Research Article

Management of the invasive Nuttall's pondweed (*Elodea nuttallii*) in Lough Arrow, a Natura 2000 designated lake in Western Ireland

Darren Garland[1,*], William Earle[1], Joe Caffrey[2], Cian Taylor[1], Sara Meehan[1], Nicolas Touzet[1] and Frances Lucy[1]

[1]*Centre for Environmental Research, Innovation and Sustainability (CERIS), Institute of Technology, Sligo, Ash Lane, Sligo F91 YW50, Ireland*
[2]*Invas Biosecurity Services, 6 Lower Ballymount Road, Walkinstown, Dublin 12, Dublin, Ireland*

**Corresponding author*
E-mail: *darren.garland@mail.itsligo.ie*

Citation: Garland D, Earle W, Caffrey J, Taylor C, Meehan S, Touzet N, Lucy F (2022) Management of the invasive Nuttall's pondweed (*Elodea nuttallii*) in Lough Arrow, a Natura 2000 designated lake in Western Ireland. *Management of Biological Invasions* 13(1): 118–130, https://doi.org/10.3391/mbi.2022.13.1.07

Received: 2 December 2020
Accepted: 8 September 2021
Published: 31 January 2022

Thematic editor: Calum MacNeil

Abstract

A benthic geotextile was used to trial the management of an invasive aquatic macrophyte Nuttall's pondweed (*Elodea nuttallii* (Planch.) H. St. John, 1920) in Lough Arrow, a premier trout angling lake in the north-west of Ireland, designated as a Natura 2000 site (Special Area of Conservation (Annex I habitat, "Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp.") and Special Protection Area for birdlife). The aim of this study was to manage *E. nuttallii*, a relatively recent arrival to this lake, while simultaneously promoting rehabilitation of native charophytes. The trial was carried out in Loughbrick bay, one of the lough's primary boating launch sites, an area determined as highly infested with *E. nuttallii*. Two experimental areas covering a total of 800 m^2 were treated by covering the invasive weed and substrate with jute textile, a single and double layer respectively. The trial was successful in controlling *E. nuttallii* for both single ($P = 0$) and double layer treatments ($P = 0.002$). The treatments applied resulted in a reduction of the mean percentage cover of the invasive species by > 60% for both treatments. Post-treatment mean percentage cover of *E. nuttallii* did not exceed 6% for either treatment. Furthermore, the mean percentage cover of indigenous charophyte flora present pre-treatment was not significantly impacted by the application of jute in either the single ($P = 0.165$) or double treatment ($P = 0.353$). For biosecurity purposes, the treatment areas were strategically positioned in close proximity to the bays pier and slipway. The treated transects were marked with navigational buoys to provide a corridor for boats entering and exiting the lake, which help to contain the invasive within the Natura 2000 site while reducing the spread risk *via* this pathway to other sites vulnerable to infestation.

Key words: macrophytes, jute matting, aquatic invasive species, biosecurity, conservation, EU Habitats Directive, charophytes

Introduction

Invasive alien species are recognised as one of the leading causes of biodiversity loss worldwide, posing a significant threat to aquatic ecosystems (Maguire et al. 2011; Mollot et al. 2017). Aquatic invasive alien plant species (IAPS) are of particular concern due to their capacity to outcompete and displace native flora (Caffrey et al. 2011; Wang et al. 2016).

Elodea nuttallii (Planch.) H. St. John, 1920, an aquatic macrophyte native to North America, introduced to Europe in 1914 (Steen et al. 2019). It has become the fourth most widespread alien aquatic plant in Europe, occurring in 20 countries causing serious problems in several (Hussner 2012). Contemporarily, the species is still spreading in Europe (Thiebaut et al. 2008) and the European Union has listed it as a "Species of Union Concern" under EU Regulation 1143/2014, due to its adverse impacts to native habitats (Zehnsdorf et al. 2015).

The species was first discovered in Ireland in 1984 (Josefsson 2011). The spread of *Elodea nuttallii* within Europe is likely due to both its reproductive mechanism and resistance to desiccation. *Elodea nuttallii* can reproduce asexually *via* fragmentation, which exacerbates local spread (Xie et al. 2010; Josefsson 2011). Furthermore, vegetative fragments can survive for extended periods in terrestrial environments, thus facilitating dispersal to new areas (Barrat-Segretain and Cellot 2007).

Elodea nuttallii commonly invades eutrophic, oligo or mesotrophic waters (Josefsson 2011). Once established, this plant has the capacity to form canopies at the water surface inhibiting the development of other aquatic flora (Barrat-Segretain et al. 2002), thus altering the ecosystem beneath its canopy (European Commission 2017).

In an Irish context, the ecological adaptations of this invasive species poses a significant threat to certain Natura 2000 sites under the European Union's Habitats Directive (92/43/EEC). Most notably, the Annex I habitat "Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp. (3140)".

One of the main features characterising this Annex I habitat is the presence of charophytes (O'Connor 2015), a benthic macroalgae community (Torn et al. 2010) that form dense perennial beds under favourable extrinsic conditions (Stewart and Church 1992; Kufel et al. 2016).

Charophytes thrive in the euphotic zone (Wang et al. 2008) and their distribution is influenced by species specific light requirements (Andrews et al. 1984; Kuster et al. 2004). Unfortunately, where light cannot penetrate the water column, their ecological niche is compromised (Lambert and Davy 2011). Due to this, charophytes are not immune to the negative impacts of canopy-forming invasive alien species (Caffrey et al. 2011) as they are prone to perishing where solar irradiance is inhibited (de Winton et al. 2004). This can potentially facilitate major ecological shifts in aquatic environments (Kelly and Hawes 2005). Notably, changes in the community composition of flora within the biotope (Hussner et al. 2017).

Ireland supports some of the best examples of the "Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp. (3140)" Annex I habitat typology, with a significant proportion of the total European habitat occurring in this geographical region. As a result, Ireland is considered a stronghold for this habitat in a European context, with a particular responsibility in ensuring its favourable conservation (National Parks and Wildlife Service 2019). Currently, this Annex I habitats conservation status is impaired, with IAPS impacts constituting a significant component of the unfavourable conservation evaluation (National Parks and Wildlife Service 2019). Negative ecological impacts, such as those caused by IAPS, can potentially trigger an onus under the Habitats Directive, for member states to introduce "Conservation Measures" to "Restore" the "Favourable Conservation Condition" of an Annex I habitat.

Elodea nuttallii has been found to occur in this Annex I habitat throughout Ireland with significant infestations occurring at certain sites, such as Lough Arrow. Currently, there are no developed *in situ* management options for this invasive species that take into consideration the aforementioned Annex I habitats "Features of Interest".

Invasive macrophytes are primarily managed in aquatic habitats through mechanical methods, as biological and chemical control options are generally restricted (Hoffmann et al. 2013). *Elodea nuttallii* has previously been successfully controlled using jute matting and it is considered a highly efficient method (Zehnsdorf et al. 2015). This is an environmentally friendly, biodegradable geotextile, which acts as a benthic barrier that excludes light inhibiting plant growth (Caffrey et al. 2010; Hoffmann et al. 2013). In addition to controlling invasive macrophytes, this geotextile has been shown to permit the regeneration of charophytes in areas where treatment occurs as they can grow through the small apertures in this benthic barrier (Caffrey et al. 2010, 2011).

This study aimed to trial jute matting as a potential *in situ* management option to control *E. nuttallii* and potentially facilitate the regeneration of *Chara* spp. in a designated Annex I habitat "Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp. (3140)". The study also trialed multiple jute matting set ups *in situ* in order to ascertain which configuration was most suitable in suppressing the invasive while promoting the regeneration indigenous flora. In addition, the applicability of jute matting to aid in the maintenance or restoration of the conservation condition of this Annex I habitat was investigated.

Materials and methods

Study site

Treatment of *E. nuttallii* was conducted in Lough Arrow, a lake situated in the west of Ireland (54°03′36.7″N and 8°19′39.1″W). The lake area is 14.58 km^2 with an average depth of 9 metres (maximum 33 metres) and a secchi depth 3.9 metres (Environmental protection Agency 2020, internal report) (National Parks and Wildlife Service 2015). A Natura 2000 site, it is both a designated Special Area of Conservation (SAC) under the EU Habitats Directive (92/43/EEC) (site code: 001673) and a Special Protection Area under the EU Birds Directive (2009/147/EC) (site code: 004050).

Lough Arrow's SAC designation is based on the presence of a representative example of the "Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp. (3140)" occurring within the lake (National Parks and Wildlife Service 2013). The current conservation condition of the lake is impaired with a classification of "Unfavourable-Poor" under Irelands Article 17 assessment criteria (Roden and Murphy 2020). While it is not known when *E. nuttallii* was first recorded in the lake, it was not present when last surveyed for macrophytes in 2002 (Central Fisheries Board, internal report). Based on its current distribution in the lake, it was probably introduced about ten years before the current trials commenced.

Localised treatment of *E. nuttallii* with biodegradable jute matting was implemented in Loughbrick Bay (54°03′46″N and 8°18′18.16″W), on the eastern side of Lough Arrow. This bay has a pier and slipway, which is utilised for recreational boating. Due to the significant infestation of *E. nuttallii* and the intermittent but high intensity utilisation of the site for brown trout (S*almo trutta*) angling, it was selected for *in situ* treatment trials.

Pre-treatment survey

Three 5 × 80 m long transects perpendicular to the shoreline in Loughbrick Bay were selected for the study. These transects extended through the depth zones where *E. nuttallii* was growing and buoys were utilised to mark the transects prior to surveying. All three transects were similar in terms of depth (max 2.4 metre), slope, benthic texture and macrophyte composition.

The pre-treatment survey (September 2018) utilised ten randomly selected 1 m^2 quadrats per transect. The percentage cover of both *E. nuttallii* and indigenous *Chara* spp. was visually estimated and recorded by divers. Additionally, each sampled quadrat was photographed utilising a GoPro (Hero 4+) for validating *in situ* estimates of percentage cover. Quadrats were placed on the lakebed by scuba divers at each sampling point and GPS positioning was recorded with a Garmin® GPSMAP® 64s. Depth was also recorded at using a Garmin® echoTM101.

Treatment using jute matting

Of the three transects used for the study, one acted as a control while the other two were utilised for treatment. One treatment involved the application of a single layer of jute matting while the other used a double jute layer. The jute matting weighed 0.203 kg/m^2 for a single layer with an aperture size of 2 mm. The double layer of jute matting was created by tying two layers of matting together at their outer edges with wire (1.6 mm diameter, 16 gauge). Treated transects were positioned perpendicular to the shoreline at both the launch point and the entry point of the pier at Loughbrick Bay. The control transect was positioned adjacent to the treated transects perpendicular to the shoreline (Figure 1).

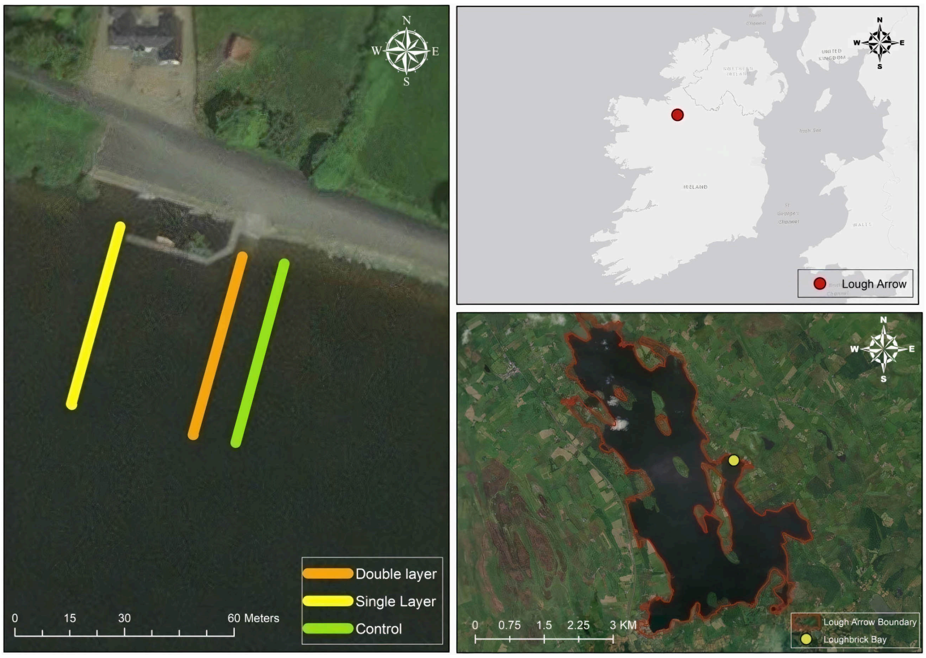

Figure 1. Lough Arrow, location, aerial map and treatment location (Loughbrick Bay). Photo credit: Darren Garland.

Figure 2. Jute mat application in Loughbrick Bay. Photo credit: Darren Garland.

The sections of jute for both the treatment transects were cut from a roll. Additionally, weights were used to anchor the jute to the substrate. 0.5 m^2 sections of jute were cut from a roll and each filled with 2 kilograms of locally sourced pea gravel. The gravel was secured in the jute envelope utilising tying wire. A 30 cm piece of wire was left exposed on each weight to enable divers to stitch weights to the matting *in situ* on the lakebed.

The jute sections were placed perpendicularly to the shoreline at the location of each treatment transect (Figure 1). A 5-metre section of decking

Figure 3. Aerial view of jute mat application in Loughbrick Bay. Photo credit: William Earle.

timber (150 × 50 mm) was wrapped into the first one metre of each jute section. Another 5 metre section of scaffolding timber was secured to the wrapped section of scaffolding timber using carpentry screws. A hole was drilled at the ends of the 5 metre sections of scaffolding timber and rope was tied to each end. This rope was then tied to the stern of an angling boat and the jute was dragged from the shoreline into place (Figure 3). The jute sections were then allowed to saturate and sink to the lake bed. The scaffolding timber was then removed.

Divers ensured the jute was correctly placed and stitched the anchoring weights to the jute at intervals of 5 metres. In the double jute treatment divers stitched both sections of jute together with tying wire as the jute was being drawn from the shoreline.

Post treatment survey

A post-treatment survey of the site was conducted 13 months after the initial treatments took place (October 2019).

The post-treatment survey recorded the percentage cover of *E. nuttallii* and indigenous *Chara* spp. in ten randomly selected 1 m^2 quadrats per transect. Percentage cover estimates were recorded visually by divers. Quadrats were positioned on the lakebed with both the depth (Garmin® echoTM101) and GPS location (Garmin® GPSMAP® 64s) recorded for each sampling point. Additionally, each sampled quadrat was photographed utilising a GoPro (Hero 4+) for validating *in situ* estimates of percentage cover.

Data treatment and analysis

Statistical analysis was conducted using IBM SPSS 26 statistical software. Data collected from each treatment was tested for homoscedasticity and normality to meet the assumptions of the tests applied. A value of $\alpha = 0.05$ was used to denote significance for all tests.

Table 1. Mean % cover (± SE) of *E. nuttallii* for control, single, and double treatments both pre- (September 2018) and post- (October 2019) treatment.

Treatment	Pre-treatment	Post-treatment	*p*-value (* < 0.05)
Control	60.0 ± 10.9	63.5 ± 9.2	1
Single	68.0 ± 12.9	6.0 ± 1.9	< 0.001*
Double	64.0 ± 13.1	3.8 ± 2.9	0.002*

Analysis of the percentage cover data collected utilised a Mann Whitney U test to compare individual treatments effectiveness in both controlling *E. nuttallii* and facilitating *Chara* spp. regeneration. Additionally, the significant differences between the control, single- and double-layer jute matting treatments were determined through the utilisation of Kruskal Wallis tests for both *Chara* spp.and *E. nuttallii* pre- and post-treatment. Post hoc Mann-Whitney pairwise multiple comparisons adjusted by Bonferroni correction were utilised to determine differences between each individual treatment pair, where a significant difference was observed.

Results

Analysis of the percentage cover of *E. nuttallii* showed no significant difference in the control transect between pre- and post-treatment (P = 1). The treated transects, however, both showed a significant difference in *E. nuttallii* percentage cover between pre- and post-treatment. The mean percentage cover from the single jute layer treatment fell significantly from 68% to 6% pre- and post-treatment (P = < 0.001), while that for the double layer was significantly reduced, from 64% and 3.8% (P = 0.002) (Table 1).

The cross comparison of each individual treatment for *E. nuttallii* cover determined there was no significant difference between the control and both jute transects pre-treatment (P = 0.654). Post-treatment analysis determined the control was significantly different from both the single and double layer of jute (P = < 0.001), while the double and the single layer treatments showed no significant difference in *E. nuttallii* cover post-treatment (P = 0.603) (Figure 4, Table 2).

Chara spp. percentage cover was not significantly different for the control, single and double jute matting transects between pre- and post-treatment, with P values of 0.912, 0.165 and 0.353, respectively (Figure 5) (Table 3). Furthermore, no significant difference was observed between the control, single and double jute matting treatment comparison in both the pre (P = 0.394) and post (P = 0.219) treatment surveys.

Discussion

Natura 2000 sites represent some of Europe's most important natural areas. The overarching objective of this ecological network is to protect Europe's vulnerable habitats and species (Guerra et al. 2018). However, invasive alien plant species are of increasing concern as they are a frequently recognised pressure on ecosystems in Europe with the potential to impair

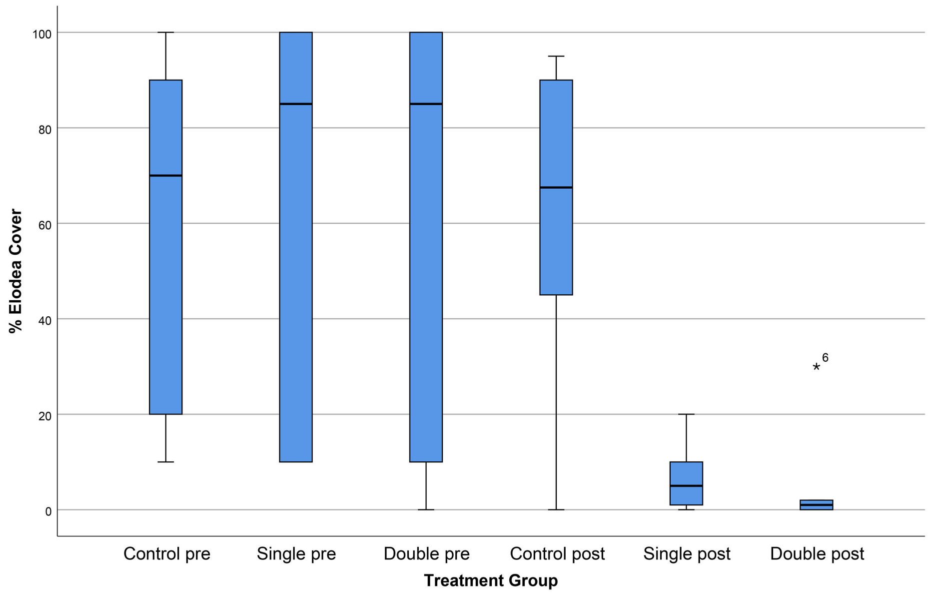

Figure 4. Boxplot of *E. nuttallii* % cover from control, single and double jute matting treatments pre and post application.

Table 2. Comparison of *E. nuttallii* % cover across the different post-treatment groups. P values (* < 0.05) were obtained by Mann-Whitney pairwise multiple comparisons test, adjusted by Bonferroni correction.

	Post-Treatment		
Groups	Control	Single	Double
Control	–	0.037*	< 0.001*
Single	0.037*	–	0.603

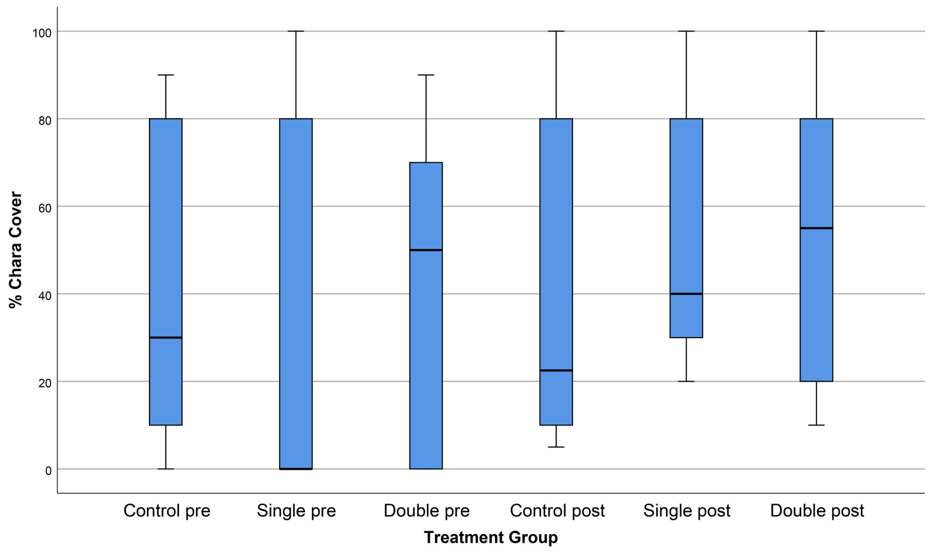

Figure 5. Boxplot of *Chara* spp. % cover from control, single and double jute matting treatments pre and post application.

Table 3. Mean % cover (± SE) of *Chara* spp. for control, single, and double treatments both pre- (September 2018) and post- (October 2019) treatment.

Treatment	Pre-treatment	Post-treatment	p-value (*< 0.05)
Control	39.0 ± 10.8	40.5 ± 12.4	0.912
Single	35.0 ± 14.4	55.0 ± 10.0	0.165
Double	41.0 ± 11.8	54.5 ± 10.1	0.353

the conservation status of Annex I habitats (Dimitrakopoulos et al. 2017; Perzanowska et al. 2019). Furthermore, they have been noted to be impacting the designated Annex I habitat utilised in this study at a national level (National Parks and Wildlife Service 2019).

Lough Arrow's conservation condition is impaired due to a number of pressures impacting its features of interest which include IAPS, primarily *E. nuttallii* (Roden and Murphy 2020). Due to the obligations of the Habitats Directive, member states are required to adopt and implement conservation measures to ensure the favourable conservation status of Natura 2000 sites. In the case of *E. nuttallii*, it is also listed in the IAS list of Union concern and as such, EU member states are obliged to prevent its spread (Steen et al. 2019).

This trial effectively suppressed the growth of *E. nuttallii* with both treatments providing similar and significant control, with negligible differences between single and double layer treatments. This indicates that a single layer of geotextile can suppress *E. nuttallii*. The results of this trial present a *circa.* 60% reduction in mean *E. nuttallii* cover for both treatments, similar to those observed in a study conducted by Hoffmann et al. (2013) (50%–75% reduction). Hoffmann et al. (2013) utilised a heavier textile (weight – 0.3 kg/m^2, mesh size – 0.5 mm) for field trials, while the current treatment successfully controlled *E. nuttallii* with a lighter textile (weight – 0.203 kg/m^2, mesh size – 2 mm).

Hoffmann et al. (2013) conducted trials to compare 2, 1 and 0.5 mm aperture sizes and found the heavier jute with a smaller aperture to be more effective in controlling the IAPS in a laboratory setting. The laboratory study formed the basis for the selection of textile composition for *in situ* trials. In comparison, the lighter geotextile with a larger aperature size utilised in this study successfully suppressed *E. nuttallii*, furthermore, it suppressed the IAPS for a duration similar to that observed by Hoffmann et al. (2013). The post-treatment surveys were conducted 13 months after the application of the benthic geotextile and the matting was still intact, with greatly reduced cover of *E. nuttallii.* Hoffmann et al. (2013) observed intact textile suppressing *E. nuttallii* 15 months after the placement in one of their treatment sites. Due to the similar *in situ* effects of both geotextiles, the implementation of lighter jute would reduce the costs incurred in implementing control measures utilising jute matting. In addition, a lighter geotextile is easier to prepare, transport and manoeuvre in the water column by personnel carrying out *in situ* control measures.

Charophytes, the feature of interest for the Annex I habitat where *in situ* trials occurred, are considered pioneers, as their oospore bank facilitates their prompt recolonisation of rehabilitated habitats (Harwell and Havens 2003; Schneider et al. 2015). Despite this trait of the taxonomic group, in conjunction with the trials overall success in controlling *E. nuttallii*, a significant increase in *Chara* spp. cover was not observed in the post-treatment surveys in comparison to pre-treatment surveys. Furthermore, neither treatment differed in relation to *Chara* spp. regeneration. However, *Chara* spp. were observed growing through both the single and double layers of jute and their cover was not negatively impacted due to the application of jute.

In comparison to other studies, Hoffmann et al. (2013) observed the regeneration of indigenous *Chara* spp. after the suppression of *E. nuttallii* in a German lake. Caffrey et al. (2010) also noted the regeneration capacity of *Chara* spp. under jute matting on Lough Corrib, a lake situated in the same geographical region as L. Arrow. Caffrey et al. (2010) observed significant regeneration in certain transects where *Chara* spp. cover exceeded 70% post-treatment. However, in some treated areas no *Chara* spp. cover was observed post-application. It must be noted that there was no *Chara* spp. cover data collected prior to application by Caffrey et al. (2010), so areas where regeneration may not have occurred may be due to other factors instead of the impacts of an invasive macrophyte. As this study utilised a geotextile with the same specifications as applied by Caffrey et al. (2010), it can be assumed that *Chara* spp. regeneration is not restricted by the geotextile but rather facilitated due to its suppression of IAPS. Invasive species are one of a number of factors negatively impacting this Annex I habitat, with water quality often cited as a main driver for degradation (National Parks and Wildlife Service 2019). A condition assessment of L. Arrow conducted by Roden and Murphy (2020) suggested water quality in conjunction with other factors such as IAPS may be impairing the ecological condition. This indicates that other extrinsic factors may explain why there was not a significant increase in *Chara* spp. cover in post-treatment surveys but rather a recolonisation of similar cover levels observed prior to treatment. Furthermore, the significant infestation of *E. nuttallii* prior to treatment is indicative of habitat degradation as these species are known for their ability to prosper in disturbed habitats (Dimitrakopoulos et al. 2017).

Multiple management methods can be implemented to control aquatic plants. However, the approach taken to control an invasive plant should be appropriate for the infestation occurring and the respective water body where the problem occurs (Thiebaut et al. 2008). Jute matting provides an ideal control measure for *E. nuttallii* in the Annex I habitat "Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp. (3140)". This study observed no impacts on indigenous flora of conservation importance in this SAC while a significant reduction in *E. nuttallii* was achieved. Other methods commonly applied to control *E. nuttallii* such as herbicides, sediment dredging, cutting and water level drawdown are generally "not species specific" and they all have their ecological disadvantages (Zehnsdorf et al. 2015), some of which may negatively impact the Annex I habitats features of interest. Furthermore, the geotextile utilised in this trial is considered a cost-effective control measure in comparison to other control options available for invasive macrophytes (Caffrey et al. 2010). However, cost effectiveness is dependent on scale and resources. *Elodea nuttallii* control has been noted to be a costly exercise, primarily due to their capacity to heavily infest vast waterbodies. Thus, the prevention of its colonisation to new areas is considered paramount (Steen et al. 2019).

Ordinarily, containment measures have been implemented to control IAS from spreading to new areas (Hussner et al. 2017). Anthropogenic activities such as boating have been highlighted to aid the spread of IAPS, both within an infested site and between waterbodies via fragments created and/or subsequently attached to boats (Cole et al. 2018; Steen et al. 2019). This recreational activity has been cited as an important dispersal pathway for *E. nuttallii* (Josefsson 2011) primarily due to its ease of dispersal and its capacity to form canopies at the water surface where interactions with boats are highly likely.

Due to the success of the trials and the strategic placement of the control measures, navigational markers were placed either side of the treated transects. This provided a pathway for boats entering and exiting the lake which potentially mitigates the spread of *E. nuttallii in situ* and minimises the potential spread of this invasive to new sites. The success of these containment measures indicates that jute matting could potentially be applied to other SACs with infestations of *E. nuttallii* as a containment measure where full lake control is not a feasible option. Furthermore, where intensive control is applied at a site wide level, jute matting is an effective control option which does not negatively impact this Annex I habitat types features of interest and is cost effective in comparison to other weed management methods.

The success of this trial in controlling *E. nuttallii* and insignificantly altering *Chara* spp. cover warrants further research to fully understand the dynamics of *Chara* spp. regeneration capacity and *E. nuttallii* suppression under different jute matting configurations.

This trial did not take into consideration the *Chara* spp. cover in treatment transects prior to the initial introduction of *E. nuttallii.* Furthermore, this study did not fully delineate other factors determining *Chara* spp. prevalence in the biotope, in particular water quality.

Further studies which utilise infested sites where there is historical data on *Chara* spp. cover and where water quality parameters have not changed significantly in the interim since establishment of the invasive would be beneficial in trialling further jute matting configurations. This could help to determine which type of jute matting provides the most cost-effective and manageable balance between suppression of the invasive and regeneration of indigenous *Chara* spp. If delineated, this control mechanism may prove to be a crucial management tool in this Annex I habitats restoration where conservation condition impairment has occurred due to *E. nuttallii* infestation. This research can be used as an IAPS management case study to provide both scientific and financial information for risk assessments of existing and proposed invasive alien freshwater aquatic plants of EU concern.

Acknowledgements

The research was made possible by funding received from Intereg Europe for the provision of the Collaborative Actions for the Natura Network (CANN) project, managed by the Special European Union's Programme Body. The project team would also wish to acknowledge the assistance provided for this research from Inland Fisheries Ireland staff (IFI). In particular, Jimmy Frazier and Ciaran Jennings, stationed in Lough Arrows IFI depot who provided expert advice in relation to the IAPS in the lake and provided on site assistance over the course of this research. The authors would also like to acknowledge the external reviewers who provided invaluable feedback over the course of the reviewing process for this manuscript.

Funding declaration

Funding for this Research was provided to the Institute of Technology, Sligo by the INTERREG VA programme, for the Collaborative Actions for the Natura Network project. The CANN project is a cross-border environment project which aims to improve the condition of protected habitats and to support priority species found within Northern Ireland, the Border Region of Ireland and Scotland, allowing the region to meet key EU biodiversity targets and ensuring the future of these internationally important habitats and species. This project is managed by the Special European Union's Programme (SEUPB) body. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Authors' contribution

The research was conceptualised by CERIS, IT Sligo (Frances Lucy, Sara Meehan and Darren Garland) who obtained funding for the purposes of this research study. The experiment was designed by INVAS biosecurity (Joe Caffrey and William Earle) and IT Sligo (Sara Meehan, Frances Lucy and Darren Garland). Experimental set up was carried out by IT Sligo (Darren Garland) and INVAS biosecurity (William Earle and Joe Caffrey) who also conducted *in situ* data collection. Data analysis and interpretation was carried out by IT Sligo (Darren Garland and Cian Taylor). Figures for the purposes of this manuscript were obtained by INVAS Biosecurity and IT Sligo (William Earle, Darren Garland and Cian Taylor). The original draft manuscript was prepared by Darren Garland and William Earle. Reviewing authors included Sara Meehan, Joe Caffrey, Cian Taylor, Nicolas Touzet, Frances Lucy. Further editing was conducted by William Earle, Darren Garland, Frances Lucy and Joe Caffrey. All authors contributed to Final submission.

References

Andrews M, Box R, Mcinroy S, Raven J (1984) Growth of *Chara hispida*: II. Shade Adaptation. *Journal of Ecology* 72: 885–895, https://doi.org/10.2307/2259538

Barrat-Segretain M, Cellot B (2007) Response of invasive macrophyte species to drawdown: The case of *Elodea* spp. *Aquatic Botany* 87: 255–261, https://doi.org/10.1016/j.aquabot.2007.06.009

Barrat-Segretain M, Elger A, Sagnes P, Puijalon S (2002) Comparison of three life-history traits of invasive *Elodea canadensis* Michx. and *Elodea nuttallii* (Planch.) H. St. John. *Aquatic Botany* 74: 299–313, https://doi.org/10.1016/S0304-3770(02)00106-7

Caffrey J, Millane M, Evers S, Moran H, Butler M (2010) A novel approach to aquatic weed control and habitat restoration using biodegradable jute matting. *Aquatic Invasions* 5: 123–129, https://doi.org/10.3391/ai.2010.5.2.01

Caffrey J, Millane M, Evers S, Moran S (2011) Management of *Lagarosiphon major* (Ridley) Moss in Lough Corrib - A Review. *Biology and Environment: Proceedings of the Royal Irish Academy* 111B: 205–212, https://doi.org/10.3318/BIOE.2011.16

Cole E, Keller R, Garbach K (2018) Risk of invasive species spread by recreational boaters remains high despite widespread adoption of conservation behaviors. *Journal of Environmental Management* 229: 112–119, https://doi.org/10.1016/j.jenvman.2018.06.078

de Winton M, Casanova M, Clayton J (2004) Charophyte germination and establishment under low irradiance. *Journal of Aquatic Botany* 79: 175–187, https://doi.org/10.1016/j.aquabot.2004.01.013

Dimitrakopoulos P, Koukoulas S, Galanidis A, Delipetrou P, Gounaridis D, Touloumi K, Arianoutsou M (2017) Factors shaping alien plant species richness spatial patterns across Natura 2000 Special Areas of Conservation of Greece. *Science of The Total Environment* 601–602: 461–468, https://doi.org/10.1016/j.scitotenv.2017.05.220

European Commission (2013) Interpretation Manual of European Habitats. DG Environent, Brussels Belgium, 146 pp

European Commission (2017) Invasive Alien Species of Union Concern. Publications Office of the European Union, Luxemborg, 36 pp

Guerra C, Baquero R, Gutiérrez-Arellano D, Nicola G (2018) Is the Natura 2000 network effective to prevent the biological invasions? *Global Ecology and Conservation* 16: e00497, https://doi.org/10.1016/j.gecco.2018.e00497

Harwell M, Havens K (2003) Experimental studies on the recovery potential of submerged aquatic vegetation after flooding and desiccation in large subtropical lake. *Journal of Aquatic Botany* 77: 135–151, https://doi.org/10.1016/S0304-3770(03)00101-3

Hoffmann M, Gonzalez B, Raeder U, Melzer A (2013) Experimental weed control of *Najas marina* ssp. *intermedia* and *Elodea nuttallii* in lakes using biodegradable jute matting. *Journal of Limnology* 72: 485–493, https://doi.org/10.4081/jlimnol.2013.e39

Hussner A (2012) Alien aquatic plant species in European countries. *Weed Research* 52: 297–306, https://doi.org/10.1111/j.1365-3180.2012.00926.x

Hussner A, Stiers I, Verhofstad M, Bakker E, Grutters B, Haury J, Hofstra D (2017) Management and control methods of invasive alien freshwater aquatic plants: A review. *Aquatic Botany* 136: 112–137, https://doi.org/10.1016/j.aquabot.2016.08.002

Josefsson M (2011) NOBANIS - Invasive Species Fact Sheet - Elodea canadensis, *Elodea nuttallii* and *Elodea callitrichoides.* Online Database of the European Network on Invasive Alien Species (NOBANIS), http://www.nobanis.org (accessed 24 July 2020)

Kelly D, Hawes I (2005) Effects of invasive macrophytes on littoral-zone productivity and foodweb dynamics in a New Zealand high-country lake. *Journal of North American Benthological Society* 24: 300–320, https://doi.org/10.1899/03-097.1

Kufel L, Kufel I (2002) *Chara* beds acting as nutrient sinks in shallow lakes - a review. *Journal of Aquatic Botany* 72: 249–260, https://doi.org/10.1016/S0304-3770(01)00204-2

Kufel L, Strzalek M, Biardzka E (2016) Site and species specific contribution of charophytes to calcium and phosphorus cycling in lakes. *Journal of Hydrobiologia* 767: 185–195, https://doi.org/10.1007/s10750-015-2498-4

Kuster A, Schaible R, Schubert H (2004) Light acclimation of photosynthesis in three charophyte species. *Journal of Aquatic Botany* 79: 111–124, https://doi.org/10.1016/j.aquabot.2004.01.010

Lambert S, Davy A (2011) Water Quality as a threat to aquatic plants: discriminating between the effects of nitrate, phosphate, boron and heavy metals on charophytes. *New Phytologist* 189: 1051–1059, https://doi.org/10.1111/j.1469-8137.2010.03543.x

Maguire C, Gallagher K, Maggs C, Dick J, Caffrey J, O'Flynn C, Fitzpatrick U, Kelly J, Harrod C (2011) Alien invasive species in Irish water bodies: Strive End of Project Report. Environmental Protection Agency, Johnstown Castle, Co., Wexford, Ireland, 44 pp

Mollot G, Pantel J, Romanuk T (2017) The Effects of Invasive Species on the Decline in Species Richness. *Advances in Ecological Research* 56: 61–83, https://doi.org/10.1016/bs.aecr.2016.10.002

National Parks and Wildlife Service (2013) Site Synopsis: Lough Arrow SAC (001673). Department of Arts, Heritage and the Gaeltacht, Dublin, Ireland, 2 pp

National Parks and Wildlife Service (2015) Natura 2000 Standard Data Form: Lough Arrow SAC (001673). Department of Arts, Heritage and the Gaeltacht, Dublin, Ireland, 5 pp

National Parks and Wildlife Service (2019) The Status of EU Protected Habitats and Species in Ireland. Habitats Assessments, Volume II, Department of Arts, Heritage and Gaeltacht, Dublin, Ireland, 1128 pp

O'Connor A (2015) Habitats Directive Annex I lake habitats: a working interpretation for the purposes of site specific conservation objectives and Article 17 reporting, National Parks and Wildlife Service, Department of Arts, Heritage and Gaeltacht, Dublin, Ireland, 85 pp

Roden C, Murphy P (2020) Sub littoral vegetation of Lough Arrow in 2019. Report to the INTERREG VA CANN project. Sligo, Ireland, 20 pp

Schneider S, Garcia A, Closas C, Chivas A (2015) The role of charophytes in past and present environments: An overview. *Journal of Aquatic Botany* 120: 2–6, https://doi.org/10.1016/j.aquabot.2014.10.001

Steen B, Cardoso A, Tsiamis K, Nieto K, Engel J, Gervasini E (2019) Modelling hot spot areas for the invasive alien plant *Elodea nuttallii* in the EU. *Management of Biological Invasions* 10: 151–170, https://doi.org/10.3391/mbi.2019.10.1.10

Stewart N, Church J (1992) Red Data Books of Britain and Ireland: Stoneworts. 1st Ed. Joint Nature Conservation Committee, Monkstone House, City Road, Peterborough, UK, 197 pp

Thiebaut G, Di Nino F, Peltre M, Wagner P (2008) Management of Aquatic Exotic Plants: The Case of *Elodea* Species. In: Sengupta M, Dalwani R (eds), The 12th World Lake Conference. Taal, pp 1058–1066

Torn K, Martin G, Kotta J, Kupp M (2010) Effects of different types of mechanical disturbances on a charophyte dominated macrophyte community. *Journal of Estuarine, Coastal and Shelf Science* 87: 27–32, https://doi.org/10.1016/j.ecss.2009.12.006

Wang H, Yu D, Xiao K (2008) The interactive effects of irradiance and photoperiod on *Chara vulgaris* L.: concerted responses in morphology, physiology and reproduction. *Journal of Hydrobiology* 610: 33–41, https://doi.org/10.1007/s10750-008-9420-2

Wang H, Wang Q, Bowler P, Xiong W (2016) Invasive aquatic plants in China. *Aquatic Invasions* 11: 1–9, https://doi.org/10.3391/ai.2016.11.1.01

Xie D, Yu D, Yu L, Liu C (2010) Asexual propagations of introduced exotic macrophytes *Elodea nuttallii*, *Myriophyllum aquaticum*, and *M. propinquum* are improved by nutrient-rich sediments in China. *Hydrobiologia* 655: 37–47, https://doi.org/10.1007/s10750-010-0402-9

Zehnsdorf A, Hussner A, Eismann F, Rönicke H, Melzer A (2015) Management options of invasive *Elodea nuttallii* and *Elodea canadensis*. *Limnologica - Ecology and Management of Inland Waters* 51: 110–117, https://doi.org/10.1016/j.limno.2014.12.010