Cabomba caroliniana *is an aquatic perennial herbaceous plant native to North and South America.*

The management of fanwort (*Cabomba caroliniana*)

Measures and associated costs

Scientific name(s)	*Cabomba caroliniana* A. Gray
Common names (in English)	Fanwort
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Common names

BG	Каролинска кабомба
HR	Kabomba
CZ	Chebule karolínská
DA	Carolina cabomba
NL	Waterwaaier
EN	Fanwort
ET	Karoliina näkijuus
FI	Karkeaviuhkalehti
FR	Cabomba de Caroline
DE	Karolina-Haarnixe
EL	–
HU	Karolinai tündérhínár
IE	Feanlus
IT	Cabomba della Carolina
LV	–
LT	Paprastasis labūstras
MT	Il-kabomba
PL	Kabomba karolińska
PT	Cabomba-verde
RO	–
SK	Kabomba karolínska
SL	Zelena kabomba
ES	Ortiga acuática
SV	Kabomba

Summary of the measures, emphasizing the most cost-effective options.

Cabomba caroliniana A.Gray (Cabombaceae) is a submersed aquatic macrophyte native to freshwaters of South and North America (Ørgaard, 1991). It is a popular aquarium species that has been introduced to the wild worldwide through unintentional disposal of surplus aquarium material and escape from culture for the trade. Today, it is a serious aquatic invasive species in many countries including Australia, USA (outside its native range), Canada, China and some European countries (for example the Netherlands and Germany) (Ørgaard, 1991; Les and Mehrhoff, 1999; EPPO, 2007; Wilson *et al.*, 2007; van Valkenburg *et al.*, 2011; Hussner, 2012; McCracken *et al.*, 2013). Another *Cabomba* species, *Cabomba furcata*, is altering wetland ecosystems in Malaysia (Sharip *et al.*, 2012).

C. caroliniana can be found in a range of freshwater systems, but prefers still to slow moving waters (Ørgaard, 1991). Water clarity permitting, it can grow to considerable depths, but biomass is highest at 2–4 m (Bickel and Schooler, 2015). *C. caroliniana* readily grows from small stem fragments comprising only a single node and predominantly reproduces asexually in its introduced range (Bickel, 2016). While *C. caroliniana* can flower prolifically, seed production is rarely observed in its introduced range (Mackey and Swarbrick, 1997). However, even in its native range, seed production is low (Ørgaard, 1991).

The history of the *C. caroliniana* invasion in Australia is an example of the potential of this plant for rapid spread and to become a significant aquatic weed. It was first recorded in Australia in 1967 and is today naturalised in four states (Victoria, New South Wales, Queensland and the Northern Territory), with populations spanning the entire eastern half of the continent from temperate to tropical regions (Mackey and Swarbrick, 1997; Schooler *et al.*, 2006). It is considered a Weed of National Significance in Australia and considerable amount of financial effort and manpower is spent annually for management of this aquatic invader.

C. caroliniana is currently not widely naturalised in the EU, but populations are present or have been recorded in Belgium, Croatia, Denmark, France, Germany, Hungary, the Netherlands, Poland, Romania, Serbia, Sweden and the UK (EPPO, 2007; Hussner *et al.*, 2010; Hussner, 2012; EASIN, 2019). The most detailed published information about *C. caroliniana* invasion and management in the EU comes from the Netherlands, where it was first recorded in 1986 (Matthews *et al.*, 2013), but did not become problematic until 2005 (van Valkenburg *et al.*, 2011).

Cabomba caroliniana is legally prohibited to be imported, cultivated and traded under EU legislation. However, *C. caroliniana* was well established in the aquarium hobby for many decades (EPPO, 2006, 2007) and therefore it is likely that the plant is still cultivated in private aquaria and passed on between hobbyists. In addition, there are several *C. caroliniana* cultivars known in aquarium hobby circles, so the possibility that enthusiasts could illegally introduce and move specific cultivars within and from outside the EU cannot be excluded. Enforcement will be important.

As *Cabomba* species are morphologically difficult to distinguish unless flowering (Ørgaard, 1991), *C. caroliniana* can be incorrectly identified as *C. aquatica* or *C. furcata*, and unintentionally introduced into the EU (Matthews *et al.*, 2013). Even for experts, the *Cabomba* species are difficult to distinguish unless flowering, therefore it is very difficult to prevent accidental importation of *C. caroliniana* through morphological screening of *Cabomba* material imported to the EU. Additional training of customs officials at borders on identification of these species is needed and, once DNA-barcoding techniques can be carried out routinely by non-specialists, this technique could also be used.

The rapid spread and potential to become a serious aquatic weed highlights the importance of containment and management of existing populations of this species in the EU. As *C. caroliniana* has been a weed worldwide, there is a range of control options available that have successfully been used. In general, no single method is superior in the control of aquatic invasive plants, but they all have their strengths and limitations, and have to be used within the right context (for example management goals, scale) (for example Hussner *et al.*, 2017). Furthermore, experience shows that the integration of various tools greatly improves aquatic plant control. The choice of control methods used to manage *C. caroliniana* in EU member states will be similar to options for other submersed aquatic weeds, but specific control tools and costs will always be situation and location dependent. Therefore, the control options, their costs and limitations described in this document are only intended as a reference. A detailed management plan needs to be developed for individual infestations to increase control efficiency and chance of success.

Due to the difficulty of controlling fanwort once it is established, containment of existing populations and prevention of further spread is critical. Containment can be achieved through user access restrictions, strategic control of *C. caroliniana* to reduce the risk of fragment uptake and transport, the provision of weed hygiene facilities and public awareness campaigns. Similarly, early detection of new invasions is critical. This can be achieved through active government surveillance in high risk areas and through citizen-science monitoring programs. Early detection of new infestations will increase the chance of eradication when populations are still small. Herbicides are effective in controlling *C. caroliniana*, but due to the legal restrictions prohibiting the use of herbicides in aquatic habitats in the EU, other control methods listed in this document need to be selected. Choice of control method mainly depends on the size of the infestation and the local situation. Small populations can be removed manually through divers or by mechanical means, for example suction dredging. Once fully established in larger systems, maintenance and prevention of spread can be achieved through the application of mechanical mowers, harvesters and strategic manual harvesting, or the installation of physical barriers such as benthic blankets. Currently, there are no biological control options available, but these could complement management in the future, the use of grass carp could be a useful tool to manage *C. caroliniana*.

This review of *C. caroliniana* control options is not exhaustive. Further methods are described in the literature that could become novel tools, such as the example of pH manipulation through the addition of lime (liming). The pH of water determines the chemical form in which carbon is available for photosynthesis. *C. caroliniana* depends on free CO_2 for photosynthesis, which is only available sufficiently in neutral to acidic water. Experimental work found significant biomass reduction in *C. caroliniana* when the pH in aquaria was elevated to pH 9–10 by addition of lime (James, 2011). The environmental effects of elevating the pH to such high levels in a natural water body would have to be weighed against any benefits of removal. However, even an elevation of the pH to 8 might be enough to reduce the competitive advantage of *C. caroliniana* and thus potentially reduce its abundance (Bickel and Perrett, 2014). The rapid advance in DNA technologies also means that in the near future there might be routine tools available for rapid species identification through DNA-barcoding on border entry points (Ghahramanzadeh *et al.*, 2013) and eDNA methods for the detection of *C. caroliniana* in the environment (Edmunds and Burrows, 2019). The availability of eDNA techniques would be invaluable for monitoring to prevent spread and reappearance post treatment.

Measures for preventing the species being introduced, intentionally and unintentionally.

This section assumes that the species is not currently present in a Member State, or part of a Member State's territory.

A ban on importing (pre-border measure), selling, breeding, growing, and cultivation, as required under Article 7 of the IAS Regulation, targeting intentional introduction of plants and propagules of *C. caroliniana*.

MEASURE DESCRIPTION

As the species is listed as an invasive alien species of Union concern, the following measures will automatically apply, in accordance with Article 7 of the EU IAS Regulation 1143/2014:

Invasive alien species of Union concern shall not be intentionally:

(a) brought into the territory of the Union, including transit under customs supervision;
(b) kept, including in contained holding;
(c) bred, including in contained holding;
(d) transported to, from or within the Union, except for the transportation of species to facilities in the context of eradication;
(e) placed on the market;
(f) used or exchanged;
(g) permitted to reproduce, grown or cultivated, including in contained holding; or
(h) released into the environment.

Also note that, in accordance with Article 15(1) – As of 2 January 2016, Member States should have in place fully functioning structures to carry out the official controls necessary to prevent the intentional introduction into the Union of invasive alien species of Union concern. Those official controls shall apply to the categories of goods falling within the Combined Nomenclature codes to which a reference is made in the Union list, pursuant to Article 4(5).

Therefore measures for the prevention of intentional introductions do not need to be discussed further in this technical note.

Mislabelled *Cabomba* plants.

MEASURE DESCRIPTION

Both *C. aquatica* and *C. furcata* are still available in the aquarium trade and can legally be imported to the EU. As even for experts, *Cabomba* species are morphologically difficult to distinguish unless they are flowering (Ørgaard, 1991), *C. caroliniana* can be unintentionally introduced when incorrectly identified as *C. aquatica* (Aubl.), or to a lesser degree, *C. furcata* (Schult. and Schult.f.; the synonym *C. piauhyensis* is still widely used by aquarists) (Matthews *et al.*, 2013).

It is unlikely that customs staff could distinguish between these species, in particular as material intended for aquaria would not be flowering, so additional training of officials at borders on identification of these species is needed. *Cabomba* species can be distinguished through DNA-barcoding (Ghahramanzadeh *et al.*, 2013). So, once DNA-barcoding techniques can be carried out routinely by non-specialists this technique could be employed to detect the unintentional introduction of *C. caroliniana*.

Compliance monitoring in the aquarium trade, as well as education of the general public, could be beneficial to prevent the sale and buying of mislabelled *Cabomba* species.

SCALE OF APPLICATION

Local control of unintentional import of mislabelled plants at entry points to the EU. Dissemination of information on a national/EU scale through suitable outlets.

EFFECTIVENESS OF MEASURE

Neutral.

Cabomba species are difficult to distinguish unless flowering, so border inspections for mislabelled unintentional introductions are likely not effective. However, if the use of DNA-barcoding techniques is implemented in the future, this measure could become effective. Nevertheless, given that *C. caroliniana* is already present or established in several EU Member States, this measure is not as critical as prevention of EU internal spread, as detailed in subsequent sections (author's opinion).

There is no published information available on the effectiveness of education provided to the general public, but considering the relatively low cost of such measures even a small gain in public perception would be justifiable.

EFFORT REQUIRED

Customs controls and training of staff have to be applied indefinitely.

RESOURCES REQUIRED

Suitable training of customs staff; in the future, resources for the application of DNA-barcoding; volunteer scientists that write articles for aquarium magazines or present talks at conventions could be very useful.

SIDE EFFECTS

Environmental: Positive
Social: Positive
Economic: Neutral or mixed

Additional training of customs officials could result in additional invasive species being detected. Education of the general public results in positive social and environmental effects, due to changes in attitude towards invasive species in general.

ACCEPTABILITY TO STAKEHOLDERS

Acceptable.

Stakeholders would not be affected by routine inspections of plant material, as this would be standard customs practice. Dissemination of information in the aquarium hobby about the impacts of invasive aquatic plants is appreciated by most aquarium enthusiasts (pers. obs.).

ADDITIONAL COST INFORMATION

Invasive aquatic plants can cause significant ecological, societal and economic impacts and, once plants are established, management costs are significant and require a long term financial commitment. Therefore, the cost of inaction can far outweigh the cost of preventing introductions and spread.

LEVEL OF CONFIDENCE[1]

Inconclusive.

There is no published information about the effectiveness of customs inspections to detect mislabelling of *Cabomba* species or the effectiveness of public education. Therefore, information on this section is based on the author's personal experience and opinion.

1 See Appendix

Measures to prevent the species spreading once they have been introduced.

Manage unintentional human-mediated transport.

MEASURE DESCRIPTION

Similar to other aquatic invasive plants, *C. caroliniana* propagates predominantly asexually through regeneration of stem fragments (Bickel, 2015, 2016). *C. caroliniana* stem fragments have a high regeneration ability (a fragment consisting of a stem portion with a single node is sufficient; Bickel, 2016) and are resistant to desiccation, therefore there is a high risk of spread of this species when fragments are transported between water bodies (Bickel, 2015). The unintentional transport of aquatic plants through boating and fishing activities is well documented for aquatic plant invaders (Johnstone *et al.*, 1985; Johnson *et al.*, 2001). Therefore, management of public access to water bodies with known infestations, prevention of fragment uptake by water craft and fishing equipment and the raising of public awareness about weed hygiene are critical for containment of this species.

Ideally, public access to known infestations is restricted to prevent unintentional transport of fragment material. However, this is often socially not acceptable to the multitude of recreational water body users such as fishermen, kayakers or swimmers (pers. obs.; J. Clayton, NIWA, pers. comm.). Therefore, a reduction of the risk of fragment uptake by water sport equipment is advisable, through the implementation of effective biosecurity measures, such as those recommended by the campaign Check, Clean, Dry and those highlighted below.

The risk of establishment of an aquatic invader in a new habitat is a probabilistic process that consists of several discreet steps (for example uptake, transport, survival, regeneration, colonisation) that each have their own statistical probability. As the probabilities are multiplicative, even a reasonable decrease in any of the risks can have a profound effect for the overall probability of establishment (Johnston, pers. comm.). The risk of uptake is the only process that can realistically be controlled through water body management. This can be achieved through complete removal or a reduction of the *C. caroliniana* extent from the vicinity of water craft launch areas and areas of high recreational use, for which the control method used will depend on the local circumstances (see detailed control methods in the following sections). The objective is to create a *C. caroliniana* free zone around access points (for example a 20 m radius, but this is site specific and depends on traffic) and to a water depth (such as maintain *C. caroliniana* at a depth that creates a weed free water column) that prevents water craft and launching equipment (trailers) to come into contact with possible fragments. Additionally, the installation of wash-down facilities near boat ramps can be beneficial, as they allow users to clean off aquatic weeds before transport (Hippolite *et al.*, 2018). The efficacy of wash-down facilities and general weed hygiene and other biosecurity measures is strongly dependent on public awareness, so these measures should be coupled with strong public awareness campaigns. Apart from physically washing boats and trailers with water only, steam treatments and aquatic disinfectants are another option to improve weed hygiene (Anderson *et al.*, 2015; Cuthbert *et al.*, 2018; Crane *et al.*, 2019).

To prevent movement of plant material within a catchment, floating booms can be installed. The efficacy of booms is highly dependent on regular monitoring and maintenance. Booms are not effective in fast flowing water. The planting of reed beds that act as natural barriers for *C. caroliniana* fragments has been successfully employed below the spillway of a reservoir (Ewen Maddock Dam) in Australia (van Oosterhout, 2009). Booms have also been installed as part of the Darwin River *C. caroliniana* eradication programme to prevent downstream dispersal (Northern Territory Government, 2008).

SCALE OF APPLICATION

This measure should be applied to all water bodies containing populations of *C. caroliniana*.

For local or entire exclusion of recreational users from water bodies, the exclusion zone depends on the extent of the infestation. For local clearance of *C. caroliniana* from high use access points, the area that needs to be cleared strongly depends on water body bathymetry and the extent of *C. caroliniana* infestation. A lake with a steep shoreline offers only a narrow littoral zone that is suitable for *C. caroliniana* growth, so the area that needs to be cleared is relatively small, but in a shallow water body extensive areas need to be cleared to a certain water depth to prevent fragment uptake by recreational equipment.

EFFECTIVENESS OF MEASURE

Effective.

Containment of known infestations by reducing fragment uptake through general biosecurity measures, access regulation to infested areas or management of aquatic weed infestations around high traffic access points can be highly effective. For example, a section of the Darwin River in Australia was placed under quarantine in 2004, prohibiting access to the river stretch for people and vehicles/boats (Northern Territory Government, 2008; van Oosterhout, 2009). Installed signage warned people of the possible fine of AU$ 50,000 for breaching this quarantine order (Northern Territory Government, 2008). Until today (2019), no new *C. caroliniana* infestations have been detected in the Northern Territory, indicating the success of the quarantine measure to prevent further spread.

While access regulation would be the most effective measure, it is less acceptable to water body users, so should be implemented along public awareness campaigns.

EFFORT REQUIRED

Implementation of biosecurity measures in general, regulation of public access and/or management of *C. caroliniana* around high use areas should be indefinite, unless the infestation is eradicated. The effort (such as the frequency of treatment) required to clear *C. caroliniana* from access points depends on local growth rates. Public awareness campaigns should be undertaken for as long as these measures are implemented.

RESOURCES REQUIRED

Resource requirements depend on the specific biosecurity measure undertaken to reduce fragment uptake from contaminated areas. For removal of *C. caroliniana* from water craft launch areas and other access points, resources depend on the method chosen to clear *C. caroliniana* (see details under control methods in the following sections).

Limiting access to areas requires adequate signage or exclusion barriers, and dissemination of notifications in suitable media outlets to inform water body users. Depending on the situation, staff is required to enforce access restrictions. An example of a brochure created by the Northern Territory Government can be found in their *Cabomba* eradication report (Northern Territory Government, 2008).

Wash-down facilities need the appropriate infrastructure installed, such as drainage, hosing down equipment and signage with instructions. The size of the installations have to be adequate for the projected usage, for example larger facilities are needed to wash down boats, as compared to kayaks. Wash down facilities are only useful if coupled with awareness campaigns to improve user uptake. In high use areas or during peak times (for example public holidays), staff/volunteers that provide information/assistance/instructions to users can be effective in increasing user uptake of facilities and thoroughness of weed hygiene actions undertaken.

SIDE EFFECTS

Environmental: Positive
Social: Negative
Economic: Negative

Raising of general awareness of the problems associated with invasive aquatic species will reduce future risk of unintentional dispersal or release, in general, and will be highly beneficial in reducing the risk of future incursions. Furthermore, the implementation of enhanced biosecurity measures in aquatic bodies (for example cleaning equipment, limiting access, installation of wash-down facilities) might prevent the spread of other aquatic invasive species, having positive environmental effects.

On the other hand, exclusion of recreational use from a water body, as well as imposing additional time consuming biosecurity measures, will have negative social and economic effects to certain water user groups (for example fishermen).

ACCEPTABILITY TO STAKEHOLDERS

Neutral or mixed.

Access restrictions, as well as undertaking extra biosecurity measures, can be unacceptable to recreational users of water bodies, such as fishermen and water craft users. Management of *C. caroliniana* at access points would be acceptable to users, as long as this would not disrupt their activities.

ADDITIONAL COST INFORMATION

Containment of infestations is economically highly beneficial due to the high management costs of established *C. caroliniana* populations; therefore, this management option has a high cost-benefit ratio.

LEVEL OF CONFIDENCE[1]

Well established.

There are several examples that illustrate the success of containment of *C. caroliniana* using this measure in Australia.

Cabomba caroliniana *can be found in a range of freshwater systems, but prefers still to slow moving waters. © Kevin Scheers*

1 See Appendix

Measures for early detection of the species and to run an effective surveillance system for an early detection of a new occurrence.

Active surveying and citizen-science.

MEASURE DESCRIPTION

The early detection of new incursions of invasive aquatic plants is highly critical and determines the probability of eradication (Anderson, 2005; Hussner *et al.*, 2017). The efficacy of monitoring water bodies for *C. caroliniana* incursions is limited by the difficulty of detection of early infestations. Similar to other submersed invasive aquatic plants, the problem often becomes only apparent when the infestation reaches a large extent (such as appears at the water surface). The reason for this is that in the early stages of invasion, *C. caroliniana* plants are simply hidden under water. As the probability of eradication declines with the size of the infestation, there is an inverse relationship between the probability of detection and feasibility of eradication.

The probability of detection depends highly on water clarity and experience of monitoring staff. A high confidence of detection can only be achieved by implementing active surveys undertaken by experienced divers or systematic surveys with submersed surveying equipment (under water drones, cameras or similar), and requires a high effort. These monitoring surveys should be carried out by government bodies/authorities. Due to the difficulty of detecting submersed weeds and the effort required (divers, under water surveying), monitoring efforts should be concentrated at high risk areas, for example water bodies that are geographically close to known infestations, or specific locations that are most likely to receive *C. caroliniana* propagules such as boat ramps. In these water bodies perceived at high risk of *C. caroliniana* incursion, a regular monitoring programme should be set up to ensure early incursions are detected at a stage where eradication is still possible.

The use of citizen-science would be a method more suitable to screen larger areas that have a low probability of *C. caroliniana* establishment. However, in the absence of a government driven monitoring programme that employs trained divers, citizen-science would still provide some benefit if utilised in high risk areas. In fact, citizen-science has successfully been used in Europe in the detection and surveying of different invasive species (Adriaens *et al.*, 2015). Nevertheless, detection and identification of submersed aquatic plants is difficult, so using citizen-science for these species might prove more challenging.

Given the difficulty in detecting submersed aquatic plants below the water surface at an early stage of infestation, future use of eDNA techniques will be invaluable for early detection programmes (Ghahramanzadeh *et al.*, 2013; Scriver *et al.*, 2015; Edmundsand Burrows, 2019).

SCALE OF APPLICATION

Active surveying and citizen-science programmes have to be conducted across all EU Member States. Member States where *C. caroliniana* is already present or established have to account for the higher risk of secondary spread of the plant, prioritise water bodies deemed at high risk of invasion and implement more stringent monitoring regimes locally.

EFFECTIVENESS OF MEASURE

Neutral.

Due to the inconspicuous growth of *C. caroliniana* at the initial stage of invasion, there is a high risk the plant will not be detected until the incursion becomes large and reaches the water surface, and this will be particularly the case with the use of citizen-science. *C. caroliniana* is frequently misidentified by untrained volunteers that cannot readily distinguish it from superficially similar looking aquatic plants, such as *Ceratophyllum demersum* or *Myriophyllum* spp., leading to many false positive detections or the non-detection of existing infestations (pers. obs.).

A structured monitoring programme of high risk areas by expert divers will have a high chance of early detection, but this can only be applied on a small scale. The early detection and subsequent eradication of the marine alga *Caulerpa taxifolia* in California, USA, serves as a good example highlighting the importance of public awareness (the invasive alga was noticed during routine monitoring of local flora by divers) that enabled detection of this invader at an early stage (Anderson, 2005).

EFFORT REQUIRED

Monitoring has to be conducted indefinitely.

High risk areas should be surveyed by expert divers at least yearly to detect early incursions.

There is a low effort required for a general monitoring programme using citizen-science. However, the efficacy of citizen-science will depend on long term commitment of scientific leadership and participation in such programmes, especially in order to validate records.

RESOURCES REQUIRED

The costs will strongly depend on the size of the water body that needs to be monitored and the frequency of surveys, as the number of expert divers required will increase with search area.

Surveying large water bodies with expert divers can be very costly. For example, the *Lagarosiphon* major monitoring programme in Lake Wanaka, New Zealand, is undertaken yearly, employing several divers that monitor the long shoreline of this large lake (Clayton, 1996, 2006).

Citizen-science programmes for environmental projects in the UK were estimated at €75,000 and €165,000 (Roy *et al.*, 2012) and would be suitable for large scale monitoring across multiple water bodies.

SIDE EFFECTS

Environmental: Positive
Social: Positive
Economic: Neutral or mixed

Monitoring programmes carried out through citizen-science or as planned surveys by government bodies will have positive environmental effects, as they might assist the detection of other aquatic invasive species. Socially, monitoring will have little effect on recreational use of water bodies, but citizen-science will help raise public awareness of the problems caused by invasive alien species, in general.

ACCEPTABILITY TO STAKEHOLDERS

Acceptable.

Monitoring has few effects on the recreational use of water bodies.

ADDITIONAL COST INFORMATION

The cost of monitoring will far outweigh the long term costs of non-detection of an incursion of *C. caroliniana*.

LEVEL OF CONFIDENCE[1]

Well established.

There are examples published in the literature that demonstrate the effectiveness of monitoring for early detections of invasive aquatic weeds.

1 See Appendix

Measures to achieve rapid eradication after an early detection of a new occurrence.

Manual removal.

MEASURE DESCRIPTION

Manual removal (hand weeding) of *C. caroliniana* by trained divers is an effective method to control small infestations in the early stage of incursion or as a follow-up to other control measures. Trained divers will remove all material, including crowns rooted in the substrate and transfer it to collection bags for later disposal. As *C. caroliniana* is able to regenerate from small fragments (Bickel and Perrett, 2014), great care needs to be taken to remove all material. Efficacy is highly dependent on the divers' skills and visibility (water clarity). Due to the high labour effort, manual removal is only efficient for small areas or low density scattered populations that remain after other control techniques were carried out. The large amount of plant material in dense established *C. caroliniana* stands practically excludes the use of this method.

Hand weeding can be conducted in conjunction with routine monitoring (see previous section) and as follow-up of previous control efforts with other techniques (such as 'mop up' remaining plant material)(Clayton, 1996, 2006; van Oosterhout, 2009).

Sometimes, hand weeding is used as a regular maintenance tool to clear strategic areas of *C. caroliniana*, see example below under 'resources required'.

SCALE OF APPLICATION

Hand weeding is useful to clear *C. caroliniana* from areas of a few m^2 or to collect low density single stands scattered over a wider area when part of a monitoring programme or post treatment inspection. For example, hand weeding was used to remove outlier stands of *Lagarosiphon major* during routine monitoring efforts in Lake Wanaka, New Zealand, spanning many kilometres of lake shore of this large lake (Clayton, 1996). Hand weeding was also successfully employed to remove remaining *Salvinia molesta* plants from a wetland (area in the range of ha) after the majority of plants had been killed with herbicides (Honey Dam, North Queensland (A. Petroeschevsky, pers. comm.) and Myall Lakes catchment (van Oosterhout, 2006).

EFFECTIVENESS OF MEASURE

Effective.

Hand weeding efficacy depends highly on the skills of trained divers, as even tiny fragments will be able to regenerate and create a new infestation in a short time frame. Therefore, efficacy depends on the thoroughness of removal. Nevertheless, this method is highly effective for removal of small stands of *C. caroliniana* and is a standard method for removing similar submersed aquatic plants.

EFFORT REQUIRED

Depending on the situation, hand weeding can be once off to remove a small infestation (early detection), or involve on-going maintenance, for example when hand weeding is used in conjunction with regular monitoring.

RESOURCES REQUIRED

As expert divers are needed to remove submersed aquatic plants such as *C. caroliniana*, the costs can be very high. For example, hand removal of *C. caroliniana* from five strategic areas in Ewen Maddock Dam, Australia, totalling an area of 26.8 ha, employed three divers plus support crew, and cost between AU$ 100,000 to AU$ 220,000 per annum (van Oosterhout, 2009).

SIDE EFFECTS

Environmental: Neutral or mixed
Social: Neutral or mixed
Economic: Neutral or mixed

Hand removal is unlikely to have any considerable environmental, social or economic side effects, mainly due to the small scale that it is applied to. As plants are removed specifically by divers, the impact on non-target species is minimal.

ACCEPTABILITY TO STAKEHOLDERS

Acceptable.

This method is highly acceptable to most stakeholders (mainly recreational users of water bodies), as it does not severely interfere with water activities. In addition, as no chemicals or heavy machinery are used, manual removal has a high public acceptability.

Fanwort is also grown commercially in Asia for export to Europe and other parts of the world. © Leslie J. Mehrhoff. CC BY 3.0

ADDITIONAL COST INFORMATION

Hand removal by trained divers is a suitable method to cost-efficiently and rapidly eradicate early incursions of *C. caroliniana* and is an invaluable control tool to remove outliers and remaining material after large scale application of other control techniques.

LEVEL OF CONFIDENCE[1]

Well established.

Manual removal is the most basic way of removing aquatic plants and has been an efficient method of small scale weed control since the beginning of human agricultural activities.

1 See Appendix

Measures for the species' management.

Chemical control.

MEASURE DESCRIPTION

Herbicides are widely used for chemical control of weeds and work by physically damaging target plants (for example desiccants) or by interfering with their physiological processes (for example interference with biosynthesis). Herbicides have a long history of use for the control of aquatic weeds (Pieterse and Murphy, 1990; Clayton, 1996; Cooke *et al.*, 2005; Gettys *et al.*, 2009). However, application of herbicides in aquatic habitats has many challenges, such as dilution, displacement through currents, deactivation by suspended particles in the water column and non-target damage (Gettys *et al.*, 2009). Some of these difficulties can be overcome through the use of suitable carriers, such as gelling agents or diatomaceous earth (Clayton, 1996). Overall, herbicides can be a highly effective tool for the control of a wide range of aquatic weeds and are particularly useful when integrated with other control techniques.

Despite its fragile appearance, *C. caroliniana* is comparatively resistant to herbicides (Bultemeier *et al.*, 2009). Nevertheless, at least four herbicides have been either identified as efficient, or successfully used, to control *C. caroliniana* in water bodies around the world: 2,4-D, carfentrazone, endothall and flumioxazin (Nelson *et al.*, 2002; Bultemeier, 2008; Northern Territory Government, 2008; Bultemeier *et al.*, 2009; Day, 2014; Hunt *et al.*, 2015).

In Australia, 2,4-D was used to control *C. caroliniana* in a range of water bodies in Queensland and the Northern Territory (Diatloff and Anderson, 1996; Anderson and Diatloff, 1999; Northern Territory Government, 2008). A *C. caroliniana* infestation in a tropical floodplain wetland (Marlow Lagoon, Northern Territory; 1 ha infestation) was completely removed with a single application of 2,4-D and the native vegetation recovered remarkably well after removal of the species (Northern Territory Government, 2008). Until it was banned from aquatic use in 2006 (APVMA, 2006), 2,4-D was applied for several years in conjunction with diatomaceous earth to control *Cabomba* along a 12 km stretch of the Darwin River (Northern Territory), achieving a reduction of the infestation to 1 km (Northern Territory Government, 2008; Price and Collins, 2016). Carfentrazone was used for *Cabomba* management in Australia and achieved 100% control with a single application in Glennbrook Lagoon, NSW (Day, 2014), although it re-established four years later. Carfentrazone was also applied in a range of small ponds and dams (0.3–3.8 ha) in sub-tropical NSW and gave excellent control, with either a single or multiple applications (Inkson *et al.*, 2014a). *Cabomba* was not detected in these lakes during post application monitoring, but again reappeared 2–3 years later (D. Officer, pers. comm.)

Endothall is not yet registered for use in Australia, but has been identified as efficiently controlling *C. caroliniana* in experimental work carried out by DPI Victoria, Australia (Dugdale *et al.*, 2012; Hunt *et al.*, 2015).

Flumioxazin was identified as a suitable herbicide to control *Cabomba* at low application rates (Bultemeier *et al.*, 2009). It is registered and has been used in the USA for control of a range of aquatic plants, including *Cabomba*, for several years (Gettys *et al.*, 2009). Efforts are currently underway to register flumioxazin for aquatic use in Australia for its high efficacy at low application rates, its low toxicity and rapid breakdown (Bickel *et al.*, 2018; Bultemeier *et al.*, 2009). Experimental trials using this herbicide showed rapid control of *C. caroliniana* from small dams in Australia (pers. obs.) and it is also being used for a *C. caroliniana* control programme in the Darwin River, Northern Territory, Australia (C. Collins and T. Dugdale, pers. comm.). Flumioxazin half-life is strongly pH dependent, with rapid hydrolysis at pH >8 (Katagi, 2003), therefore it should be applied early in the morning when pH levels are favourable to achieve high efficacy (Mudge *et al.*, 2012).

The herbicides carfentrazone, 2,4-D and flumioxazin are able to rapidly control *C. caroliniana* efficiently and are suitable for large scale reduction in plant biomass or eradication. As such, this measure can also be applied for eradicating established populations of *C. caroliniana* in the long-term.

Long term monitoring after *Cabomba* management is vital to prevent re-establishment, as experience in Australia has shown that even after *Cabomba* had been removed from a water body through herbicide application for up to four years, the plant was able to re-establish, presumably from dormant stem material on the substrate (T. Dugdale, pers. comm.).

The application of herbicides in aquatic environments is limited by EU and Member State regulations, which should always be strictly followed.

SCALE OF APPLICATION

Good control of *Cabomba* with herbicides was achieved in wetlands and farm dams measuring up to 8 ha in the Northern Territory and New South Wales, Australia, with single applications (Northern Territory Government, 2008; Day, 2014; Inkson *et al.*, 2014a,b). Experimental work in Australia achieved complete removal of *C. caroliniana* from small water bodies (~1 ha) with flumioxazin (pers. obs.; C. van der Hoven, pers. comm.).

Herbicides can also be applied on a larger scale from boats and helicopters, for example for the management of *Lagarosiphon major* in New Zealand with diquat, in areas in excess of 100 ha (Clayton, 1996). Application of 2,4-D from a boat achieved good control of *C. caroliniana* on a 12 km stretch of the Darwin River, Australia (Northern Territory Government, 2008; Price and Collins, 2016).

EFFECTIVENESS OF MEASURE

Effective.

Herbicides (2,4-D, carfentrazone and flumioxazin) have successfully been applied for long term *Cabomba* control in small dams and wetlands in Australia (Northern Territory Government, 2008; van Oosterhout, 2009; Day, 2014; Inkson *et al.*, 2014a; pers. obs.), as detailed in the examples above. Herbicides are also routinely used in the USA to control *Cabomba* in a range of water bodies (Bultemeier, 2009; M. Heilman, pers. comm.).

EFFORT REQUIRED

Herbicidal control of *C. caroliniana* can be achieved with one or multiple applications, depending on the herbicide used and circumstances, such as the extent of the infestation (biomass), bathymetry, water physico-chemical parameters and application technique. Control is usually achieved within days after application, but long term monitoring after treatment is necessary to prevent re-establishment.

RESOURCES REQUIRED

Effort required in terms of personnel depends on the scale of application, ranging from single operators using backpack sprayers in a small dam or pond, to small crews for boat and helicopter applications.

The cost of herbicides depends on the product, as the following examples illustrate. At the time of writing, 4 l of carfentrazone sells for ~$AU 500 (~ €300) in Australia (R. Gurney, pers.comm.), which can treat ~500m^3 of water at an application rate of 2 ppm (at a water depth of 2 m this translates to $AU 20,000 (~€12,000) per ha). Flumioxazin is currently priced at $US 180–200 (~€180) per lbs in the USA, which is enough to treat ~1000m^3 of water at 200ppb (this would be equivalent to $US 4,000 (~€3,600) per ha at 2 m water depth). The use of carriers (for example diatomaceous earth) would incur additional costs, but improve efficacy and/or reduce application rates.

Equipment costs range widely, and depend on the application technique used, varying from ~US$ 100 for a backpack sprayer to thousands of dollars for specialised spray equipment mounted on suitable boats or helicopter hire costs. If plant biomass is high, aeration equipment needs to be hired to prevent fish kills due to deoxygenation.

SIDE EFFECTS

Environmental: Neutral or mixed
Social: Neutral or mixed
Economic: Neutral or mixed

Herbicides can have direct (toxicity) and indirect (deoxygenation) impacts on non-target organisms. Deoxygenation of the water column following the collapse of large aquatic weed beds is a common problem when applying herbicides on a large scale (for example Day, 2014), although this can be prevented through aeration of the water body during herbicide treatment. Damage to non-target plants can be reduced by the use of carriers, selection of appropriate herbicide and correct dosing. The application of herbicides carries the risk of toxicity to other aquatic species, as well as to recreational water users or the drinking water supply. To prevent issues with human toxicity, access to water bodies for recreational use can be temporarily restricted, which is often unpopular with users. Depending on specific withholding periods, the use of herbicides can temporarily restrict the use of water for irrigation or livestock watering.

ACCEPTABILITY TO STAKEHOLDERS

Neutral or mixed.

Acceptability of the use of herbicides in water bodies depends on the specific local community. While some local communities reject the use of herbicides in water outright for their perceived health and environmental risks (chemo-phobia), other communities are highly supportive of herbicidal use, as herbicides provide a rapid and visible reduction in plant infestations.

There are often legal issues associated with herbicide use in drinking water situations.

ADDITIONAL COST INFORMATION

While herbicides can cause non-target damage, they can be highly cost-efficient in removing invasive species or enabling eradication and subsequent restoration of water bodies. The long term environmental impacts of invasive species can far outweigh the short term damage caused by herbicidal control.

LEVEL OF CONFIDENCE[1]

Well established.

The use of herbicides for aquatic plant control is well established and there is a good support in the literature that *Cabomba* can be efficiently controlled with a range of herbicides.

1 See Appendix

Mechanical control.

MEASURE DESCRIPTION

There are a range of control options that use mechanical devices to remove or dislodge aquatic weeds from the substrate (in contrast to mowing, see next section), such as suction dredging, rototilling and hydro-venturi. These methods are more useful for areas larger than manual removal, but the costs can be high due to the considerable initial outlay for the machinery and ongoing staff costs (Pieterse and Murphy, 1990; Clayton, 1996; Cooke *et al.*, 2005; Gettys *et al.*, 2009). The environmental impacts are also higher, mainly due to the disturbance of the natural substrate. The length of control depends on the prevention of recolonization from remaining stem fragments or untreated areas (van Valkenburg *et al.*, 2011).

Suction dredging uses machines originating from the mining industry (in-stream alluvial gold mining), which are basically large aquatic vacuum machines that suck up weeds and the upper substrate layer, and pump the material onto a barge for later disposal on land. The suction device is manipulated by divers and can be targeted to remove all plants from a designated area. The removal efficiency can be very high, as plant and embedding substrate are removed, and non-target damage is relatively low as the suction hose is guided by divers. Suction dredging is more suitable to small and strategic areas and, in some cases, it can also be suitable for eradication of early incursions. In Australia, management of *C. caroliniana* with suction dredging in Ewen Maddock Dam and Lake Macdonald (monthly treatment) provided short term control in strategic areas for containment (D. T. Roberts, pers. comm.; van Oosterhout, 2009).

Rototilling uses an underwater rotary hoeing machine that tills the underwater substrate and thereby uproots aquatic plants. Rototilling gives good medium to long term control, depending on substrate penetration. For example, experimental rototilling of *Lagarosiphon major* resulted in a 0.5–2 year control in Lake Wanaka, NZ[1] (Clayton *et al.*, 2000). However, rototilling efficacy depends on the contour of the lake bed and the presence of obstacles.

The hydro-venturi water jet is used to dislodge aquatic plants from the substrate. The plant material can be collected afterwards. *C. caroliniana* was experimentally removed by hydro-venturi from a canal in the Netherlands which resulted in efficient, but short term, control (van Valkenburg *et al.*, 2011).

Excavation is frequently used to remove nuisance aquatic plant vegetation from irrigation canals. An experiment conducted in the Netherlands showed that repeated removal of *C. caroliniana* with an excavator along a 100 m stretch of a ditch only provided short term control (van Valkenburg *et al.*, 2011).

SCALE OF APPLICATION

Hydro-venturi and suction dredging can be used on a small scale (especially the latter can be a useful tool for early eradication or control around structures such as jetties and boat ramps), but the high initial costs would rarely justify the use of these machines on a small geographical and temporal scale (Clayton, 1996; Cooke *et al.*, 2005; Hussner *et al.*, 2010). The area that can be cleared in a day depends on the density of the plants, but would be in the scale less than a hectare per day. Frequently, these machines are used for ongoing maintenance of lakes (up to several hundred ha), or rotated between lakes to clear high use recreational areas on a regular basis (for example swimming areas; Clayton, 1996; van Oosterhout, 2009; van Valkenburg *et al.*, 2011). Rototilling could be effective on a larger scale in terms of hectares, provided the bathymetry (shallow, flat and obstacle free areas) is suitable. The estimated clearance rate is 4–5 days per ha (Clayton *et al.*, 2000; Cooke *et al.*, 2005). Excavation is usually applied in flowing waters, such as drains and canals. It can be used to clear long stretches of drains on a scale of 100 metres to kilometres. Excavation is limited to shallow areas and narrow canals, and by the reaching ability of the excavator equipment (Clayton, 1996; Hussner *et al.*, 2010).

EFFECTIVENESS OF MEASURE

Effective.

These methods have routinely provided efficient control of *C. caroliniana* (see examples above) and of similar submersed aquatic weeds, such as *Lagarosiphon major* in New Zealand lakes (Clayton, 1996). However, similarly to other physical control methods (see next table), they usually provide only short to medium term control of aquatic weeds.

EFFORT REQUIRED

In large scale infestations, these methods provide control for about one year, such as yearly maintenance has to be carried out. Small scale suction dredging has the potential to eradicate small scale infestations, if carried out thoroughly. *C. caroliniana* has been managed under a continuous

1 https://www.niwa.co.nz/our-science/aquatic-biodiversity-and-biosecurity/our-services/aquaticplants/outreach/weedman/control#mechanical

maintenance programme in Ewen Maddock Dam (a 450 ha drinking reservoir) in sub-tropical Queensland, Australia, for several years now (D. Roberts, SEQwater, Brisbane, pers. comm.). One suction dredging machine with two divers is employed on a regular basis and works its way around the shoreline of the reservoir to control strategic areas.

Rototilling provides short to medium term control of aquatic weeds and thus has to be reapplied on a scheduled basis. Removal of *C. caroliniana* with hydro-venturi provided only short term control and thus has to be part of a long term management regime as well. Integration of hydro-venturi with other control options, such as hand weeding, could greatly improve efficacy of this method.

RESOURCES REQUIRED

It is difficult to directly compare the costs of the various mechanical control options, as efficacy and speed of application varies and is situation dependent. Also, costs will vary significantly between different countries, so estimates have to be seen as approximate. All these methods rely on heavy and expensive machinery. The initial outlay to purchase these can be significant (in excess of $ 100,000), or there are ongoing hire costs. The clearance rates are fairly low, typically below 1 ha per day, leading to high staff costs. For example, suction dredging is a high effort control method that requires two divers, plus a surface support crew. In NZ costs have been estimated at about NZ$ 15,000–20,000 ha^{-1} and this does not include the initial purchase or hire of the equipment (Clayton, 1996). The suction dredge programme in Ewen Maddock Dam added up to a yearly cost of AUD$ 245,000 (van Oosterhout, 2009). Rototilling costs have been estimated at NZ$ 1,000–5,000 per ha when using hired equipment (Clayton *et al.*, 2000). Excavation has been estimated at NZ$ 1,000 per km in New Zealand (Clayton, 1996). There are no published records on the cost of hydro-venturi, but it would be in a similar range as compared to the other mechanical control methods.

SIDE EFFECTS

Environmental: Negative
Social: Negative
Economic: Negative

These control methods rely on the use of heavy machinery, which could negatively impact public perception or amenity values. There are also negative environmental impacts due to the disturbance of the aquatic substrate and possible temporary increase of turbidity. The use of heavy machinery can also restrict access to water bodies, and therefore disrupt economic revenue from water recreational activities.

ACCEPTABILITY TO STAKEHOLDERS

Neutral or mixed.

Mechanical devices for aquatic weed control are usually more acceptable to the public than the use of herbicides, mainly due to the perceived lower environmental impacts. However, this depends on the local urgency and interest in getting the plants removed quickly and cheaply (using herbicides) vs. slowly and costly (via mechanical means) (pers. obs.). Furthermore, water users may object to this measure, if access to water bodies is restricted.

ADDITIONAL COST INFORMATION

While mechanical control options usually incur fairly high management costs, the long term costs of inaction potentially far outweigh initial outlay for mechanical control.

LEVEL OF CONFIDENCE[1]

Established but incomplete.

Mechanical methods have successfully been used in aquatic weed control for many years. There are examples of successful *Cabomba* management applications, but little has been reported in the literature (pers. obs.).

Cabomba caroliniana. © *Kevin Scheers*

1 See Appendix

Mechanical control via mowing, cutting, shredding.

MEASURE DESCRIPTION

There are different types of weed cutting machinery available. They usually cut submersed aquatic weeds down to a certain depth (~2 m) and remove the cut plants via conveyer belts and barges for later disposal. As this is practically similar to mowing a lawn, this control technique has to be applied at regular intervals during the growing season. Mowing efficiency depends on weed density (amount of material to be removed), water clarity, the contour of the water body bottom and the presence of obstacles (Clayton, 1996; Hussner *et al.*, 2017).

Mowing of submersed aquatic plants has been used for many years for maintenance of water bodies for recreational use, for example to clear swimming areas. Mowing of *C. caroliniana* has been carried out for several years in Lake Macdonald (260 ha, virtually 100% *C. caroliniana* cover), the largest *C. caroliniana* infestation in Australia. A harvester was used for on-going maintenance of two priority areas (5% area of the lake; van Oosterhout, 2009). The programme was eventually terminated due to the high yearly costs, with little long term effect, due the rapid healthy regrowth of *Cabomba* (D. T. Roberts, pers. comm.) and the fact that only a small portion of the *C. caroliniana* infestation in this large lake was being controlled.

SCALE OF APPLICATION

The method is usually applied to clear strategic areas measuring some hectares. Mowing was used for a few years to manage *C. caroliniana* in a 260 ha Lake in Australia (van Oosterhout, 2009).

EFFECTIVENESS OF MEASURE

Effective.

The method is effective for short term clearing of defined areas for recreational use and is relatively cheap (van Oosterhout, 2009). There is no long term control and ongoing maintenance is required.

The method has to be applied correctly, as inefficient mowing resulted in the production of fragments that aided in the spread of *C. caroliniana* in the Netherlands (Matthews *et al.*, 2013).

EFFORT REQUIRED

The method has to be applied repeatedly, often multiple times per growing season (Clayton, 1996; Cooke *et al.*, 2005; Gettys *et al.*, 2009). It should be part of an ongoing maintenance programme (Cooke *et al.*, 2005). Cutter-harvesters can clear 1.25 ha per day (Cooke *et al.*, 2005).

RESOURCES REQUIRED

The method employs a cutting machine, plus a driver and a support crew to dispose the cut weed. The harvesting programme in Lake Macdonald (9 ha) was operating costs of AUD$ 120,000 per year (excluding the machinery and disposal) (van Oosterhout, 2009). Cutting and harvesting aquatic weeds in the USA is estimated at US$ 500 per ha (Cooke *et al.*, 2005).

SIDE EFFECTS

Environmental: Negative
Social: Neutral or mixed
Economic: Neutral or mixed

Mowing is less environmentally damaging than the mechanical options mentioned in the previous section, as it does not interfere with the substrate, although it can damage non-target plant species and aid the spread of weeds.

Mowing does not have long term effects on the recreational use of water bodies.

ACCEPTABILITY TO STAKEHOLDERS

Acceptable.

Similarly to other mechanical control options, mowing is usually more acceptable to recreational water users than the use of chemicals (pers. obs.). Mowing also interferes little with the recreational use of water bodies, so it is generally acceptable.

ADDITIONAL COST INFORMATION

No information available.

LEVEL OF CONFIDENCE[1]

Established but incomplete.

Mowing of aquatic weeds is a standard practice for aquatic weed control (Clayton, 1996; Cooke *et al.*, 2005; Gettys *et al.*, 2009; Hussner *et al.*, 2017). There are examples of its use for *C. caroliniana* control, but there are few published records (but see van Oosterhout, 2009).

1 See Appendix

Biological control.

MEASURE DESCRIPTION

Two types of biological control exist for the control of aquatic weeds, 1) 'classical' biological control that relies on host specific invertebrate herbivores or pathogens that consume and/or damage the target plant and 2) generalist herbivores (grass carp).

The principle of classical biological control is based on the 'enemy release' hypothesis, which suggests that invasive organisms do so well outside their native range because their natural predators are missing (Murdoch *et al.*, 1985; Williamson, 1996; McFayden, 1998; Keane and Crawley, 2002; Muniappan *et al.*, 2009). Thus, the logical step is to introduce predators from their natural range to provide natural control. Once the natural predators are present, the target plant and its herbivore will establish a new equilibrium, resulting in a much lower density of the target plant.

Potential biological control agents have to go through a rigorous host testing regime (such as they need to be host specific) before they can be deemed safe for release. There are examples of spectacular successes of biological control of weeds, and there are several aquatic agents that have provided good control of aquatic weeds. However, most research efforts so far have largely neglected submersed aquatic weeds such as *Cabomba* (but see efforts regarding *Lagarosiphon major* and *Hydrilla verticillata*) (Wheeler and Center, 2001; Baars *et al.*, 2010), so most of the efficient biological control agents available are for floating aquatic weeds, for example *Salvinia molesta* and *Eichhornia crassipes* (Gassmann *et al.*, 2006).

Surveys conducted in the native range of *C. caroliniana* (Argentina) identified a weevil species (*Hydrotimetes natans*) as a potential future biological control agent for the species (Schooler *et al.*, 2006; Cabrera-Walsh *et al.*, 2011). Scientists of CSIRO, Australia, are currently conducting host testing for this weevil species (R. Sathyamurthy, pers. comm.). If host testing proves this weevil to be specific to *C. caroliniana* and if the agent is approved for release by relevant authorities, field trials will follow to test if this weevil is an efficient control agent for the species.
There is currently no research investigating the potential of biological control of *C. caroliniana* using pathogens. Past surveys in *C. caroliniana*'s area of origin did not find any potential pathogen candidates for biological control and there is little research in terms of aquatic weed control with pathogens in general (R. Sathyamurthy, pers. comm.)

Grass carp (*Ctenopharyngodon idella*) is a large herbivorous cyprinid fish that has been used for aquatic plant control for several decades in the EU, USA and New Zealand (Chilton and Muoneke, 1992; Clayton *et al.*,1992; Bain, 1993; Rowe and Champion, 1994; Pípalová, 2006). Grass carp are generalist feeders and, while showing preference for certain plant species (Mitchell, 1980; Chilton and Muoneke, 1992; Hanlon *et al.*, 2000), they will, at the correct stocking density, consume all aquatic vegetation in a water body (Fowler and Robson, 1978; Rowe and Champion, 1994; Hanlon *et al.*, 2000; Pípalová, 2006). Once the desired level of control is achieved (complete removal of the target species), the fish can be removed by netting or with the use of rotenone (Rowe and Champion, 1994). While there are few published records for the use of grass carp to control *C. caroliniana* (but see Hanlon *et al.*, 2000), it is unlikely that this fish would not consume this plant, as it readily consumes and has even eradicated a wide range of other submersed aquatic plants (for example *Lagarosiphon major*, *Hydrilla verticillata* and *Egeria densa*; Mitchell, 1980; Clayton *et al.*, 1992; Rowe and Champion, 1994).

SCALE OF APPLICATION

Once biological control agents are established, they control a target aquatic plant infestation at the scale of an entire water body. Some biological control agents are able to naturally disperse and thus control the target plant at a landscape level (Williamson, 1996; Muniappan *et al.*, 2009). Biological control agents are usually less suitable for smaller water bodies (ponds, farm dams), as plant infestations in these can be more efficiently managed with other tools (herbicides, physical methods and habitat manipulation; pers. obs.).

Grass carp controls aquatic plants within any stocked water body, independently of the area. Efficient control depends only on appropriate stocking density (Fowler and Robson, 1978; Noble *et al.*, 1986; Chilton and Muoneke, 1992). However, the feasibility of stocking grass carp in large lakes can be limited by the large number of fish required and subsequent difficulty of removal, if required. Stocking of large lakes can also result in unpredictable macrophyte control due to fish movement (Noble *et al.*, 1986). Large systems are also likely part of a wider catchment, so grass carp stocking can become problematic in terms of the containment of the fish and prevention of non-target damage in case of escape (Bain, 1993).

EFFECTIVENESS OF MEASURE

Unknown.

Currently, there is no host specific classical biological control agent available for *C. caroliniana*. However, efforts are underway to develop such a tool (R. Sathyamurthy, pers. comm.; Schooler *et al.*, 2006, 2009).

Grass carp are highly effective for aquatic plant control (Fowler and Robson, 1978; Chilton and Muoneke, 1992; Rowe and Champion, 1994), but there are few published records of their use against *C. caroliniana*. One review reports *C. caroliniana* cover reduction in a lake in Florida after grass carp stocking, but failure of control in another system (Hanlon *et al.*, 2000). Control of *C. caroliniana* with grass carp is listed as a management option by the Department of Wildlife and Fisheries Sciences, Texas and by Cooke*et al.*, (2005). However, there is some evidence that *C. caroliniana* is not very palatable to grass carp (P. Champion, pers. comm.), and the plant was not consumed by a grass carp x European carp hybrid (Dhutu and Kilgen, 1975). At the same time, there are reports that grass carp will consume the next relative *Brasenia schreeberi* (Leslie *et al.*, 1987). In addition, palatability of certain plant species can be location dependent, and as grass carp will eventually consume practically any aquatic plant in a water body if stocked at sufficient density (Leslie *et al.*, 1987), there is a high likelihood that they would provide good control at sufficient stocking densities (Fowler and Robson, 1978; Chilton and Muoneke, 1992).

EFFORT REQUIRED

Depending on the biology of the classical control agent, a once-off application might be sufficient to achieve the desired control; multiple introductions are required if, for example, the climate is sub-optimal or in case of unusual events, such as a flood.

If a correct stocking density is chosen, a single application of grass carp is sufficient for efficient control.

RESOURCES REQUIRED

Biological control agents initially require a high effort in scientific personnel and funds, and are time consuming (multiple years). This is due to the extensive field work required in the natural host range, the rigorous testing for specificity and the need for specialised scientific infrastructure (quarantine facilities) for this. Furthermore, there is no guarantee that a specific agent will be identified. However, experience with other weed species demonstrates a high cost-benefit ratio of this measure in the long term.

Grass carp stocking is a once-off effort needing little resources and personnel. Water body size will determine stocking density and thus the financial cost. In case of risk of escape, more expensive triploid grass carp may need to be purchased. Depending on the situation, grass carp may have to be removed when the aquatic weed has been controlled.

SIDE EFFECTS

Environmental: Neutral or mixed
Social: Positive
Economic: Neutral or mixed

Biological control has no direct environmental impacts. Stocking of grass carp has positive social effects to fishermen, as they add a further target species. Grass carp have highly specific breeding requirements and are thus unlikely to reproduce in stocked water bodies (the risk can be ameliorated by using triploid fish; Bain, 1993; Pípalová, 2006). In case of escape (for example after floods), the fish can potentially cause non target damage off-site, but as they would be dispersed at low densities, large scale damage is unlikely (Clayton and Wells, 1999).

ACCEPTABILITY TO STAKEHOLDERS

Acceptable.

Classical biological control is usually a highly acceptable control method for water body recreationists, as it does not interfere with their activities. Stocking of grass carp is usually appreciated by fishermen, as it adds another target species.

ADDITIONAL COST INFORMATION

There is currently no fully developed biological control agent for *C. caroliniana*. Grass carp would be a cost-effective control option, depending on the situation. The cost of inaction would far outweigh initial capital outlay for management.

LEVEL OF CONFIDENCE[1]

Unresolved.

Currently, no specific classical biological control agent is available. The conclusion of an Australian research programme and future field trials will provide more confidence in this information in the near future (<5 years, pers. opinion). There are few published reports of *C. caroliniana* control attempts using grass carp, with contrasting results.

1 See Appendix

Habitat manipulation (shading, dyes, benthic blankets, water drawdown).

MEASURE DESCRIPTION

Habitat manipulation is a tool commonly used to control aquatic weeds and usually involves management actions that interfere with aquatic plant growth, such as the use of benthic blankets, shading with plastic sheets or artificial dyes and the removal of water through the means of a drawdown. The suitability of each of these methods depends on the specific circumstances, for example shading through plastic or dyes is only suitable for small water bodies, while benthic blankets can be strategically placed in large water bodies to support recreational users. The water level can only be manipulated in lakes and dams that have the necessary infrastructure for that.

A reduction of light availability for photosynthesis, and subsequent plant death, can be achieved through artificial shading of water bodies, either through dyes that specifically filter out light necessary for photosynthesis, or through the use of shading material (for example plastic sheeting). Shading of a small farm dam (an outlier from the large infestation in the Lake Macdonald catchment) with dark plastic sheets that covered the entire water surface provided several months of *Cabomba* control (Schooler, 2008; van Oosterhout, 2009). Shading was also used in the Darwin River, Australia (in combination with herbicides), to prevent flowering of *C. caroliniana* and thus reduce seed production (van Oosterhout, 2009). Trials with shading have also been performed in a canal in the Netherlands and were able to remove the plant from a 100 m stretch (van Valkenburg *et al.*, 2011). Dyes are used mainly in small artificial water bodies, such as golf courses.

The installation of benthic blankets, either made of geotextile or of natural fibre material, is a popular aquatic weed control tool. The blankets are either installed by divers or during lake drawdowns. The blankets suffocate and shade plant material trapped underneath and also prevent colonisation on top of the blanket. Efficacy of benthic blankets relies on the absence of wave action or currents, and on the contour of the bottom of the water body. The choice of benthic blanket material depends on the situation and management goals. Natural fibres can break down over time and help native plants to re-establish after invasive species are removed. Blankets made out of artificial material will potentially provide a longer term control than natural fibre ones, because they will not break down over time. However, long term efficacy to prevent plant colonisation will depend on maintenance and preventing the build-up of organic material which will render benthic blankets ineffective. Plastic sheets are probably the most inexpensive option, but they can create problems when large amounts of plant biomass are covered, as the subsequent decomposition will accumulate gas that can lift the blankets off the lake bottom.

A trial with benthic blankets to control *C. caroliniana* in Lake Benalla, Australia, was carried out as part of a lake drawdown experiment (Dugdale *et al.*, 2013). The geotextile blankets were installed on the exposed lake bed and provided good control for 2 years after filling (Tony Dugdale, pers. comm.). Generally, benthic blankets are successfully used to control other submersed aquatic invaders such as *Lagaroshiphon major* (Caffrey *et al.*, 2010). Benthic blankets are particularly useful for long term control around boat ramps or in swimming areas.

The suitability of drawdowns (winter and summer drawdowns, 4-6 weeks) for *C. caroliniana* control was trialled in Lake Benalla, Victoria, Australia. Despite the duration of the draw-downs, the mud remained wet and some of the *Cabomba* material was viable after treatment (Dugdale *et al.*, 2013). However, the combination of four drawdowns and a natural flood event resulted in the eradication of *Cabomba* from the site (T. Dugdale, pers. comm.). There are other records that show mixed success with lake drawdown for *C. caroliniana* control (Cooke, 1980). Success with drawdowns relies on sufficient drying out of the substrate, susceptibility of the target species and occurrence of temperature extremes (heat or cold) (Cooke, 1980).

SCALE OF APPLICATION

Dyes or shading material are only effective for small areas, such as creeks or ponds in golf courses. In particular, shading trough plastic sheets becomes impractical for infestations larger than 1 ha (van Oosterhout, 2009). Experimental shading of a canal in the Netherlands ran over a distance of 100 m (van Valkenburg *et al.*, 2011).

Benthic blankets are used to control aquatic weeds in recreational areas for swimming or boating.

Drawdown of water levels is not limited in a geographical sense, but depends on the availability of structures to control water levels. Repeated drawdowns provided *Cabomba* control in a 17 ha dam in Australia, but the incidence of flooding events might have been part of the success.

EFFECTIVENESS OF MEASURE

Effective.

There are examples for effective use of these methods for submersed aquatic plant control (see details above). Shading provided temporary control of *Cabomba* in a farm dam in Queensland and in a creek in the Netherlands (Schooler, 2008; van Oosterhout, 2009). Benthic blankets were also trialled in Lake Benalla, Australia, and provided control for 2 years (Dugdale *et al.*, 2013). Multiple drawdowns were also able to control *C. caroliniana* in Lake Benalla in Australia (Dugdale *et al.*, 2013), but it cannot be excluded that flood events that took place during the management regime played a part in the success. The author is unaware of any published record of the use of dyes to control *C. caroliniana*. However, it is unlikely that dyes would not, at least, produce some level of *C. caroliniana* control, as they work on the same principle as the other shading tools that are documented to control *Cabomba*.

EFFORT REQUIRED

Shading through plastic sheets has to be applied for at least 2 months (van Oosterhout, 2009).

Benthic blankets have to be installed and maintained for long periods. If only applied in strategic areas, benthic blankets will have to be replaced as necessary.

Experience with drawdowns in Australia show that several consecutive drawdowns are necessary to achieve long term control. The drawdown period must be long enough to ensure drying out or freezing of *Cabomba* material, which includes drying of *Cabomba* fragments buried in the substrate (Dugdale *et al.*, 2013).

Cabomba caroliniana *Gray. © Champion, P. D.. CC BY 4.0*

RESOURCES REQUIRED

Application and maintenance of shading structures or benthic blankets require divers. The shading trial on a small farm dam in Queensland, Australia, ended up costing more than AUD$ 15,000, even though a large part of the work was carried out by volunteers (van Oosterhout, 2009).

Costs of synthetic dyes will depend largely on the volume of the treated water body. But, as an example, a synthetic dye (Aquashade) currently retails for ~US$ 50 per gallon (~3.8 l), which will treat an area of up to an acre (~4,000 m^2), according to the label (equivalent to US$ 123 per ha).

Costs of drawdowns depend on the loss in productivity or wasted product, for example cost of drinking or irrigation water resources that are lost.

SIDE EFFECTS

Environmental: Negative
Social: Negative
Economic: Negative

Shading and benthic blankets will affect all aquatic plants and impact water quality due to the lack of photosynthesis. The level of environmental impact will strongly depend on the area that is treated (complete water body vs. strategic areas). Drawdown also has significant environmental impacts. In addition, the loss of water for irrigation and power generation (in hydro-power lakes) is often prohibitive. The empting of a water body also carries a high risk of spreading *C. caroliniana* elsewhere. While these methods are socially acceptable, most of them will detrimentally affect the recreational use of water bodies.

ACCEPTABILITY TO STAKEHOLDERS

Neutral or mixed.

While habitat manipulation control techniques might be more acceptable to the public than the use of herbicides, due to the lower perceived environmental impact, some of the methods have a high impact on the recreational and economic use of water resources, and are thus less acceptable (for example to irrigators, drinking water producers).

ADDITIONAL COST INFORMATION

No information available.

LEVEL OF CONFIDENCE[1]

Established but incomplete.

Many of the methods described here have been used for *C. caroliniana* management, but there are still many knowledge gaps, for example the time period needed to completely kill the plant by water level manipulation. Complete shading has been tested and found effective on a small scale, but lower shade levels might be useful to at least suppress *Cabomba*; this has not been tested yet.

1 See Appendix

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Appendix

Level of confidence provides an overall assessment of the confidence that can be applied to the information provided for the measure.

- **Well established:** comprehensive meta-analysis or other synthesis or multiple independent studies that agree.
- **Established but incomplete:** general agreement although only a limited number of studies exist but no comprehensive synthesis and/or the studies that exist imprecisely address the question.
- **Unresolved:** multiple independent studies exist but conclusions do not agree.
- **Inconclusive:** limited evidence, recognising major knowledge gaps.

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