their production of phytotoxins, if such diseases can be found that are also efficient and selective. A study of 30 isolates of fungal species found 12 that caused chlorotic damage to hydrilla (Charudattan & Lin, 1974). It was not known which chemical in the extract caused the damage, but if this could be isolated it offers the chance of using a manufactured chemical rather than fungal spores. There is considerable overlap between the use of micro-organisms as biological control, and chemical control (discussed below).

More recent studies focus on hydrilla control in the USA. No similar studies were found for *Elodea*. A recent study on hydrilla control attempted to survey all micro-organisms associated with hydrilla and investigate the potential for biocontrol for each one (Shabana *et al.*, 2003a). Over 2000 micro-organisms found in and around hydrilla were investigated. Of these, 2 strains of bacteria and 42 fungal isolates were found that were effective at killing hydrilla. This represented a very low proportion of the total screened; 0.6% of bacteria and 6.5% of fungi. This is an intensive approach which took one year, and suggests good potential for *Elodea* control if sufficient time and funds were available to undertake a similar study on *Elodea* in the UK.

3.6.2.4 Beavers

One last example of biological control of *Elodea* noted in the literature is the use of beavers. The European beaver *Castor fiber* is native to the UK but became extinct about 400 years ago. In 2009, three families of beavers were reintroduced to sites in Argyll, and two produced their first litters in 2010 (Scottish Beaver Trial, 2010). In America, *Elodea* is a preferred food of the North American species of beaver *Castor canadensis* (SEPA, 2009). Although it is not suggested that *Elodea* control is a primary reason for beaver reintroduction, it would be interesting to see if a reduction in *Elodea* populations will be observed as a side-effect of their presence in Scottish lochs with an *Elodea* problem. Beavers are a keystone species in aquatic habitats and their presence may stabilise trophic relationships and prevent future infestations of invasive species.

3.6.3 Chemical Control

3.6.3.1 Herbicides

Use of herbicides to control aquatic invasive plants is one of the oldest methods (LALMS, 1990), with research dating from the 1960s (Mackenzie & Hall, 1967; Ware & Gorman, 1967). Herbicides are also cheaper and easier to use in comparison to other control methods (Chisholm, 2007). A perfect herbicidal control is one that is quickly effective, kills only the target plant species, is safe for humans, fish and other wildlife, and breaks down completely so that its effect is not sustained (Chisholm, 2007). The problem lies in finding a chemical that fulfils these criteria. There are concerns over the use of chemicals in water (Greaves & Shaw, 1999). Water increases the potential for uncontrolled dispersal, therefore exacerbating the negative impacts. It has been suggested that herbicides are only suitable as a short-term solution to tackling invasive aquatic weeds where the problem is urgent, whilst more targeted methods are researched, for example water hyacinth control in the USA (LALMS, 1990). Due to the potential problems with aquatic herbicides, their use in the UK is tightly regulated. In England and Wales, agreement is required with the Environment Agency before any herbicides can be applied to water (Environment Agency, 2003). In Scotland, the use of herbicides for aquatic weed control is covered under the Control of Pesticides

Regulations 1996, and enforced by the Food and Environmental Protection Act 1985. SEPA consent must be sought for the use of any herbicide in water, and the herbicide treatment must be applied by an appropriately qualified person. SNH consent must also be sought if herbicide is to be used within an SSSI (Murphy, undated). Despite these legal caveats, there is significant published research on the use of herbicides for aquatic weeds, including *Elodea*.

A range of herbicides has been recorded as used on either *Elodea* or hydrilla. Diquat has been researched for hydrilla control since the 1960s (Mackenzie & Hall, 1967), and is also effective on *Elodea* (LALMS, 1990; Glomski *et al.*, 2005). Diquat is a contact herbicide that disrupts electron flow in photosystem I, eventually destroying cell membranes (Glomski *et al.*, 2005). Diquat causes tissue death within one to three days, and has been used in New Zealand for submerged macrophyte control for over 40 years. One study suggests that control with diquat was undertaken with little harm to native species, which "recover rapidly" after treatment (Chisholm, 2007). However this is not necessarily borne out by findings elsewhere. Diquat is not active in turbid water as it adheres to particles, and remains active in the sediment for months (Chisholm, 2007), although it degrades rapidly in the water (Harper *et al.*, 2007). A recent study (Glomski *et al.*, 2005) found that *Elodea* absorbed diquat rapidly from solution and was extremely sensitive, with 96% to 100% control (measured in remaining biomass). Interestingly, it was much less successful for hydrilla control, which suggests that even closely related species differ markedly in their response to the same herbicide. The concentrations of diquat required for effective control of *Elodea* were very low; equivalent to one drop per ten litres of water (Harper *et al.*, 2007). Control is effective for two to three years, with spot treatments recommended thereafter to contain any future increase (CEH, 2004). It would seem that although diquat has good potential for the control of *Elodea*, its use is tightly regulated by Scottish law, and it may also be difficult to purchase in the UK due to a lack of manufacturers. Newman (2009) states that "we have continued to attempt to reinstate diquat for aquatic weed control…it has not yet been possible to make any progress…without the complete support of manufacturing companies and others it will not be possible to get diquat back".

Several other herbicides are mentioned in the literature as having good potential for aquatic weed control, although none are as extensively researched as diquat. Murphy (undated) states that diquat and dichlobenil are the only two herbicides suitable for use on submerged (as opposed to emergent) aquatic weeds. Endothal is another herbicide that has been recently registered for use on aquatic weeds in New Zealand, although with many restrictions (Harper *et al.*, 2007). Endothal is more effective in turbid water than diquat, and provides more effective control of hydrilla (Chisholm, 2007). However, there is no evidence to date for any research on *Elodea* control using endothal. Fluridone is another possibility. *Elodea* is sensitive to fluridone, and although it can take seven to ten days to activate a response, control from a single application may last a season (LALMS, 1990). Fluridone is persistent in the environment and sediments may remain toxic for a year or more (LALMS, 1990). Other herbicides mentioned include acrolein for the use of *E. canadensis* control in Australia (Bowmer & Sainty, 1977), and butachlor and bensulfuron-methyl for *E. nuttallii* control in China (Huiyun *et al.*, 2009).

The mode of delivery of herbicide is a prime consideration, when determining how best to target the weed species. Recent advances have been made in the use of polysaccharide gels to deliver herbicides. Known as 'Aquagel' or 'Hydrogel', this is a guar gum-derived non-toxic starch in powder form that can be mixed with water to the desired viscosity, which is maintained at a range of temperatures (Chisholm, 2007). This is then mixed with the herbicide and used to apply to the vegetation, with the advantage of targeting the species more precisely with no spray drift (Harper *et al.*, 2007). Hydrogel has been found to aid the success of hornwort *Ceratophyllum demersum* control in New Zealand (Chisholm, 2007).

One potential problem for herbicide use is that of resistance. Fluridone has been heavily used in the USA for aquatic plant management, and as a result, biotypes of hydrilla have developed that are resistant (Richardson, 2008). The development of fluridone resistance has significantly impacted hydrilla management, and further research is underway to find alternative products (Puri *et al.*, 2009).

In conclusion, it would seem that research into the use of herbicides in controlling *Elodea* has good theoretical potential for finding a chemical that fits the criteria of specificity and low toxicity/persistence. Although aquatic herbicide use carries a risk of indirect effects on the aquatic environment, application of a suitable herbicide could be significantly improved by using a gel suspension. However, continuing aquatic herbicide research in the UK would be expensive, and it may cost more to develop and test herbicides than could be recouped from sales. Combined with the ever-tightening legal restrictions on the use of aquatic herbicides, this means that, at the moment, opportunities for aquatic weed control using herbicides are limited (Newman, 2009).

3.6.3.2 Nutrient Control Agents

One early study on hydrilla control describes the use of nutrient-control agents; substances which deprive aquatic weeds of essential nutrients through chemical modification of the water (Martin *et al.*, 1970). The study found that a range of cation-control resins were effective in controlling hydrilla in an American lake. No more recent references to this technique were found in the literature. However, this treatment has close overlaps with environmental control, discussed in section 3.6.5.

3.6.4 Physical Control

Physical control of aquatic weeds appears to be a well-used technique, described as being “the most widespread means of managing aquatic weed problems…on a worldwide basis” (Murphy, 1988), and “the only sensible option available” (Newman, 2009). Physical control measures include all physically destructive techniques, from simple manual removal to large and expensive machinery, and are all recommended as appropriate techniques by CEH for control of *E. canadensis* (Newman & Duenas, 2010) and *E. nuttallii* (CEH, 2004). CEH recommends that cutting is best undertaken before July when peak biomass is reached, preferably in March. This will provide approximately eight to ten weeks of control, and will delay the production of peak biomass. It is claimed that repeated cuttings during the growth season will limit the floating material produced, and therefore the amount of propagules available for dispersal and overwintering, and may eventually cause disappearance from the system (CEH, 2004; Newman & Duenas, 2010).

3.6.4.1 Manual Removal

Simple manual methods include cutting, dragging, raking or forking plants out of the water (Murphy, 1988). Cutting may be undertaken with scythes, knives, sickles or machetes. In the 1980s it was reported that manual clearance was still widely used in the UK for canal clearance, although even then it was decreasing due to rising costs (Murphy, 1988). Manual labour is costly, and not usually very efficient, leaving at least 10% of the weed untouched (Soulsby, 1974). This leads to rapid regrowth and the need for more than one cut per season, with three being the norm (Murphy, 1988). A recent study of hand-removal of *E. nuttallii* in France showed that two harvests caused almost complete disappearance of *E. nuttallii* in the same season; however, it was not reported what the subsequent seasons' growth were, and it was also found that harvesting had a detrimental effect on native plant diversity (Di Nino *et al.*, 2005).

3.6.4.2 Mechanical clearance

Mechanical clearance of aquatic weeds in the UK is a specialised and growing industry, with some companies specialising in this. Machinery available includes cutter bars, dredgers, sediment rotovators, lake mowers, weed cutting buckets, and harvesters such as the AquaTractor (Kingcombe Aquacare, Somerset, UK). In general, mechanical clearance is faster and cheaper than manual control, although with a similar removal rate and rapid regrowth to original levels within a few weeks of clearance (Murphy, 1988). This will obviously increase the cost as repeat harvests will be required to maintain a level of control. Bottom dredging, i.e. removal of the vegetation and sediment (and the vegetative propagules it contains), is the most effective in terms of proportion removed and regrowth potential (Murphy, 1988).

It is evident that the use of large machinery in a waterbody will exert some negative environmental impacts, which are not generally mentioned when recommending mechanical removal (CEH, 2004: Newman & Duenas, 2010), although, of course, these have to be balanced against the negative impacts of alternative techniques. Harvesting machinery is destructive and non-selective, unlike manual harvesting which can select the correct species of plant. It would not be suitable for mixed-species stands of vegetation where *Elodea* is present alongside species of conservation interest such as *N. flexilis.* Physical removal of any sort is only a short-term solution (possibly the shortest-lived out of all techniques discussed so far), offering control for around two months during summer. It is expensive to hire and operate machinery, and these costs cannot be offset by finding a use for the plant, as *Elodea* has a low nutritional value and high water content making it unsuitable for use as livestock fodder (Langeland, 1996). Composting is the only viable use for removed material (Newman & Duenas, 2010). The use of manual removal could be made more cost-effective by the use of conservation volunteers.

The success of physical removal of *Elodea* is variable. It has been found that *Elodea* is especially less susceptible to harvesting methods in comparison to other aquatic weeds such as spiked water-milfoil *Myriophyllum spicatum* (Abernethy *et al.*, 1996). The main problem appears to be the fragmentation of *Elodea* strands by harvesting, and the rapid regrowth of individual fragments causing spread (Abernethy *et al.*, 1996). This is because stem fragmentation is a natural propagation strategy of *Elodea*, with stems becoming especially brittle in summer to enhance this. It has even been suggested that mechanical disturbance promotes even more rapid growth than before, by increasing the number of lateral shoots in cut sections compared to intact plants, which may aggravate the invasion (Mielecki & Pieczyńska, 2005). Another problem is the removal of invertebrates attached to leaves and shoots. A study in Irish canals found that macroinvertebrate populations were reduced immediately after harvesting using a mowing bucket, which cuts vegetation at the sediment level, although recovery was relatively rapid and fish populations were unaffected (Monahan & Caffrey, 1996).

Turion removal is one option for *Elodea* control, which has been trialled successfully on whorled water-milfoil *Myriophyllum verticillatum*, another turion-producing aquatic plant. Turions were removed from the sediment during early winter using a weed harvester. It was found that this gave effective control for the following year, and that growth was reduced for subsequent growing seasons (Caffrey & Monahan, 2006). This offers an interesting avenue of exploration for *Elodea* control, since turion removal would be undertaken during winter rather than spring or summer, which may reduce impacts on other wildlife, and would reduce regrowth by stem fragmentation. Effects on *N. flexilis* could be minimised since seed set would have occurred, providing some kind of filtration mechanism could be used that ensured seeds remained in the sediment. Control methods that disturb the sediment create the problem of sediment disturbance, nutrient release and associated anoxia and turbidity. However, it has been suggested that such conditions may be favourable for *N. flexilis* germination, since it is an early coloniser of new water bodies, and this would mimic such conditions (SEPA, 2009).

3.6.5 Environmental Control

Environmental controls seek to modify the environment in order to make it less favourable to the nuisance plant. For this to be successful it requires a thorough knowledge of the species' ecology. Factors that can be modified include light intensity, water levels, and water quality (SEPA, 2009).

3.6.5.1 Shading

Reducing light intensity by shading has been said to "control most aquatic plants" (Newman & Duenas, 2010). It has been shown that *E. canadensis* is adversely affected by shading from floating-leaved plants where they exist in its natural habitat (Larson, 2007). Artificial shading may therefore produce the same effect. There are a number of ways this can be undertaken. Firstly, planting trees on the south side of the waterbody to produce a permanent increase in shading has been recommended for *E. canadensis* and *E. nuttallii* control (CEH, 2004; Newman & Duenas, 2010). An experimental study in the USA found that tree cover significantly reduced total biomass of submerged macrophytes, although not specifying which species were most and least affected (Madsen & Adams, 1989). Increasing tree cover may be suitable in some situations, but may not be desirable in sites of nature conservation interest, as it may conflict with conservation objectives, and may decrease cover of desirable plants as well as the invasive species.

The alternative to tree planting is to use some form of temporary shading material, which is also recommended for *Elodea* control (CEH, 2004; Newman & Duenas, 2010). However, experimental results in the literature show contradictory results. An early study by Dawson and Mallows (1983) concluded that using a light-weight permeable opaque membrane gave good results for *Elodea* control, although it took longest for *Elodea* compared to other submerged macrophytes; about 12 weeks of cover was sufficient to reduce leaf size and plant vigour. A more recent experimental study showed no significant effects of low or high shading using a floating membrane compared to no shading, and concluded that *Elodea* was less susceptible to shading effects than the water-milfoil species *Myriophyllum spicatum*, with no significant reduction in total biomass or shoot length caused by shading (Abernethy *et al*, 1996). This would agree with physiological studies of *Elodea* that suggest it has a good capacity for maintaining photosynthesis at low light intensities (Mielecki & Pieczyńska, 2005). Interestingly, one study has shown that shading followed by increased light intensity may have a negative effect on *Elodea* as, although it can adapt to some extent to low light intensities, its capacity to acclimatise to higher light intensity when adapted to shade is much lower (Hussner *et al.*, 2010). This may offer a line of future research into control methods.

Use of surface shading material can be targeted locally, and results suggest that it may be reliable under some circumstances. It does not cause physical disturbance to the water or sediment, and does not cause chemical pollution. Disadvantages include that it is aesthetically displeasing, may need to be *in situ* for several months, and is non-selective in terms of target species (Dawson & Mallows, 1983). Installation of material may also be labour intensive (SEPA, 2009). One alternative that has been suggested is to add dyes such as the Canadian/US dye 'Aquashade' to the water which create a temporary shading effect (SEPA, 2009). This is also a recommended technique for *Elodea* control by CEH, reported as being successful in static waters (Newman & Duenas, 2010). Early application before spring growth begins is recommended, with a further application after six to eight weeks depending on the longevity of the original application, and all colour dyes are said to be successful. No particular type of dye is mentioned in the CEH advice note (Newman & Duenas, 2010), and no reference to any experimental trial using dye has been found in the scientific literature. SEPA (2009) suggest dyes as a possible method, stating that they are only effective in smaller waterbodies and, as with other shading methods are non-selective; however, no references are made to published work.

One last technique relating to shading is to use materials at the benthic level rather than on the surface. Shading materials are attached to the substrate and cause die-back of all rooted vegetation. An early study in the USA showed that benthic barriers resulted in plant decomposition over a three week period to produce a weed-free environment, with no adverse environmental effects (Mayer, 1978). This method has been recently trialled successfully in Ireland for the control of curly waterweed *Lagarosiphon major*, although there were problems with anchorage and material floating to the surface (SEPA, 2009). It has been suggested that geojute may be a better option as it sinks readily and can be easily positioned by divers. A recent study (Caffrey *et al.*, 2010) researched the use of geojute at the benthic level for control of *L. major* in Ireland. Promising results were reported, with almost complete control taking place within four to 17 months. Geojute has the additional advantages of being biodegradable, stabilising the substrate, and allowing native species such as charophytes and angiosperms to grow through the weave. However, as with all shading methods these techniques are non-selective and would need to be applied to mono-specific stands of *Elodea.* Caffrey *et al.* (2010) used buoys to mark out the *L. major* sites, and divers with weights were used to target jute placement.

3.6.5.2 Draw-down

Draw-down means to reduce the water level of the waterbody, and can be used for aquatic plant management in sites with water level control methods and where draw-down would not interfere with other water uses such as reservoirs, navigation or hydro-electric power (Langeland, 1996). The principle is that draw-down induces desiccation in overwintering propagules at the sediment surface. Draw-down has been trialled in the field for hydrilla control in the USA, but was found to be unsuccessful due to high tuber resistance to drought (Langeland, 1996). Another study using mesocosms found that hydrilla could be controlled using draw-down, with the effect depending on the type of substrate, and that turion production was restricted by draw-down (Poovey & Kay, 1998). Draw-down has been tested in the laboratory and field in France and was found to be less effective for *E. nuttallii* than *E. canadensis* in the laboratory, and ineffective at controlling *E. nuttallii* in the field during a natural draw-down (Barrat-Segretain & Cellot, 2007). *E. nuttallii* seems to be more resistant to drought than *E. canadensis*, and a summer draw-down would not provide effective control. Draw-down may only be suitable for a minority of sites with *E. canadensis*, where it is possible to achieve water level management, and where it would not conflict with other site objectives.

3.6.5.3 Nutrient management

At many sites with an *Elodea* problem, changes in water quality have also arisen, notably an increase in nutrient loads. It may not be the case that there is a direct link; however, it is possible that modifying water quality may provide some means of control of *Elodea* (SEPA, 2009). Certainly it is the case that reversing anthropogenic eutrophication will aid restoration of the habitat, and may provide either direct or indirect benefits to vegetation. It may not be sufficient simply to remove the cause of eutrophication, since elevated nutrient levels will remain in circulation within the system; therefore it is necessary to reduce levels in the water. One method that has been trialled for aquatic management is the use of Phoslock ®, a P-binding agent which strips phosphorus from the water column and prevents its release from sediments (Spears *et al.*, 2010; Traill, 2010). This is preferable to sediment removal as it retains the vegetation and seed bank. This is in the early stages of investigation, and it not currently known whether its use will have any benefits for aquatic weed control.

3.7 Combining Control Methods

The above sections deal with individual control treatments for *Elodea*. It is possible that a combination of two or more techniques may provide greater control than each technique used in isolation. However, the use of combined control methods is, in general, very poorly researched to date. The exception to this was the use of fungal control; several studies were found that examined the use of fungal control in conjunction with another control technique. Netherland and Shearer (1996) and Nelson *et al.* (1998) investigated various combinations of the herbicide fluridone and a fungal pathogen of hydrilla, *Mycoleptodiscus terrestris*. It was found that moderate doses of the fungus in conjuction with fluridone greatly increased susceptibility of hydrilla to the herbicide, with minimal effect to non-target plants. This suggests that finding a suitable fungal control for *Elodea* may enable herbicides to be used at a much lower dosage. Another study assessed the use of four fungal species in conjunction with the biocontrol leaf-mining fly *H. pakistanae* and found that a combined approach caused much greater hydrilla damage than insects alone (Shabana *et al.*, 2003b). Again, this suggests that finding a suitable fungal control for *Elodea* may improve the efficacy of an insect biocontrol. There is certainly great scope for future research into combined control methods for *Elodea*.

3.8 Prevention of Invasion

Although not a control method *per se*, suggestions as to prevention of invasion are deserving of discussion here, given the old adage that “prevention is better than cure”. It is particularly relevant for sites without *Elodea* that are close to infested sites, given the difficulties of controlling an invasion after it has happened, and where the site has a nature conservation interest such as *N. flexilis.* Tightening of legislation, such as the recent inclusion of *Elodea* onto Schedule 9 of the Wildlife and Countryside Act, and the publication of Defra’s Horticultural Code of Practice (Defra, 2005) will go some way towards minimising future new invasion nuclei (Manchester & Bullock, 2000). However, for sites where *Elodea* is perilously close, it is perhaps more likely that *Elodea* will invade by natural means such as waterfowl or natural dispersal. In these cases, it has been found that invasion risk can be minimised by promoting a healthy native vegetation cover, for example by restoration of native species, which will fill any potential ‘empty niche’ for invasion (Chadwell & Engelhardt, 2008; Owens *et al.*, 2008). Invaders have the largest performance advantage in degraded habitats, therefore maintaining good ecological conditions will act as a self-defence measure against *Elodea* colonising pressure (Thiébaut & Di Nino, 2009).

3.9 Case Studies in Scotland

In Scotland, invasive non-native species have been identified as a major cause of poor condition (based upon site condition monitoring data) for many freshwater designated natural heritage sites (Mackey & Mudge, 2010). Across Scotland, there are approximately 18 SSSIs and 5 SACs that are known to support *Elodea*. In SNH’s Forth and Borders area, site condition monitoring data has indicated that the following designated natural heritage sites have been colonised by *Elodea*: Ballo and Harperleas Reservoirs; Carriston Reservoir; Black Loch (Abdie); Lochmill Loch; Lindores Loch; and Cullaloe Reservoir. *Elodea* has also been identified as an issue at freshwater sites within Tayside and Clackmannanshire and the Western Isles.

Staff at SNH were contacted for this review, with regard to specific cases at a number of sites. The conversations highlighted the fluctuations in populations of *Elodea*, plus several attempts at control.

3.9.1 *<u>Dunkeld – Blairgowrie Lochs SAC</u>*

The Dunkeld – Blairgo wrie Lochs SAC comprises 5 linked lochs along the Lunan Burn. The aquatic flora is exceptionally diverse, with *N. flexilis* present and an outstanding number of pondweeds (SNH, 2001a). *N. flexilis* populations have been studied in some detail (James & Barclay, 1996; Howson *et al.,* 1997; Wingfield, 2002; Murphy and Hall, 2005; SNH, 2007), and water quality has been monitored by SEPA in relation to a catchment management scheme, which has operated on the Lunan Lochs for 5 years to improve water quality by reducing inputs from farming (SNH, 2004). While the Lunan Natural Care Scheme realised significant reductions in total P in the waterbodies (SEPA, 2010), *N. flexilis* is now thought to be extinct from all five Lunan Lochs and *Elodea* populations are reported to have reduced in Butterstone in more recent years (pers. Comm. Nicki McIntyre, SNH). Due to concerns over *Elodea* abundance in Butterstone in 2005, enquiries were made into commissioning specialist weed removal services, but no work was ever carried out here as there were concerns over potential impacts upon the fishery and because *Elodea* populations seemed to be reducing naturally.

3.9.2 Cameron Reservoir

Cameron Reservoir is notified as an SSSI, SPA and Ramsar site for its winter roosting pink-footed geese in north east Fife. The site has been managed as a water supply since 1919 and supports a trout fishery, managed by the St Andrews Angling Club (SNH 2010). Cameron Reservoir is not known for an interesting aquatic flora, but *E. canadensis* growths were considered by the anglers to be adversely affecting the fishery. In 2008 the angling club obtained permission to manage *Elodea* via cutting – a measure which was reportedly unsuccessful (pers. Comm. David Shepherd, SNH).

3.10 Direction of Future Research

The above discussion of the current status of *Elodea* control methods, and those for similar species, has suggested several avenues of further research that would be worth pursuing.

3.10.1 Biological Control

The only biological control currently available for *Elodea* is grass carp, and this is unsuitable for many reasons, not least being the fact that grass carp are generalist herbivores and do not feed exclusively, or even preferentially, on *Elodea* in mixed-species stands. Biological control of *Elodea* offers huge scope for future research, given the success of biological control hydrilla in the USA using insects and fungi and the control of *Azolla* in the UK using weevils. The main problem hindering development of a good biological control for *Elodea* is the total lack of knowledge of its natural pests and pathogens in its native habitats. Hydrilla pests and pathogens are particularly well known, and this has instigated several successful uses of them in control schemes. Invertebrate and fungal pests have been especially useful for hydrilla control, so it would seem likely that these present the best opportunities for *Elodea* control. *Elodea* is native to North America and Canada, so this would be the starting-point for research into targeted biological control.

3.10.2 Herbicides

Herbicide use has decreased markedly over the last 20 years (Hemmings, 2010), despite the significant advances made during the last 50 years in the production and use of aquatic herbicides (Newman, 2010). This progress will be to no avail if the unpopularity of herbicide use continues. Herbicides have been found that act upon *Elodea,* with minimal impacts on native vegetation. These herbicides can be used at low dosages, and do not persist, notably the herbicide diquat. There are no herbicides currently registered for use on aquatic weeds in the UK, due to the removal in recent years of previously authorised products (listed in Murphy, undated). However, it would seem that herbicides do have a useful role to play in

Elodea control, and research should be allowed to continue until sufficient advances have been made to enable them to find favour once more. In particular, the use of hydrogel or other similar products to deliver herbicides enables much closer targeting of the herbicide, allowing for better control of chemicals in the environment. This may make herbicide use more palatable to the government and the public. Herbicide use also offers opportunities for combining it with other techniques that may produce a synergistic effect and enable even lower levels of herbicide to be effective.

3.10.3 Physical Control

Physical control of *Elodea* is widely available in the form of a variety of commercial machinery from specialist firms, and appears to be a continuing developing technology. Research to date has suggested that such large-scale control may only be suitable for mono-specific stands of *Elodea* in sites of low conservation value. It would be interesting to know whether continued mechanical removal of *Elodea* actually perpetuated the cycle of boom-bust population dynamics in comparison to lower-impact methods, or even doing nothing at all, but this would hardly be a commercially viable avenue of research (plus of low value to nature conservation). It would perhaps be more useful to undertake research into hand removal methods, particularly using nature conservation volunteers such as British Trust for Conservation Volunteers, and/or student projects researching the effectiveness of manual control. This would be worthwhile, as it is a relatively low-cost research proposal, into a relatively low-cost technique, that is also of low general impact on the environment and can be species-specific.

Another potential avenue for future research on physical control methods would be turion removal. This has been shown to be very effective in controlling other aquatic weeds that produce turions, and to date appears to be unresearched for *Elodea.* The potential advantages for turion removal over other forms of mechanical control include better timing of treatment to coincide with low biomass over winter and spring, less biomass to dispose of, less removal of attached invertebrates, and could be undertaken in such a way as to filter out seeds of native annual flora such as *N. flexilis.* There is a significant bias in the literature in favour of control methods undertaken during summer, when *Elodea* is at its most highly visible, and little consideration appears to have been given to adapting techniques to winter use when some of the disadvantages may be ameliorated in terms of adverse environmental impacts.

3.10.4 Environmental Control

Benthic shading using weed suppressing fabric provides a good potential avenue of research into *Elodea* control. This could be done during winter and spring, again during the period of low *Elodea* biomass and visibility. If areas of summer infestations could be identified in advance, these areas could be targeted on a local scale for benthic shading over winter, which would prevent re-growth in spring when temperatures rise above the critical point. There would be no aesthetic issues here as with surface shading techniques, and the areas to be covered could be kept away from known *N. flexilis* populations.

Nutrient management of habitats has good potential for improving the control of *Elodea*, but is perhaps less well-suited to a research programme tailored to this purpose due its large scale. However, it would be useful to research sites with *Elodea* problems that are the subject of wider-scale habitat restoration, of which several are described under the case studies, for example Lunan Lochs, to find out whether such strategies also result in reduced population sizes of *Elodea.* This would apply to water quality improvement schemes, and even to beaver re-introduction schemes which are currently in their early stages in Scotland.

3.10.5 Combined Control Methods

This aspect has been very poorly researched to date, probably because individual techniques still have scope for major improvement. Knowledge of combined control methods relies on good initial data on the success of individual techniques, and until these have been better developed, research into combined methods will lag behind. However, one particular area that offers excellent potential is the combination of fungal control of *Elodea* with herbicides, and with insect (e.g. weevil) control. There is evidence from hydrilla control research in the USA that a) fungi plus herbicides and b) fungi plus weevils offer much better control of hydrilla than each method in isolation. This is because the fungal infection weakens the plant and increases its susceptibility to herbicides and insect damage.

3.10.6 Previous Control Efforts

Evidence suggests that significant money has been spent on *Elodea* control in the UK to date. One estimate for freshwater invasive species control in Great Britain came in at £25 million per annum, with *E. canadensis* control costs being a high percentage of that (Aldridge *et al.*, 2010). However, it is difficult to find any information on which methods were attempted, at which sites, and what the success was. It would be most productive if a nation-wide survey could be undertaken of site managers etc. asking about attempted *Elodea* control and its efficacy. If no methods have been found to be particularly effective, this would give good justification for taking some funds away from ill-advised control methods and targeting it instead into better research programmes as suggested above.

4 CONCLUSIONS

Control and eradication of *Elodea* is particularly problematic, since being a submersed species it may not be appropriate to use some of the many methods available for floating or emergent weeds (Gassmann *et al.*, 2006). The literature review into control and eradication methods for *E. canadensis* and *E. nuttallii* has shown that there is no single perfect solution. There are a suite of options available which may be suitable in some circumstances and not others, and the current option is to tailor these to a particular site bearing in mind the advantages and disadvantages of each method alongside the characteristics and uses of the site. The development of new techniques for aquatic weed control has been described in the literature as “glacial” (Chisholm, 2007). However, there are many opportunities for developing further research which are recommended, based on the findings of the literature review. These can be summarised as:

- pests and pathogens of *Elodea* in their native habitats;
- combining fungal and insect pests as biological control;
- continuing research into hydrogel applications of herbicides;
- combining herbicides with fungal pathogens;
- hand removal using volunteer labour;
- turion removal during winter;
- benthic shading from winter onwards;
- surveys of sites with habitat restoration programmes that may indirectly aid *Elodea* control;
- surveys of control methods attempted in the UK and their success or failure.

It would seem that there is currently a large amount of investment into *Elodea* control across the UK, using techniques that are of questionable efficacy. We would therefore recommend that some of the funding that is currently utilised for potentially inappropriate control and eradication methods be re-directed into researching opportunities for improving current methods and developing innovative approaches to *Elodea* control. The best investment into future research, if one could be chosen from many, would be to investigate the pests and pathogens of *E. canadensis* and *E. nuttallii* in their native habitats. This knowledge could then be used in developing a safe and closely targeted biological control. The biological control/s could then be tested in combination with low dosage herbicide applied using hydrogel application. It is suggested that this would create the best control and eradication method for *E. canadensis* and *E. nuttallii.*

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