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Invasive aquatic and riparian vegetation: a review of new threats and novel solutions

By JOHN P H READE

Crop and Environment Sciences Department, Harper Adams University, Newport, Shropshire TF10 8NB, UK
Author Email: jreade@harper-adams.ac.uk

Summary

Aquatic and riparian habitats are particularly prone to the establishment and spread of invasive plant species, and vegetation control measures are often very limited compared to those available for use in terrestrial habitats. Poor control of species in aquatic habitats leads to difficulties in use of water bodies/water courses, decline of native species, and erosion and related issues. As such, vegetation management in aquatic and riparian habitats is a vital but often difficult.

Management should consider manual/physical, mechanical, cultural, biological and, where available, chemical techniques. However, prevention of establishment of invasive plant species should underpin all management plans. The difficulty of vegetation management in aquatic and riparian habitats has resulted in, and continues to result in, development of novel and site-specific management tools and techniques. These is vital given the uncertain long-term future of glyphosate, currently the only herbicide active ingredient registered for use in aquatic environments in the UK.

Key words: Invasive aquatic vegetation, riparian vegetation, glyphosate, terrestrial habitats, aquatic habitats

Introduction

In 1981 the AAB held a conference entitled "Aquatic Weeds and their Control" (AAB, 1981). Here, the vegetative threats to aquatic and riparian habitats, and the changing focus of vegetative management, are reviewed and updated with reference to the outcomes from this conference. There have been not only major changes in the chemical and non-chemical controls available for management of such vegetation, but also in the species that are perceived to cause problems and present a subsequent need for management.

Vegetation in Aquatic and Riparian Habitats – Characteristics and Threats

For the purposes of this review, aquatic habitats that are being discussed include all non-tidal, permanent or temporary, mobile or static bodies of water. These include anthropogenic habitats such as canals, drainage ditches, and reservoirs as well as natural or semi-natural habitats such as rivers, streams, ponds, and lakes. Riparian habitats are those adjacent to such bodies of water, and are often defined as the habitat up to 1 m from the break of the bank slope, although in practice this is not always easy to define due to bank characteristics and changing water levels. Riparian habitats, the interface between land and a body of water, and are typically water-rich wetlands.

Aquatic habitats can be classified into a number of zones that are described by their abiotic and biotic properties: in the littoral zone, sunlight penetrates all the way to the bed of the water body and allows macrophytes to grow from surface to sediment; the limnetic zone is the open surface of a water body that is well lit but, due to depth, possesses less vegetation than the littoral zone; the euphotic zone is the area close to the water surface within the limnetic zone, where photosynthesis can occur effectively enough to allow vegetation to flourish; below this is the profundal zone, where insufficient light penetrates to support photosynthesis; the benthic zone is the lowest level of a body of water, including the surface and subsurface sediment. These demarcation of these zones is often dynamic in practice, dependent on water level, water flow, vegetation and algal presence, and clarity of the water due to sediment and pollutants.

Vegetation associated with aquatic and riparian habitats, including non-native and invasive species, can also usefully be classified into a number of relatively distinct categories, dependent on where it most often occurs. *Bankside vegetation* (examples: *Fallopia japonica, Impatiens glandulifera)* is found on damp soil that experiences periods of both flooding and drying out. As such, bankside vegetation tends to possess characteristics that allow it to adapt well to changing water conditions. This is the vegetation of the riparian zone. *Emergent vegetation* (examples: *Stratiotes aloides*, *Typha* sp.) grow, in part, below the water surface for much of the time. These species are rooted in the sediment, but a significant portion of growth takes place above the water surface for at least part of the time. These species are generally less tolerant to drying out than bankside species, but can often survive transient periods of this. *Partially emergent vegetation* (example: *Hydrocotyle ranunculoides*) have leaves on the water surface but lack the above water growth of emergent species; *Submerged vegetation* (example: *Elodea* sp.) complete their life-cycle below the water surface and may be free floating or rooted in sediment. Algae are often included in this category.

Aquatic habitats can be considered to be at a greater risk from invasive vegetation than many terrestrial habitats due to the lack of competition that is often offered by native vegetation. Put simply, there is often more space to be invaded in aquatic habitats than in many terrestrial ones, along with less competition from existing flora for resources. Although competition is often greater in riparian habitats, the periodic flooding and drying out of such areas can result in increased space that is then exploited by invasive species. In addition, for a number of reasons, nutrient levels can be greater in both aquatic and riparian habitats, favouring the growth of nutrient-responsive invasive species. In addition, aquatic habits often allow relatively free movement of plant matter, vegetative propagules, and seed, which favours the spread of any invasive species present.

A number of problems are associated with the occurrence if invasive species, and the over-occurrence of native species, in aquatic and riparian habitats. Access to water can be reduced, affecting use of water courses and bodies for commercial and amenity purposes; flow of water can be hindered resulting in increased flood risk and to the reduction in the ability to abstract water, vegetation can obscure the presence of the water body leading to health and safety concerns, dense vegetation can lead to eutrophication and anoxia of the water, negatively impacting on native flora and fauna, replacement of native flora an issue too, sometimes completely. This is especially true for where the invasive annual species (e.g. *I. glandulifera)*. When the annual dies back there is reduced soil support and a greater risk of bank erosion, something that is prevented in part by presence of native perennial species. Although invasive species can, and do, invade native habitats, they are more successful where habitats are physically-damaged. This can take place where habitats are over- , under- or mis-used, where too much water is abstracted, where natural drainage is hindered, and where pollution of water by nutrients is an issue. Toxicity issues related to algal blooms are particularly associated with this.

Aquatic and Riparian Habitats – Invasive Species

Aquatic and riparian genera/species that were discussed in papers presented in the 1981 conference in are presented in Table 1. All the native and non-native genera/species discussed in the proceedings of this conference are still reported as causing problems and requiring control currently. However, the focus has shifted over the decades towards invasive species that have increased and are causing far more significant issues both with regard to habitat management and economic cost. A similar conference held today would undoubtedly contain reference to *F. japonica*, *I. glandulifera*, and *Heracleum mantegazzianum*, which were not included in the 1981 proceedings. Although not the only invasive aquatic and riparian plant species of concern currently, these three occur extensively, and a large proportion of the financial cost of aquatic vegetation management is attributed to them. In addition, all three continue to increase in spite of these management efforts.

Impatiens glandulifera (Himalayan balsam) is an annual species that grows to 1–3 m in height. It has a long flowering period, generally from June – October, but extended where climatic conditions are suitable. It was introduced to the UK in the early 19th Century and was first recorded in the wild in 1855. The species thrives in damp conditions, tolerates low light, and as such is very much suited to establish in riparian habitats. Seed production is reported to be in excess of 800 plant^{-1}, and these are explosively ejected from pods to several metres distance. Seed is also spread via water and in soil movement (vehicles, clothing, and footwear). Seed is viable in soil for at least 2 years. *I. glandulifolia* will very successfully outcompete native vegetation, often to its complete exclusion. This has a knock-on effect for native fauna too. Plants die back in autumn leaving little or no support for river and stream banks. This results in increased bank erosion and can lead to localised flooding. The species can also reduce water flow and access to riverbanks. In 2003 The Environment Agency estimates that it would cost up to £300 million to eradicate this species from the UK (CABI, 2017).

Heracleum mantegazzianum (Giant Hogweed) was introduced as a horticultural species in the 1820s. It has subsequently has become naturalised over much of the UK. It is a perennial species that grows up to 3.5 m in height and forming dense stands to the exclusion of other species. Each plant can produce 50–100,000 seed, which are spread on wind and via water. In autumn the above-ground growth dies back and leaves banks exposed to erosion. Where present it will impede water flow and is also a risk to public health due to the blistering nature of its sap, which causes phyto-photodermatitis. The risk to the public is often what promotes its removal.

Fallopia japonica (Japanese Knotweed) (and associated *Fallopia* species and hybrids) was first introduced to the UK in the 1880s. It is a tall perennial species growing 2–3 m tall. It has very rapid growth and form dense thickets completely out-competing all native vegetation. In the UK it does not produce fertile seed so its spread is down to vegetative growth via rhizomes, and movement of rhizome fragments in soil. Through this means it has been incredibly successful in its spread through much of the UK. Problems associated with *F. japonica* include exclusion of native species and the knock-on effect on native fauna, restrict water flow and of access to river banks, damages to structures and buildings, and also reduced value of land and property. *F. japonica* will regenerate from at little at 7 g of rhizome (Booy *et al.*, 2015).

Other invasive and aquatic flora, as identified in Booy *et al.* (2015), are given in Table 2. It is interesting to compare this with Table 1, and to notice that only *Elodea* sp., *Lemna* sp. and *Myriophyllum* sp. appear in both tables. This clearly indicates the changes in problem species in aquatic and riparian habitats over the last 30–40 years.

A more recently reported species invasive to riparian habitats is *Lysichiton americanus* (American Skunk-cabbage), found in terrestrial, semi-aquatic and aquatic habitats. This species, native to western North America, thrives in waterlogged soil adjacent to water bodies and water courses as well as in swamp and flooded woodlands. In its native region it is found in forested and shaded habitats, as well as in more open ones. Although first introduced into the UK in 1901 as a horticultural ornamental species (EPPO, 2006), reports of it as an invasive species date from the late 1940s. It is a long-lived perennial which reproduces via thick fleshy rhizome. It flowers between March and May. It is still a popular horticultural species (available from over 100 growers in EU countries in 2005) although recent legislation (see below) has banned its sale in the UK. As an invasive species, it spreads via rhizome fragments, seed, water, and via rhizome growth, leading to patches that exclude native vegetation.

Table 1. *Number of papers presented in 1981 AAB conference "Aquatic Weeds and their Control" (AAB, 1981) on a selection of aquatic and riparian weed species*

Genus/Species	Papers mentioning Genus/Species
Algae *	13
Potamogeton sp.	11
Ranunculas sp. / *Lemna* sp.	10
Callitriche sp. / *Elodea* sp. / *Sparganium* sp.	8
Phragmites australis	7
Glyceria maxima / *Nuphar* sp.	6
Rorippa nasturtium-aquaticum / *Myriophyllum* sp.	5
Ceratophyllum sp.	4
Phalaris sp. / *Nymphaea* sp./ *Typha* sp.	3

*For Algae, all mention of algal species have been combined.

Unlike *F. japonica*, *L. americanus* can produce viable seed under UK conditions, giving it a further means of spread. Seed have been reported to survive up to 6 years in soil (Klingenstein & Alberternst, 2006). Undoubtedly its invasive potential is contributed to by its tolerance of a wide range of growing conditions (terrestrial through to aquatic, shade to full light), and its means of successful sexual and asexual reproduction under UK environmental conditions. Within Europe, *L. americanus* has been reported as invasive in Denmark, Germany, Ireland, Netherlands, Norway, Sweden, Switzerland, as well as UK. (EPPO, 2006). As is often the case with invasive flora, this is unlikely to be a comprehensive list of its occurrence in Europe. This species will readily form large colonies under appropriate conditions (for instance in wet woodland) and this is being increasingly reported in the UK. Such colonies can consist of plants which are decades old, as the species is slow growing and long lived. There is some evidence of long distance spread via water in the UK, increasing invasive potential even where care is taken not to fragment and spread rhizome. *L. americanus* is winter hardy (down to temperatures in the region of -15°C) so is less likely than some other introduced species to be partially controlled by harsh UK winters. Water movement of seed (and rhizome fragments) and movement of rhizome fragments with soil (similar to *F. japonica*) should also be considered a key risk factor in this species' spread. Control options include hand pulling (for small populations, with a risk of leaving rhizome behind to support regrowth), repeated cutting (to gradually reduce the carbohydrate reserves in the rhizome. This is likely to require repeated cutting over a number of years, mechanical removal (but care needs to be taken with rhizome fragments and with the disposal of removed fragments and soil). In addition, mechanical methods are less realistic where other vegetation, especially woodland, provides obstruction to soil movement. Where glyphosate has been used, it has required a number years of treatment to successfully control this species. Other chemical controls, such as those used in the USA, are not appropriate in or near water in the UK due to these active ingredients not being registered for aquatic use. Undoubtedly integrated approaches will give the best long term management of this species. These integrated approaches need to focus on reducing seed return (by removing the spadix prior to seed formation), as well as controlling young plants before they have produced the extensive rhizome that proved difficult to eradicate. Such young plants will require less repeat cutting and/or less repeat glyphosate application to destroy their less well developed rhizomes. Injection of glyphosate directly into the rhizome has been suggested, and needs to be carried out at a time when there is active translocation of food reserves to the rhizome. This will depend to an extent on how photosynthetically-active a plant is and may be less successful where plants are growing in shaded conditions.

Other problem plant species are listed in Table 2. After *F. japonica*, *I. glandulifera*, and *H. mantegazzianum*, the invasive species reported as infesting the largest areas of Britain are *Elodea* sp., *Crassula helmsii*, and *Azolla filiculoides*. It will be interesting to see how both range of species and their distribution develops in light of the expanding management options, herbicide limitations, and increased legislation discussed below.

Table 2. *Aquatic and Riparian invasive species listed in Booy* et al. *(2015). Species have been ordered, from greatest to least area, based upon distribution maps from the same reference*

Species	Riparian (R) or Aquatic (A)
Fallopia japonica / sachalinesis and *hybrid*	R
Impatiens glandulifera	R
Heracleum mantegazzianum	R
Elodea sp.	A
Crassula helmsii	A
Azolla filiculoides	A
Lagrosiphon major	A
Persicaria wallichii	R
Impatiens capensis	R
Lemna minuta	A
Myriophyllum aquaticum	A
Lysichton americanus	R
Hydrocotyl renunculoides	A
Gunnera tinctoria	R
Egeria densa	A
Ludwigia grandiflora	A
Cabomba caroliniana	A

Invasive Vegetation in Aquatic and Riparian Habitats – Management Options

Successful management of invasive species in aquatic and riparian habitats will require use of a number of methods of management in a mutually-supportive manner, and should be viewed as a long term control strategy rather than a quick, short term, solution. *Physical and manual methods*, including hand-pulling, raking, cutting, mechanical cutting, harvesting, excavating and dredging can be successful where large amounts of vegetation are present and where some disruption of the water body and the bank sides is not considered to be a problem. Such methods result in fragmentation of vegetation, which can lead to re-infestation and, in water courses, further spread of the species. Care also needs to be taken with the disposal of the plant matter that is removed, as it will often regenerate from fragments in appropriate aquatic conditions. These methods are generally useful for bankside species, emergent species, and semi-emergent species, and prove less successful with surface and submerged species, and are not useful for small species such as *Lemna* sp. or *Azola* sp. *Environmental management methods* can include shading, dyes, buffer strips, nutrient and pollution management, and physical disruption via manipulation of water level or flow. These methods involve reducing light to invasive vegetation (via tree planting, artificial barriers, dyes absorbing at specific wavelengths), managing nutrients and pollutants to better support native vegetation rather than invasive species, and changing both water level and movement to make the habitat less suitable for invasive species. Such methods tend to be more long term than physical and manual methods, but can also be slower acting and may cause more disruption to those wanting to use bodies of water.

There has been a lot of interest in developing *biological management methods* for riparian and aquatic vegetation, but to limited success to date. Although this has often involve finding a pest (or disease) that controls the invasive species in its native geographical region, and aiming to introduce this to region where the invasive species is a problem, the use of domesticated terrestrial species, waterfowl, and (native) fish should not be overlooked. If a biological control species is to be introduced that is not native to the region then great care needs to be taken that the biological control species does not subsequently become a problematic invasive species itself. It is this that has prevented the introduction to the UK of certain fish species that, elsewhere in the world, have been successfully used for aquatic vegetation management. A recent success story of the use of biological control has been the use of the Azolla weevil (*Stenopelmus rufinasus*) in the control of *Azolla filiculoides*. This system, developed by CABI, has the benefit of being self-regulating in that, once the *A. filiculoides* has been controlled, the weevil dies out due to lack of food supply (CABI, 2018). Such specificity of biological control is of great use in controlling the introduced species. Barley straw, and barley straw extracts, have proved very useful in the management of aquatic algae, and represent arguably one of the largest moves forward in aquatic weed management over the last few decades. Papers in the 1981 AAB abstract that focussed on algal control were largely looking towards the use of synthetic chemicals to achieve this. Of the *novel control options* that have been developed, use of ultrasound for the management of algal blooms has been the most successful. These systems can be left running permanently and are reported to be very effective whilst having little or no effect on non-target organisms. They also cause little or no disruption to users of bodies of water, and are unobtrusive. Floating spheres, originally developed to reduce evaporation from reservoirs, have been trialled as methods for shade management of submerged aquatic vegetation. This will undoubtedly be successful but is limited where bodies of water are used for amenity or where aesthetics are important. Management of both submerged and floating vegetation has been carried out using a variety of suction systems. These can be particularly useful for small species such as *Lemna* sp.

For more details, a good overview of management methods for aquatic and riparian species has been published by The Environment Agency (2014).

Invasive Vegetation in Aquatic and Riparian Habitats – Herbicide Options

In 1981 Barrett reported that there were 10 herbicide active ingredients that were registered for use in aquatic weed management in the UK. Of these, four are no longer registered for use in any situation in the UK and five are no longer registered for use in or near water. In February 2018, only glyphosate is registered for use in aquatic situations in the UK. Given the uncertain future for glyphosate then the future of herbicide use in or near water is in doubt. In November 2017, glyphosate was granted a (5 year) extension of registration across the EU, guaranteeing its availability in the short term. After this period there is uncertainty, and it is unlikely that other herbicides will be granted registration for 'on and near water' in its place. There is a very real possibility that we may have to face management of aquatic and riparian vegetation, including the 'big three' riparian species *F. japonica*, *I. glandulifera*, and *H. mantegazzianum*, without herbicides. This will undoubtedly put too much pressure on the 120 day pesticide emergency approval system (via Article 53 of Regulation (EC) 1107/2009) as vegetation management professionals attempt to get temporary approval for other herbicide active ingredients. With respect to the toxicity of glyphosate-containing products, it is interesting to note that Defarge *et al.* (2016) highlighted the relatively greater toxicity of the other components/adjuvants of these products than the toxicity of glyphosate active ingredient itself. It may be that in the future, use of glyphosate-containing products in or near water will require reformulation with very careful selection of the adjuvants that are being included. There is great concern within much of the agricultural sector regarding the potential loss of glyphosate, with focus on what alternative products, including essential oil based products, can be used to replace it. Essential oil based herbicide products would be totally inappropriate for aquatic situations due to the adverse effects such products would have on non-target organisms.

Invasive Vegetation in Aquatic and Riparian Habitats – Legislation, Prevention, and Biosecurity

Attempts have been made to limit the spread of invasive plant species in the UK, with particular focus on *F. japonica*, through a number of pieces of legislation. The Wildlife and Countryside Act 1981 (and various amendments), Natural Environment and Rural Communities Act 2006, Countryside and Rights of Way Act 2000, along with Antisocial Behaviour, Crime and Policing Act 2014 and Environmental Protection Act 1990, all offer some legal ability to attempt to reduce spread of invasive plant species. The WLC Act contains a list of invasive plant species (Schedule 9) of which a number are of importance in aquatic and riparian habitats. These are listed in Table 3. Sale of these species was banned as it was believed that the careless use and disposal of these species was leading to a rise in invasive populations of them in the UK and in Europe. Although the lack of availability of these species will undoubtedly reduce their introduction as horticultural species to lakes, ponds and gardens, it is worth noting that many are still available to buy over the internet, both from commercial companies and through private sale sites. In addition, at least one company in the UK is breeding a 'sterile' hybrid of *L. americanum* that they claim will not be invasive as it does not produce viable seed. This overlooks the role the rhizome plays in the reproduction and spread of this species, and it is unclear how the legality of such a hybrid will be viewed by current legislation.

Table 3. *Aquatic plant species banned from sale in the UK under Schedule 9 of the Wildlife and Countryside Act*

Species	Year 'banned from sale' can into force
Water Fern (*Azolla filiculoides*)	2015
Australian Swamp Stonecrop (New Zealand Pygmyweed) (*Crassula helmsii*)	2015
Floating Pennywort (*Hydrocotyle ranunculoides*)	2015
Water Primrose (*Ludwigia grandiflora*)	2015
Floating Primrose-willow (*Ludwigia peploides*)	2015
Parrot's Feather (*Myriophyllum aquaticum*)	2015
Alligator Weed (*Alternanthera philoxeroides*)	2017
Cabomba (*Cabomba caroliniana*)	2017
Water Hyacinth (*Eichhornia crassipes*)	2017
Nuttall's Waterweed (*Elodea nuttallii*)	2017
Giant Rhubarb (*Gunnera tinctoria*)	2017
Curly Waterweed (*Lagarosiphon major*)	2017
American Skunk-cabbage (*Lysichiton americanus*)	2017
Broadleaf Water-milfoil (*Myriophyllum heterophyllum*)	2017

There has also been attempts to encourage increased biosecurity through initiatives such as "Be Plant Wise", where users of aquatic habitats are encouraged to "Know what you Plant", "Stop the Spread", and "Compost with Care". This is a move in the right direction, but it does seem that biosecurity with respect to flora is not taken as seriously in general as it is with respect to fauna or pathogens, both specifically to aquatic habitats and more generally. The result of this, both in aquatic situations and in terrestrial weed management, is too often the 'firefighting' approach to deal with out-breaks of invasive vegetation rather than a long term integrated approach that begins with the aim of preventing out-breaks from occurring. This can only be accomplished by moving from short term focus to a medium and long term focus to integrated vegetation management. In many cases the management also needs to be focussed over a larger, catchment, area if reinvasion is going to be prevented.

Conclusions

Unlike agricultural weed management, vegetation management in aquatic and riparian habitats is not underpinned by large amounts of finance driving research and development, mainly because the small market size for any chemical product. Historically, herbicides became available to this sector via 'trickle down' from the agricultural sector. This is not likely to happen in the future and there is a possibility that the one active ingredient we do have, glyphosate, may not be available to us in years to come. The funding and support for R and D in this sector is one of the great challenges we face, especially in focussing this on issues that have not become a major problem yet, rather than waiting until other species are as problematic as *F. japonica* and *I. glandulifera*. Dedicated research programmes not only looking at individual management methods but also at integrated vegetation management systems as a whole will give us the best possible chance of avoiding adding to the problems we already face with aquatic and riparian invasive species.

References

AAB. 1981. *Aspects of Applied Biology* **3**, *Aquatic Weeds and their Control.* Wellesbourne, UK: Association of Applied Biologists.

Barrett P R F. 1981. Aquatic Herbicides in Great Britain, Recent Changes and Possible Future Development. *Aspects of Applied Biology* **3**, *Aquatic Weeds and their Control*, pp. 95–103.

Booy O, Wade M, Roy H. 2015. *Field Guide to Invasive Plants and Animals in Britain.* London, UK; New York, USA: Bloomsbury Academic.

CABI. 2017. *Impatiens glandulifera* (Himalayan Balsam) datasheet. www.cabi.org/isc/datasheet/28766.

CABI. 2018. www.azollacontrol.com.

Defarge N, Takáces E, Lozano V L, Mesnage R, Spiroux de Vendômois J, Séralini G-E, Székács A. 2016. Co-Formulants in Glyphosate – Based Herbicides Disrupt Aromatase Activity in Human Cells below Toxic Levels. *International Journal of Environmental Research and Public Health* **13**(3):1–17.

EPPO. 2016. Lysichiton americanus *Data sheet on quarantine pests.* Paris, France: European and Mediterranean Plant Protection Organization.

Klingenstein F, Alberternst B. 2006. *NOBANIS - Invasive Alien Species Fact Sheet* - Lysichiton americanus. Akureyri, Iceland: North European and Baltic Network on Invasive Alien Species – NOBANIS.

The Environment Agency. 2014. *Aquatic and riparian plant management. Control for vegetation in watercourses. Technical Guide.* Rotherham, UK: The Environment Agency.