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Management options of invasive *Elodea nuttallii* and *Elodea canadensis*

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ABSTRACT

Elodea nuttallii and *Elodea canadensis*, two invasive submerged and rooted aquatic macrophyte species, are receiving increasing attention for their rapid and lasting invasion of many freshwater habitats throughout Europe, Asia and Australia. This review summarizes the present scientific knowledge about means of controlling *E. nuttallii* and *E. canadensis* within of aquatic weed management programs. Both species exhibit high growth rates with a high tolerance to wide ranges of environmental conditions, low vulnerability to grazing and other stress factors, high distribution and reproduction potential, and relatively high resistance to common conventional aquatic weed management procedures. Possibilities for the further use of harvested *Elodea* biomass are presented and novel approaches to the improvement of the monitoring and management of *Elodea* plagues are discussed.

Introduction

Submerged aquatic plants play a key role in the functioning of freshwater ecosystems. They affect the physical and chemical conditions of water and sediment, alter the nutrient cycle, influence the interaction between predator and prey, and act as a food source either directly or indirectly through the periphyton (Jeppesen et al., 1998). However, mass developments of submerged aquatic plants can cause serious problems for human use of water bodies (Hilt et al., 2006). Introduced alien aquatic plant species are known to modify the macrophyte community composition by forming mass developments (Stiers et al., 2011; Hussner, 2014). *Elodea canadensis* Michx. and *Elodea nuttallii* (Planchon) H. St. John are two alien aquatic plant species that have been introduced into Europe and have become widespread (Hussner, 2012). Even if in most cases no obvious negative effects of either species were found, in some cases they formed mass developments and became a nuisance for water users and, as a result, countermeasures had to be taken. In this paper, we review the management techniques available for these two common aquatic plant species and evaluate the success and costs of the various management approaches.

Invasion history

E. canadensis and *E. nuttallii*, two members of the family of Hydrocharitaceae that are native to North America, have been introduced as ornamental elements into a wide spectrum of aquatic habitats. In their native range, *Elodea* populations rarely seem to reach plague proportions (Nichols and Shaw, 1986). However, the number of ecological investigations on *Elodea* in its native range is limited (Lawrence, 1976; Argus and White, 1977; Bouchard et al., 1983; Catling and Wojtas, 1986).

After its introduction in the 19th century, *E. canadensis* became the most common alien aquatic species in Europe (Hussner, 2012). *E. nuttallii* was introduced into Europe in 1939 (Wolff, 1980). It spread rapidly and became the most abundant alien aquatic plant species in several European countries, displacing *E. canadensis* from numerous sites (Barrat-Segretain and Cellot, 2007). A high degree of ecological and functional redundancy exists between *E. canadensis* and *E. nuttallii*, which leads to wide niche overlaps (Hérault et al., 2008). After their introduction, both became dominant aquatic macrophyte species in temperate shallow lakes of different trophic levels. In Germany, mass developments of introduced aquatic plant species are mainly caused by *E. canadensis* and *E. nuttallii* (Hilt et al., 2006; Hussner et al., 2010).

Due to their rapid spread in their introduced range in Europe, Asia and Australia, for example, *E. canadensis* and *E. nuttallii* have

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been attracting increasing scientific and public interest. Water use programs, including aspects of energy generation, nature conservation and recreation, can be severely impeded by extended canopies of *E. nuttallii*. In addition, mass developments hinder boat traffic or make lakes unattractive for swimmers. After root decay in autumn, canopy-forming *Elodea* stands form non-anchored floating mats, which can increase the hydraulic pressure at piers of downstream bridges or can block the inflow section of hydroelectric power plants. Nutrients and environmental pollutants bound in *Elodea* biomass are released within a short period of time after plant decay in autumn and winter, negatively affecting the ecological status of the water body. The wide distribution of *E. nuttallii* indicates the relatively flexible use of different nutrient sources from the water column or sediment (Angelstein and Schubert, 2008). In oligo-mesotrophic lakes in particular, *E. nuttallii* has to use several nutrient sources, and nutrient uptake via root absorption is particularly relevant (Carignan and Kalff, 1980; Barrat-Segretain, 2001; Nagasaka 2004). The mass development of aquatic plants such as *E. nuttallii* may play an important role in the phosphorus cycle of lake ecosystems (DeMarte and Hartman, 1974; Ozimek et al., 1993). By taking up phosphorus from sediment, roots reduce the phosphorus content in the surrounding pore water. Subsequently, this phosphorous may be released into the water via leakage from the plant in autumn and winter, grazer recycling, or decomposition (McRoy and Barsdate, 1970; DeMarte and Hartman, 1974; Carignan and Kalff, 1980). Sand-Jensen et al. (2000) describe the abundance of aquatic macrophytes in Danish lakes and streams over the past 100 years and present a symptomatic picture of the changing species diversity of submerged aquatic macrophytes over the past decades. While eutrophication of freshwater habitats due to industrialization and urbanization has caused reduced macrophyte abundance and species richness – for example of the genus *Potamogeton* – throughout the 20th century, improving water quality over the past ten to twenty years has not led to the recovery of the lost macrophyte species (Bakker et al., 2013). Instead, the ecological niches of the lost macrophytes have been occupied by introduced exotic plants such as *E. canadensis*, which – due to their high competitiveness – prevent the recovery of the historically indigenous species. In general, global warming might facilitate the expansion of warm-adapted non-native plant species to moderate or colder climate zones.

The role of environmental factors in the growth of *Elodea* spec.

Growth cycle

E. nuttallii and *E. canadensis* exhibit active growth of shoots and roots at temperatures above 10 °C (Kunii, 1984; Madsen and Brix, 1997), but slow growth of lateral shoots of *E. nuttallii* fragments has also been observed at 4 °C at the bottom of a water body (Kunii, 1981). In many lakes where water temperature in winter is rarely lower than 4 °C, there is practically no strict winter dormancy of *E. nuttallii*. As temperature increases in spring, leafy stems grow upwards to the water surface, followed by lateral shooting and canopy formation. During this extensive growing period, *Elodea* plants act as a sink for nutrients such as phosphorus and nitrogen and may cause nutrient deficiencies for competing macrophytes and phytoplankton (Van Donk et al., 1993).

Conventional biomanipulation of shallow lakes has focused primarily on the reduction of nutrient content and phytoplankton in order to trigger the transition of eutrophicated water bodies into macrophyte-dominated lakes (Lauridsen et al., 1994; Köhler et al., 2005). The establishment of submerged vegetation is a major goal of almost all restoration measures in formerly macrophyte-free shallow water bodies, which can be achieved through nutrient reduction and reduced phytoplankton growth (Hussner et al. 2014a). In these cases, the success of a given species is often a pattern of "first come, first win", but the re-establishment of submerged vegetation – regardless of whether this consists of aliens or natives – is considered a very important factor for ecosystem functioning in the context of successful restoration (Hussner et al., 2014a).

Defoliation and root decay occur in late summer in dense macrophyte stands as a result of self-shading by the canopy, and this is accompanied by the release of the macro-nutrients phosphorus and nitrogen (Van Donk et al., 1993). The population then exists as a non-anchored floating mat, which is subject to easy displacement and spread to other areas (Pot and Ter Heerdt, 2014). Ongoing disintegration of the floating mat during autumn leads to sinking of residual fragments to the bottom in early winter (Kunii, 1984). The released macro-nutrients are subject to deposition in the sediment (Van Donk et al., 1993).

Elodea sp. can easily colonize new areas by means of plant fragments with a high survival capacity and through peripheral propagation. In spring, most plant fragments develop propagules, whereas in summer and autumn most fragments anchor themselves to increase survival during winter (Barrat-Segretain and Bornette, 2000).

Light

Elodea species are adapted to relatively low light conditions; thus they can act as pioneer macrophytes of eutrophic freshwater habitats in the transition from the phytoplankton-dominated to the macrophyte-dominated state and they can tolerate moderate shading by periphyton and other submerged macrophytes (Abernethy et al., 1996).

Comparing the light requirements of *E. canadensis* and *E. nuttallii*, it has been found that light favors biomass formation in both monocultures and mixtures, but that *E. canadensis* is more sensitive to low-light conditions than *E. nuttallii* (Barrat-Segretain, 2004). Furthermore, *E. nuttallii* stems grow more slenderly, meaning that biomass formation contributes more to length extension in comparison with *E. canadensis* (Barrat-Segretain and Elger, 2004). Rapid stem elongation is an essential trait for reaching the water surface and forming shading canopies. Other macrophytes that develop later or more slowly can therefore be affected in their growth by light deficiency (Barrat-Segretain, 2004), and intraspecies and interspecies competition is less restrictive for the growth of species that are capable of rapid canopy formation such as *E. nuttallii* (Barrat-Segretain and Elger, 2004).

Macronutrients

The sensitivity of aquatic macrophytes to nutrient availability in freshwater habitats allows for a categorization of shallow lakes according to their nutrient levels using aquatic macrophyte species abundance and the degree of nutrient pollution of the habitat. In Alpine calcareous lakes, both *E. nuttallii* and *E. canadensis* have been observed to indicate massive nutrient pollution and reflect the fact that *Elodea* species require and tolerate moderate to high nutrient levels in the ecosystem (Melzer, 1999). In running waters such as in the Northern Vosges streams (France), *E. canadensis* and *E. nuttallii* grow preferentially in mesotrophic sections. *Elodea* sp. follow an upstream to downstream zonation of stream eutrophication and coincide with increasing nutrient levels as well as increasing buffer capacity and increasing pH (Thiébaut and Muller, 1999).

Phosphorus

Elevated dissolved phosphorus levels promote biomass formation in both *Elodea* species. Additional phosphorus supplies can be invested in stem elongation and rooting (Eugelink, 1998) or in the formation of lateral branches (Barrat-Segretain, 2004). *E. nuttallii* is able to maintain high growth rates over a wide range of phosphorus concentrations in the sediment.

Phosphorus can be taken up through the leaves and through the roots (Eugelink, 1998) in both *E. nuttallii* and *E. canadensis*. Root uptake of phosphorus appears to be the preferential mechanism in many aquatic macrophytes and accounts for about 99% of phosphorus uptake in *E. canadensis* in experiments with ^{32}P-labeled sediment (Carignan and Kalff, 1980). In *E. nuttallii*, the root uptake of phosphorus is faster than in *E. canadensis* (Eugelink, 1998). It has been shown in ^{33}P-spiked sediment-free laboratory experiments that specimens of *E. nuttallii* can meet their phosphorus requirements by uptake of dissolved phosphorus from the water through the shoots in eutrophic waters (Angelstein and Schubert, 2008). Indeed, phosphorus uptake through the shoots is only significant in hypertrophic waters (Carignan, 1982) or in wastewater treatment wetlands (Ulén and Tonderski, 2005) with elevated dissolved phosphorus levels. Consequently, net translocation of phosphorus in submerged macrophytes is assumed to be dominantly directed from the root to the shoot (Eugelink, 1998) and macrophytes should therefore be considered as active sediment phosphorus recyclers and potential phosphorus pumps to the water body (Carignan and Kalff, 1980, 1982). Phosphorus taken up from the sediment by plant roots and released by the plant into the water is preferentially channeled through the epiphyton's phosphorus metabolism and represents a seasonal input of bioavailable phosphorus to the littoral zone (Hérault et al., 2008). Phosphorus uptake through the leaves has been found to be light-dependent in *E. nuttallii* (Angelstein and Schubert, 2008), implying that a diurnal cycle of phosphorus release during the night and re-absorption during daytime might exist in addition to seasonal phosphorus cycling between aquatic macrophytes and water or sediment. *E. canadensis* and *E. nuttallii* exhibit a high potential for phosphorus storage and can thrive over a wide range of dissolved and sediment phosphorus concentrations. The total phosphorus content of *Elodea* plants in and along rivers may differ considerably by up to three orders of magnitude (Clarke and Wharton, 2001), but positive linear correlations have been obtained between dissolved reactive phosphorus in the water or total phosphorus in the sediment and the tissue phosphorus content of *Elodea* plants (Thiébaut and Muller, 2003; Thiébaut, 2005).

E. canadensis and *E. nuttallii* assimilate phosphorus in similar proportions, accounting for 1.0–1.6 mg P per g dry weight (Ozimek et al., 1993), although somewhat lower levels have been published as well (Garbey et al., 2004; Angelstein and Schubert, 2008). Under eutrophic conditions, *E. nuttallii* has been shown to accumulate higher phosphorus amounts and the phosphorus tissue contents in *E. nuttallii* and in some other aquatic macrophytes have been found to depend on phosphorus availability along a resource gradient (Garbey et al., 2004).

Effects of mass developments of *Elodea* spec.

Massive growth of aquatic macrophytes, i.e. of introduced invasive species such as *Elodea*, can have both economic and ecological effects. *Elodea* sp. are in direct public focus, however, when the plant covers huge lake areas and hampers boat traffic or recreational activities (Podraza et al., 2008). Dislocated floating *Elodea* mats block the entrance section of hydroelectric power plants (Clayton and Champion, 2006) and mass developments of *Elodea* have consequences for the hydrosystem balance. In addition, the decomposition of *E. nuttallii* at the end of the growing season induces secondary eutrophication (Di Nino et al., 2005), conducing to an intense bacterial metabolism and producing anoxic, reducing conditions. These result in decreased rates of mineralization and in the accumulation of fermentation end-products that are toxic to many plants (Santamaria, 2002). Spreading *Elodea* depress native aquatic macrophyte flora and decrease biodiversity in invaded freshwater ecosystems (Howard-Williams, 1993; Mjelde et al., 2012).

Management of invasive *Elodea* spec.

Due to the ecological and economic problems caused by mass developments of *Elodea* sp., both species are often categorized as pest species with a moderate to high weed potential (Champion et al., 2010).

Several countries have performed a ranking and classification of alien species, and both *Elodea* species are included in the "Black List" in certain European countries, e.g. in Germany (Verbrugge et al., 2012; Hussner et al., 2014b). The EU Council adopted a new regulation on invasive alien species on 29 September 2014. This new legislation seeks to address the problem of invasive alien species (including alien aquatic species) in a comprehensive manner (http://ec.europa.eu/environment/nature/invasivealien/index_en.htm). The aim of this regulation is to protect native biodiversity and ecosystem services and to minimize and mitigate the impacts that these species can have.

Even though prevention of introduction and early eradication measures are considered the most successful ways to limit the spread of invasive species, trading bans generally appear to be a less effective option in the case of *Elodea* due to the already wide range of infested habitats in most regions. In Europe, *E. canadensis* is the most common alien aquatic plant species, and *E. nuttallii* ranks fourth (Hussner, 2012).

However, once established, *Elodea* stands may become a nuisance and have to be managed in these cases. The methods used for aquatic weed management (Table 1) include water level drawdown, sediment dredging, measures to reduce nutrient input into lakes, food web manipulation by diminishing planktivorous fish populations or by introducing fish grazing on macrophytes, and the application of herbicides (Bowmer et al., 1995). None of the methods are free of drawbacks, but long-term experience in the field and the education of regional authorities may help to improve the situation.

Nutrient reduction

Nutrient reduction is essential for the improvement of water quality in eutrophic lakes and streams and may be the key factor in governing the transition from a phytoplankton-dominated to a macrophyte-dominated habitat. The decrease of the phosphorus and nitrogen load of inflowing wastewater may trigger a decrease in the phytoplankton biomass and the appearance of aquatic macrophytes such as *Elodea* sp. The dosing of ferric iron or aluminum to precipitate phosphorus has been used as a management strategy to reduce dissolved phosphorus levels and has resulted in *Elodea* dominance (Perkins and Underwood, 2002).

The massive growth of *Elodea* sp. cannot be controlled by artificial phosphorus limitation (Daldorph, 1999). Presumably, the reason for the prevalence of *Elodea* sp. in lakes low in dissolved phosphorus is the ability to mobilize phosphorus resources from the sediment and to take them up through the roots (Carignan and Kalff, 1980; Barko et al., 1991; Eugelink, 1998). The history of industrial or municipal water pollution of a lake or stream over the last decades is reflected in sediments which serve as long-term reservoirs of nutrients and pollutants for rooted aquatic macrophytes. Accordingly, the establishment of long-term nutrient equilibria after nutrient reduction has been observed to take more than one decade,

Table 1
Methods for aquatic weed management.

Species name	Method	Efficiency	Comments	Reference
Biological control				
E. canadensis and *E. nuttallii*	Stocking grass carps	Medium	Not species-specific	Bonar et al. (2002), Pipalova (2006), Dibble and Kovalenko (2009)
E. nuttallii	Stocking rudd	Medium	Not species-specific	Prejs (1984), Van Donk et al. (1993), 1994, Van Donk and Otte (1996), Podraza et al. (2008)
E. canadensis	*Fumarium* spec.	N.A.	N.A.	Gollasch (2006)
Mechanical control				
E. canadensis and *E. nuttallii*	Wed cutting	Low to medium	Not species-specific, fast regrowth	Podraza et al. (2008)
E. nuttallii	Shading with jute mats	High	Not species-specific, efficient only during the first year after installation	Hoffmann et al. (2013)
E. canadensis	Lime application to reduce C availability	Low	Only short time effects, not species-specific	James (2008)
E. nuttallii	Water level drawdown	Low	Not species-specific	Barrat-Segretain and Cellot (2007)
Chemical control			Not allowed in some European countries	
E. canadensis	Diquat application to the water	High	Not species-specific	Glomski et al. (2005)
E. canadensis	Diquat spraying of the harvester to minimize the risk of dispersal	N.A.	Not species-specific	Howard-Williams et al. (1996)
E. canadensis	Acrolein application to the water	High	Not species-specific	Bowmer and Smith (1984)
Prevention				
E. canadensis and *E. nuttallii*	Trading bans	Low to high	Trading bans are only efficient for species that are absent or only with limited distribution in a given area	Champion et al. (2010)

during which the macrophyte population is unstable, may change from year to year and may transform the lake into a turbid state when the macrophyte population dies back (Jeppesen et al., 2007).

The artificial limitation of dissolved inorganic carbon (DIC) might be more promising for the control of massive aquatic macrophyte growth. Although *Elodea* sp. use alternative mechanisms to utilize inorganic carbon sources (Sand-Jensen and Gordon, 1986; Jahnke et al., 1991; Jones et al., 1993), the general artificial limitation of DIC would reduce the availability of a usable carbon source. It was found in mesocosm experiments that the addition of lime (as $Ca(OH)_2$) decreased the HCO_3^- and DIC concentration by about 60–90%, resulting in remarkably reduced shoot and root growth in *E. canadensis* and other aquatic macrophytes (James, 2008). Whereas increased pH recovered within 20 days, limited DIC concentrations remained low throughout post-treatment.

Mechanical methods

Mechanical harvesting, cutting and dredging have become widespread techniques to control plagues of *Elodea* sp. This is reflected in the large number of reports on aquatic weed management in "gray" literature. These techniques represent the first attempts to take into account local viewpoints at sites with massive proliferation of aquatic macrophytes and appear to solve the problem at least for a short period of time. The most widely used instruments for mechanical aquatic weed management are weed-cutting boats often with a cutting depth of 2–3 m, weed rakes usable from banks, or bucket-like shallow or deep dredges (Sabbatini and Murphy, 1996; Howard-Williams et al., 1996).

Unfortunately, *Elodea* appears to be quite resistant to cutting and plant survival is usually not impaired in the long term (Abernethy et al., 1996; Baattrup-Pedersen et al., 2002; Podraza et al. 2008). On the contrary, cutting produces and spreads plant fragments with a high potential for regeneration and the residual plant tends to form more lateral branches in response to cutting (Mielecki and Pieczynska, 2005). Furthermore, light availability increases in cut regions, which promotes fast re-growth (Baattrup-Pedersen et al., 2002). Biomass production can, however, be significantly reduced when harvests are performed at the time of the beginning of regeneration of *Elodea* plants after winter and can be further reduced to almost zero by a second harvest before the beginning of the fragmentation of *Elodea* plants in May (Di Nino et al., 2005). However, any mechanical or manual removal of *Elodea* stands benefits species that are resistant to disturbance – such as *Elodea* sp., ironically – and will not enable the recovery of native species that are sensitive to disturbance (Di Nino et al., 2005). In addition, shifts in species dominance in favor of species with a high re-growth potential, such as *Elodea*, after mechanical harvesting have been reported (Howard-Williams et al., 1996). Both *E. canadensis* and *E. nuttallii* have a relatively fragile structure that can be easily disrupted by harvesting and dredging procedures. Alternatively, the use of biodegradable jute matting for covering of *E. nuttallii* has been investigated, but up to now only with effects on growth for one vegetation period; after this, the mattings were damaged and ineffective (Hoffmann et al., 2013).

A new tool for managing submerged plants is the Hydro-Venture system (Van Valkenburg et al., 2011). This method can be used to uproot submerged vegetation from soft sediments by using a powerful artificial water stream. Initial control measures of *Cabomba caroliniana* Gray in the Netherlands have documented the success of this control method in a case where a formerly completely covered channel was freed from submerged vegetation (Van Valkenburg et al., 2011). Even if experiences with other species like *Elodea* are lacking, it seems likely that this method is a more powerful management strategy than the commonly used cutting techniques.

Apart from the direct impact on aquatic vegetation, mechanical harvesting and dredging activities have immediate adverse effects for higher organisms that live and proliferate in stands of aquatic macrophytes. It has been found that weatherfish (*Misgurnus* *fossilis* L.) almost completely disappeared from drainage channels after cutting of dominant *E. canadensis* (Meyer and Hinrichs, 2000). Although weatherfish are generally regarded as bottom-oriented, adult animals preferentially inhabit patches with dense *E. canadensis* stands near the water surface in mid-summer. Consequently, they lose protected food supply zones upon aquatic weed cutting and protected muddy sediment habitats upon dredging. Machine dredging removes fish that live close to the sediment, such as weatherfish, burbot (*Lota lota* L.) or tench (*Tinca tinca* L.). The dredged material, which includes these fish, is disposed of on land and left to dry out or be eaten by avian predators. In order to allow the fish to escape, it has been recommended to carefully revise existing weed management strategies with respect to higher water organisms and to dredge or harvest drainage channels, for example, only in short sections and alternating between the two sides of streams (Meyer and Hinrichs, 2000).

Although mechanical harvesting is labor-intensive and involves problems such as uncontrolled dispersal of the harvested plant by re-settling of ruptured plant fragments in downstream areas, it represents the only applicable weed control method where other methods, such as the introduction of herbivorous fish and the use of herbicides, are forbidden and draining is not possible.

Utilization of harvested Elodea biomass

A further issue associated with harvesting is the disposal or utilization of harvested Elodea. The cutting of *Elodea* plant biomass is restricted to the summer and autumn months and is characterized by unpredictable quantities for potential users. It is therefore necessary to explore those disposal or utilization strategies that work independently of *Elodea* harvesting, but have the capacity to deal with the relevant biomass quantities. Biogas plants and composting facilities appear to be likely candidates for the accommodation of occasionally occurring biomass of *E. nuttallii*, even of large amounts. Although anaerobic digestion of the water hyacinth *Eichhornia crassipes* (Mart.) Solms has been intensively investigated (Srivastava, 1995, for example), general information on the behavior of other aquatic macrophytes in biogas plants is very limited. *Elodea* species contain valuable constituents such as protein, cellulose, starch and sugars (Lindstrom and Sandstrom, 1939), making the plant a promising substrate for biomethanization. *Elodea potamogeton* (Bertero) Espinosa, an *Elodea* species that grows in South America, has been successfully digested in blends with other aquatic macrophytes and manure from cattle, sheep and lamas (Alvarez and Lidén, 2008).

As recently reported by Zehnsdorf et al. (2011), biogas generation with 100% *E. nuttallii* biomass is possible, though economically unviable due to the decrease of biogas yield generated by the low organic dry matter of *E. nuttallii*. Better results were obtained with a mix of 30% *E. nuttallii* biomass with 70% maize silage, generating a biogas yield of 580 SL/kgoDM, which remains within the range of biogas yields from maize silage.

Among other potential uses of harvested *Elodea* are hydrothermal carbonization (HTC) and the use for pharmaceutical extracts. For HTC, the high water contents of hydrophytes fulfill the prerequisites for running these processes. HTC strategies could be suitable for the use of *E. nuttallii* in biochar-related concepts of carbon sequestration and soil amelioration as well as for energy recovery of feedstock chars in combustion plants (Muñoz Escobar et al., 2011).

On the other hand, the content of up to 462 ppm of β-sitosterol in *E. nuttallii* (Muñoz Escobar et al., 2011) indicates its potential use as a raw material for the extraction of this substance that is used for the medical treatment of hyperplasia. Even though this concentration is lower than that found in other plants, the availability of the biomass once *E. nuttallii* is harvested might save production costs in the extraction of β-sitosterol.

Water level drawdown

Water level drawdown refers to the exposure of aquatic vegetation to winter frost or summer dryness by reducing the water level, and the lowered water level can then be used for easy mechanical removal of *Elodea* (Chapman et al., 1974). In practice, this method mostly is restricted to ponds or reservoirs, although natural shallow lakes or creeks can dry out in summer as a result of dry and hot weather.

Drawdown of vegetative fragments or whole plants of *Elodea* species by long summer dryness or artificial lowering of the water level does not necessarily reduce *E. nuttallii* biomass in the long run. No substantial decrease of biomass of *E. nuttallii* was observed one year after desiccation of a channel with dense *Elodea* stands in a long dry period, although laboratory experiments had shown that *E. canadensis* is more susceptible to desiccation than *E. nuttallii* (Barrat-Segretain and Cellot, 2007). Generally, the longer plant fragments are, the better the chances for fast re-growth of both *Elodea* species (Barrat-Segretain and Cellot, 2007). Although *Elodea* plants disintegrate rapidly outside water, sufficiently moist areas may remain under a desiccated surface of macrophytes in a drawdown event, giving rise to rapid re-growth of *Elodea* shoots from the protected sub-surface layer (Barrat-Segretain and Cellot, 2007).

Introduction of herbivorous fish and waterfowl

Extensive grazing of fish and waterfowl on *E. nuttallii* and other macrophytes in shallow temperate lakes can substantially increase animal population numbers, but can also decrease macrophyte biomass (Prejs, 1984; Van Donk et al., 1994; Van de Haterd and Ter Heerdt, 2007). Thus the introduction of herbivorous fish is one method for controlling aquatic macrophyte growth. In Lake Zwemlust (The Netherlands), high numbers of rudd (*Carassius* sp.) were introduced as part of lake biomanipulation and were assumed to be responsible for the sudden disappearance of *E. nuttallii*, which had been the predominant macrophyte species the year before (Van Donk and Otte, 1996). *E. nuttallii* was replaced by *Ceratophyllum demersum* in this case, a submerged macrophyte with a calcareous structure, which is probably less palatable for rudd (Van Donk et al., 1993). Although herbivorous fish are known to reduce aquatic vegetation, they can even promote macrophyte growth in summer, as they prefer young shoots and thereby trigger a growth stimulus for the macrophyte (Prejs, 1984).

The rudd introduced into Lake Zwemlust consumed large volumes of macrophytes during the summer months, while herbivory by coots (*Fulica* sp.) was dominant in autumn and winter.

The introduction of the Asian grass carp (*Ctenopharyngodon idella* Valenciennes) has been widely studied as a biological control practice to reduce aquatic macrophyte biomass in freshwater ecosystems in the past. Extensive research on this subject has been reviewed by Dibble and Kovalenko (2009) and can be summarized as follows: grass carp are selective generalists in terms of their foraging behavior, disliking aquatic macrophytes in order of decreasing palatability (Dorenbosch and Bakker, 2011). Species rich in cellulose, silica and iron seem to be refused by grass carp, whereas those containing calcium and lignin are favored. Consequently, *Elodea* species can be considered as moderately palatable for grass carp. The introduction of grass carp may efficiently diminish *Elodea* biomass in an invaded ecosystem, but may have a multitude of negative ecological impacts. A large number of introduced grass carp may cause complete eradication of macrophytic vegetation (such as in Herrenwieser Weiher, Bavaria, see Morscheid et al., 2005), disturbance of the sediment layer, decrease of water transparency, deposition of fecal matter and a dramatic increase of dissolved nutrient concentrations, sometimes followed by algal blooms. In addition, grass carp consumption leads to eutrophication because of the inefficient digestion of macrophyte material (Di Nino et al., 2005).

Moreover, there seems to be a very narrow range of conditions under which the introduction of grass carp reduces macrophyte communities to a level with an acceptable ecological outcome for the ecosystem. In a study on 98 lakes and ponds stocked with grass carp to control macrophytic vegetation, only about 20% of the cases resulted in the desired effect. In 39% of the lakes, submerged macrophytes were completely eradicated and in 42% of the lakes macrophyte vegetation could not be controlled (Bonar et al., 2002).

It has been observed that detrivorous invertebrates (*Asella* sp.) exhibit faster growth when they consume fecal pellets from grass carp fed on *Elodea* sp. in comparison to consumption of fresh *Elodea* (Pertridis, 1990). The intestinal digestion of *Elodea* biomass in grass carp seems to concentrate nutrients and to present food in a more favorable constitution for some invertebrates, which actually results in accelerated cycling of nutrients and decoupling from macrophyte growth and decay due to the enormous herbivorous consumption of the introduced fish. This imbalance of macrophyte growth and decomposition velocities may be one important reason for the small range of apparently stable conditions in lakes where grass carp have been introduced and for the unpredictability of the results.

As a concluding remark here, the introduction of exotic species in freshwater systems is not allowed in many countries; special permission is necessary in some.

In shallow lakes, all biological control methods using herbivorous vertebrates or invertebrates currently do not appear to be applicable due to the risk of overexploitation and an associated switch back to the turbid, phytoplankton-dominated state of the water body (Hilt et al., 2006).

Herbicide application

Herbicide application as an aquatic weed control method has a long tradition, and extensive knowledge is available on the chemical control of *E. canadensis* (Bowmer et al., 1995). In particular, diquat application appears to be highly efficient (Glomski et al., 2005). Spraying of diquat on mechanical harvesters before use in order to minimize the risk of transferring undesirable plant fragments from one lake or channel to another has been reported in aquatic weed management protocols in New Zealand (Howard-Williams et al., 1996).

E. nuttallii, in contrast, is much less studied with regard to chemical weed control, presumably because the problems caused by this historically younger invader are more recent and the acceptance of chemical application in natural habitats has been restricted in many countries in recent years.

The do-nothing option

It has often been observed that massive populations of invasive aquatic macrophytes have collapsed rapidly without any recognizable reason. There are numerous examples for the almost complete disappearance of *E. canadensis* and *E. nuttallii* from freshwater habitats (see Simberloff and Gibbons (2004) for a summary and discussion). Sometimes *Elodea* is replaced by other aquatic macrophytes, sometimes it comes back some years later, and sometimes a lake tends to develop a turbid phytoplankton-dominated state. The peculiarity of these population crashes is that they cannot be predicted. This unpredictability, however, demonstrates that the mechanisms underlying macrophyte population dynamics in freshwater ecosystems are not yet sufficiently understood. Whether and in which cases it is an option to do nothing and wait until a massive *Elodea* population disappears by itself depends on the respective situation and alternatives.

Novel approaches to aquatic weed management and mapping

Up to now, invasion monitoring and management efforts are mostly restricted to locally applied measures. National or supranational programs, such as the European Water Framework Directive, demand the restoration of degraded water bodies to good ecological status, but invasion management is mostly restricted to local interventions when the invader causes practical problems. The distribution of invasive aquatic macrophytes may occur rapidly within a water body, but the time needed by the invader to overcome the gap between rivers or lakes that are not directly connected may provide some temporal advantage for invasion management measures when regarded on a metapopulation level. On this basis, more comprehensive landscape-oriented approaches instead of isolated regional measures have been recommended (Willby, 2007).

It has been pointed out that canopy-forming aquatic macrophyte species such as *Elodea* sp. can cause severe limitations to the use of a water body even at relatively low biomass concentrations since most of the biomass is floating on the surface (Van Nes et al., 2002). This implies some discrepancy between natural conservation of macrophyte occurrence and the use of a lake for recreation and tourism. For this reason, more comprehensive natural conservation approaches favor separate zones for both aspects in lake management (Van Nes et al., 2002).

In combination with interregional management strategies, novel methods for mapping aquatic macrophytes are being published. Thematic maps for invasive macrophyte species which implement "Inverse Distance Weighting" of the discovery date can help to illustrate the dispersal channels and velocities of macrophyte species beyond the regional scale (Boylen et al., 2006). This method is based on the compilation of historical data about pioneer records of an invasive macrophyte species in combination with Geographic Information System (GIS) data. In terms of aquatic plant management, however, information on current macrophyte coverage, plant height or biomass data are required. For this purpose, modern optical or acoustic methods have been developed for mapping macrophyte distribution in order to overcome the typical limitations of manual sampling procedures by rakes or diving teams.

Aerial photographs of lake or river surfaces can provide information about the distribution of aquatic macrophytes, especially for floating-leaved and emergent species. Digital image analysis of aerial photographs may recognize spectral signatures of particular macrophyte species or groups, which can result in plant distribution maps when a GIS overlay is applied (Marshall and Lee, 1994). Applying vertical echo-sounding, different categories of aquatic macrophytes can be mapped depending on plant height (Fortin et al., 1993). The evaluation of vertically oriented echo-sounder data emitting at 420 or 200 kHz in combination with GPS data has revealed a good correlation with underwater video camera information and with direct measurements by a team of divers (Sabol et al., 2002; Winfield et al., 2007). Echo-sound systems were not capable of providing species information on aquatic macrophytes, but they were able to distinguish between species with substantially different growth forms, for example, between low-growing *Chara* species and tall-growing *E. nuttallii* (Winfield et al., 2007). It has been shown in a large-scale case study that an established acoustic-based Submersed Aquatic Vegetation Early Warning System (SAVEWS^{TM}) could reliably reflect the response of *Myriophyllum spicatum* to the application of chemical control measures in a lake area of over 2 km^2 (Sabol et al., 2009). The decline of aquatic macrophyte coverage and biomass showed a highly significant positive correlation with rake sampling data. However, the authors emphasized that some physical ground-truth sampling was required, primarily to establish a species list.

Commercially available software packages generate output data on water depth, relative macrophyte coverage, macrophyte height and location from acoustic echo signals (Sabol et al., 2002; Winfield et al., 2007). Applying a regression model using the total echo strength as the general input parameter, macrophyte biomass can be estimated (Haga et al., 2007) and acoustic macrophyte mapping data can be integrated into standards for status classification of lakes in accordance with the Water Framework Directive or other guidelines (Jäger et al., 2004).

Although echo-sounding methods are preferentially directed vertically, a few authors have described horizontal echo-sounding for the assessment of aquatic macrophyte biomass. The basic limitation of species differentiation cannot be overcome by this approach either. However, positive linear relationships between the volume backscattering strength and plant biomass and different slopes of this relationship have been found for different macrophyte species (Hohausova et al., 2008).

Further advances in mapping aquatic macrophyte abundance are promised by the application of airborne optical methods. Remote sensing by Compact Airborne Spectrographic Imagers (CASI) has been shown to be a powerful modern strategy for the assessment of abundance and distribution of aquatic vegetation and may overcome the principal logistical and time constraints of echo-sounding methods (Hunter et al., 2010).

Conclusions

A range of management options is available for dealing with invasive *E. nuttallii* and *E. canadensis*. These generally aim to reduce the amount of biomass of these species and have varying degrees of success depending on the conditions of the water body. However, the intensive reduction of *Elodea* biomass should be confined to isolated cases – such as when the recreational use of bodies of waters is both a priority usage and is strongly inhibited by the biomass. After all, these two *Elodea* species can also play a positive role in the ecosystem. For instance, *E. nuttallii* is a very palatable species that provides food for a number of waterbirds, particularly coots (Perrow et al., 1997). In addition, both *Elodea* species – like all aquatic plants – have a stabilizing effect on the ecosystem.

Mechanical harvesting is currently the most commonly used method of weed control in waters in Germany. Various methods are available for utilizing the harvested *Elodea* biomass – such as in cosmetics, biofertilizers and as a substrate for biogas plants (Muñoz Escobar et al., 2011). Consideration has recently been given to the targeted cultivation of *E. nuttallii* for biomass production. To achieve this, knowledge of possible management options for the controlled development of biomass stock will be beneficial.

References

Abernethy, V.J., Sabbatini, M.R., Murphy, K.J., 1996. Response of *E. canadensis* Michx. and *Myriophyllum spicatum* L. to shade, cutting and competition in experimental culture. Hydrobiologia 340, 219–224.

Alvarez, R., Lidén, G., 2008. Anaerobic co-digestion of aquatic flora and quinoa with manures from Bolivian Altiplano. Waste Manage. 28 (10), 1933–1940.

Angelstein, S., Schubert, H., 2008. *Elodea nuttallii:* uptake, translocation and release of phosphorus. Aquat. Bot. 3, 209–216.

Argus, G.W., White, D.J., 1977. The rare vascular plants of Ontario. Report No. 14. National Museum of Natural Sciences, Ottawa, Canada.

Baattrup-Pedersen, A., Larsen, S.E., Riis, T., 2002. Long-term effects of stream management on plant communities in two Danish lowland streams. Hydrobiologia 481, 33–45.

Bakker, E.S., Sarneel, J.M., Gulati, R., Liu, Z., Van Donk, E., 2013. Restoring macrophyte diversity in shallow temperate lakes: biotic versus abiotic constraints. Hydrobiologia 710, 23–37.

Barrat-Segretain, M.-H., Bornette, G., 2000. Regeneration and colonization abilities of aquatic plant fragments: effect of disturbance seasonality. Hydrobiologia 421 (1), 31–39.

Barrat-Segretain, M.-H., 2001. Invasive species in the Rhone River floodplain (France): replacement of *Elodea canadensis* Michaux by *E. nuttallii* St. John in two former river channels. Arch. Hydrobiol. 152, 237–251.

Barrat-Segretain, M.-H., 2004. Growth of *E. canadensis* and *Elodea nuttallii* in monocultures and mixture under different light and nutrient conditions. Arch. Hydrobiol. 161 (1), 133–144.

Barrat-Segretain, M.-H., Elger, A., 2004. Experiments on growth interactions between two invasive macrophyte species. J. Veg. Sci. 15 (1), 109–114.

Barrat-Segretain, M.-H., Cellot, B., 2007. Response of invasive macrophyte species to drawdown: the case of *Elodea* sp. Aquat. Bot. 87 (4), 255–261.

Barko, J.W., Gunnison, D., Carpenter, S.R., 1991. Sediment interactions with submersed macrophyte growth and community dynamics. Aquat. Bot. 41, 41–65.

Bonar, S.A., Bolding, B., Divens, M., 2002. Effects of triploid grass carp on aquatic plants, water quality, and public satisfaction in Washington State. North Am. J. Fish. Manage. 22, 96–105.

Bouchard, A., Barabé, D., Dumais, M., Hay, S., 1983. The rare vascular plants of Quebec. Report No. 48. National Museum of Natural Sciences, Ottawa, Canada.

Bowmer, K.H., Smith, G.H., 1984. Herbicides for injection into flowing water: acrolein and endothal-amine. Weed Res. 24, 201–211.

Bowmer, K.H., Jacobs, S.W.L., Sainty, G.R., 1995. Identification, biology and management of *E. canadensis*, Hydrocharitaceae. J. Aquat. Plant Manage. 33, 13–19.

Boylen, C.W., Eichler, L.W., Bartkowski, J.S., Shaver, S.M., 2006. Use of geographic information systems to monitor and predict non-native aquatic plant dispersal through north-eastern North America. Hydrobiologia 570, 243–248.

Carignan, R., Kalff, V., 1980. Phosphorus sources for aquatic weeds: water or sediments? Science 207, 987–989.

Carignan, R., 1982. An empirical model to estimate the relative importance of roots in phosphorus uptake by aquatic macrophytes. Can. J. Fish. Aquat. Sci. 39, 243–247.

Carignan, R., Kalff, J., 1982. Phosphorus release by submersed macrophytes: significance to epiphyton and phytoplankton. Limnol. Oceanogr. 127, 419–427.

Catling, P.M., Wojtas, W., 1986. The waterweeds (*Elodea* and *Egeria*, Hydrocharitaceae) in Canada. Can. J. Bot. 64, 1525–1541.

Champion, P.D., Clayton, J.S., Hofstra, D.E., 2010. Nipping aquatic plant invasion in the bud: weed risk assessment and the trade. Hydrobiologia 656, 167–172.

Chapman, V.J., Brown, J.M.A., Hill, C.F., Carr, J.L., 1974. Biology of excessive growth in the hydro-electric lakes of the Waikato River, New Zealand. Hydrobiologia 44, 349–363.

Clarke, S.J., Wharton, G., 2001. Sediment nutrient characteristics and aquatic macrophytes in lowland English rivers. Sci. Total Environ. 266, 103–112.

Clayton, J.S., Champion, P., 2006. Risk assessment method for submerged weeds in New Zealand hydroelectric lakes. Hydrobiologia 570, 183–188.

Daldorph, P.W.G., 1999. A reservoir in management-induced transition between ecological states. Hydrobiologia 395/396, 325–333.

DeMarte, J.A., Hartman, R.T., 1974. Studies on absorption of ^{33}P, ^{59}Fe, and ^{45}Ca by water-milfoil (*Myriophyllum exalbescens* Fernald). Ecology 55, 188–194.

Dibble, E.D., Kovalenko, K., 2009. Ecological impact of grass carp: a review of the available data. J. Aquat. Plant Manage. 47, 1–15.

Di Nino, F., Thiébaut, G., Muller, S., 2005. Response of *Elodea nuttallii* to manual harvesting in the north-east of France. Hydrobiologia 551, 147–157.

Dorenbosch, M., Bakker, E.S., 2011. Herbivory in omnivorous fishes: effect of plant secondary metabolites and prey stoichiometry. Freshw. Biol. 56, 1783–1797.

Eugelink, A.H., 1998. Phosphorus uptake and active growth of *E. canadensis* Michx. and *Elodea nuttallii* (Planch.) St. John. Water Sci. Technol. 37 (3), 59–65.

Fortin, G.R., Saint-Cyr, L., Leclerc, M., 1993. Distribution of submersed macrophytes by echo-sounder tracings in Lake Saint-Pierre, Quebec. J. Aquat. Plant Manage. 31, 232–240.

Garbey, C., Murphy, K.J., Thiébaut, G., Muller, S., 2004. Variation in P-content in aquatic plant tissue offers an efficient tool for determining plant growth strategies along a resource gradient. Freshw. Biol. 49, 1–11.

Glomski, L.A.M., Skogerboe, J.G., Getsinger, K.D., 2005. Comparative efficacy of diquat for control of two members of the Hydrocharitaceae: *Elodea* and *Hydrilla*. J. Aquat. Plant Manage. 43, 103–105.

Gollasch, S., 2006. *Elodea canadensis*. DAISIE (Delivering Alien Invasive Species Inventories for Europe), Available from: http://www.europe-aliens.org/pdf/Elodea_canadensis.pdf

Haga, H., Ohtsuka, T., Matsuda, M., Ashiya, M., 2007. Echosounding observations of coverage, height, PVI, and biomass of submerged macrophytes in the southern basin of Lake Biwa, Japan. Limnology 8, 95–102.

Hérault, B., Bornet, A., Trémolières, M., 2008. Redundancy and niche differentiation among the European invasive *Elodea* species. Biol. Invas. 10, 1099–1107.

Hilt, S., Gross, E.M., Hupfer, M., et al., 2006. Restoration of submerged vegetation in shallow eutrophic lakes – a guideline and state of the art in Germany. Limnologica 36, 155–171.

Hoffmann, M.A., Benavent González, A., Raeder, U., Melzer, A., 2013. Experimental weed control of *Najas marina* ssp. intermedia and *Elodea nuttallii* in lakes using biodegradable jute matting. J. Limnol. 72 (3), 485–493.

Hohausova, E., Kubecka, J., Frouzova, J., Husak, S., Balk, H., 2008. Experimental biomass assessment of three species of freshwater aquatic plants by horizontal acoustics. J. Aquat. Plant Manage. 46, 82–88.

Howard-Williams, C., 1993. Processes of aquatic weed invasions: the New Zealand example. J. Aquat. Plant Manage. 31, 17–23.

Howard-Williams, C., Schwarz, A.-M., Reid, V., 1996. Patterns of aquatic weed regrowth following mechanical harvesting in New Zealand hydro-lakes. Hydrobiologia 340 (1–3), 229–234.

Hunter, P.D., Gilvear, D.J., Tyler, A.N., Willby, N.J., Kelly, A., 2010. Mapping macrophytic vegetation in shallow lakes using the Compact Airborne Spectrographic Imager (CASI). Aquat. Conserv. Mar. Freshw. Ecosyst. 20 (7), 717–727.
Hussner, A., van de Weyer, K., Gross, E.M., Hilt, S., 2010. Comments on increasing number and abundance of non indigenous aquatic macrophyte species in Germany. Weed Res. 50, 519–526.
Hussner, A., 2012. Alien aquatic plants in European countries. Weed Res. 52, 397–406.
Hussner, A., van de Weyer, K., Gross, E.M., Hilt, S., 2014a. Handlungsempfehlung zur Abschätzung der Chancen einer Wiederansiedlung von Wasserpflanzen bei der Restaurierung von Flachseen Deutschlands. Deutsche Gesellschaft für Limnologie, Hardegsen, 75 S.
Hussner, A., Nehring, S., Hilt, S., 2014b. From first reports to successful control: a plea for improved management of alien aquatic plant species in Germany. Hydrobiologia 737, 321–331.
Hussner, A., 2014. Long-term macrophyte mapping documents a continuously shift from native to non-native aquatic plant dominance in the thermally abnormal River Erft (North Rhine-Westphalia, Germany). Limnologica 48, 39–45.
Jäger, P., Pall, K., Dumfarth, E., 2004. A method of mapping macrophytes in large lakes with regard to the requirements of the Water Framework Directive. Limnologica 34 (1-2), 140–146.
Jahnke, L.S., Eighmy, T.T., Fagerberg, W.R., 1991. Studies of *Elodea nuttallii* grown under photorespiratory conditions. I. Photosynthetic characteristics. Plant Cell Environ. 14, 147–156.
James, W.F., 2008. Effects of lime-induced inorganic carbon reduction on the growth of three aquatic macrophyte species. Aquat. Bot. 88 (2), 99–104.
Jeppesen, E., Sùndergaard, Ma., Sùndergaard, Mo., Christophersen, K., 1998. The Structuring Role of Submerged Macrophytes in Lakes. Springer, Berlin/Heidelberg/New York.
Jeppesen, E., Søndergaard, M., Meerhoff, M., Lauridsen, T.L., Jensen, J.P., 2007. Shallow lake restoration by nutrient loading reduction – some recent findings and challenges ahead. Hydrobiologia 584, 239–252.
Jones, J.I., Eaton, J.W., Hardwick, K., 1993. Physiological plasticity in *Elodea nuttallii* (Planch.) St. John. J. Aquat. Plant Manage. 31, 88–94.
Köhler, J., Hilt, S., Adrian, R., Nicklisch, A., Kozerski, H.P., Walz, N., 2005. Long-term response of a shallow, moderately flushed lake to reduced external phosphorous and nitrogen loading. Freshw. Biol. 50, 1639–1650.
Kunii, H., 1981. Characteristics of the winter growth of detached *Elodea nuttallii* (Planch.) St. John in Japan. Aquat. Bot. 11, 57–66.
Kunii, H., 1984. Seasonal growth and profile structure development of *Elodea nuttallii* (Planch.) St. John in Pond Ojaga-Ike, Japan. Aquat. Bot. 18, 239–247.
Lauridsen, T.L., Jeppesen, E., Søndergaard, M., 1994. Colonization and succession of submerged macrophytes in shallow Lake Væng during the first five years following fish manipulation. Hydrobiologia 275/276, 233–242.
Lawrence, D.K., 1976. Morphological variation of *Elodea* in western Massachusetts: field and laboratory studies. Rhodora 78, 739–749.
Lindstrom, H.V., Sandstrom, W.M., 1939. The nature of carbohydrates of species of *Elodea*, *Myriophyllum*, *Ceratophyllum*, *Ruppia* and *Ranunculus*. Nutritive value and chemical composition of certain fresh-water plants of Minnesota. Minnesota Agricultural Experiment Station Technical Bulletin, pp. 43–47.
Madsen, T.V., Brix, H., 1997. Growth, photosynthesis and acclimation by two submerged macrophytes in relation to temperature. Oecologia 110 (3), 320–327.
Marshall, T.R., Lee, P.F., 1994. Mapping aquatic macrophytes through digital image analysis of aerial photographs: an assessment. J. Aquat. Plant Manage. 32, 61–66.
McRoy, C.P., Barsdate, R.J., 1970. Phosphate absorption in eelgrass. Limnol. Oceanogr. 15, 6–13.
Melzer, A., 1999. Aquatic macrophytes as tools for lake management. Hydrobiologia 395/396, 181–190.
Meyer, L., Hinrichs, D., 2000. Microhabitat preferences and movements of the weatherfish, *Misgumus fossilis*, in a drainage channel. Environ. Biol. Fish. 58 (3), 297–306.
Mielecki, M., Pieczynska, E., 2005. The influence of fragmentation on the growth of *E. canadensis* Michx. in different light conditions. Pol. J. Ecol. 53 (2), 155–164.
Mjelde, M., Lombardo, P., Berge, D., Johanson, S.W., 2012. Mass invasions of non-native *Elodea canadensis* Michx. in a large, clear water, species rich Norwegian lake – impact on macrophyte diversity. Ann. Limnol. 48, 225–240.
Morscheid, H., Mattukat, F., Kucklentz, V., 2005. Biomanipulation in bayerischen "Flachseen": Vorstellung des Forschungsvorhabens zum Praxistest an fünf ausgewählten eutrophen Gewässern. German Limnology Society (DGL) – Meeting Report 2004 (Potsdam), pp. 501–506.
Muñoz Escobar, M., Voyevoda, M., Fuhner, C., Zehnsdorf, A., 2011. Potential uses of *Elodea nuttallii*-harvested biomass. Energy Sustain. Soc. 1 (1), 1–8.
Nagasaka, M., 2004. Changes in biomass and spatial distribution of *Elodea nuttallii* (Planch.) St. John, an invasive submerged plant, in oligomesotrophic Lake Kizaki from 1999 to 2002. Limnology 5, 129–139.
Nichols, S.A., Shaw, B.H., 1986. Ecological life histories of the three aquatic nuisance plants, *Myriophyllum spicatum*, *Potamogeton crispus* and *E. canadensis*. Hydrobiologia 131, 3–21.
Ozimek, T., Van Donk, E., Gulati, R.D., 1993. Growth and nutrient uptake by two species of *Elodea* in experimental conditions and their role in nutrient accumulation in a macrophyte-dominated lake. Hydrobiologia 251, 13–18.
Perrow, M.R., Schutten, J.H., Howes, J.R., Holzer, T., Madgwick, F.J., Jowitt, A.J.D., 1997. Interactions between coot (*Fulica atra*) and submerged macrophytes: the role of birds in the restoration process. Hydrobiologia 342, 241–255.
Perkins, R.G., Underwood, G.J.C., 2002. Partial recovery of a eutrophic reservoir through managed phosphorus limitation and unmanaged macrophyte growth. Hydrobiologia 481 (1–3), 75–87.
Pertridis, D., 1990. Utilization of grass carp faeces by the isopod *Asellus aquaticus* (L.) in the laboratory. Hydrobiologia 194 (1), 47–56.
Pipalova, I., 2006. A review of grass carp use for aquatic weed control and its impact on water bodies. J. Aquat. Plant Manage. 44, 1–12.
Podraza, P., Brinkmann, T., Evers, P., et al., 2008. Untersuchungen zur Massenentwicklung von Wasserpflanzen in den Ruhrstauseen und Gegenmaßnahmen, 364. Final report of the R&D project commissioned by the Ministry for the Environment and Conservation, Agriculture and Consumer Protection of the State of North Rhine-Westphalia (MUNLV), Essen, Germany.
Pot, R., Ter Heerdt, G.N.J., 2014. Succession dynamics of aquatic lake vegetation after restoration measures: increased stability after 6 years of development. Hydrobiologia 737, 333–345.
Prejs, A., 1984. Herbivory by temperate freshwater fishes and its consequences. Environ. Biol. Fish. 10, 281–296.
Sabbatini, M.R., Murphy, K.J., 1996. Submerged plant survival strategies in relation to management and environmental pressures in drainage channel habitats. Hydrobiologia 340, 191–195.
Sabol, B.M., Melton, R.E., Chamberlain, R., Doering, P., Haunert, K., 2002. Evaluation of a digital echo sounder system for detection of submersed aquatic vegetation. Estuaries 25, 133–141.
Sabol, B.M., Kannenberg, J., Skøgerbøe, J.G., 2009. Integrating acoustic mapping into operational aquatic plant management: a case study in Wisconsin. J. Aquat. Plant Manage. 47, 44–52.
Sand-Jensen, K., Gordon, D.M., 1986. Variable HCO_3^- affinity of *E. canadensis* Michaux in response to different HCO_3^- and CO_2 concentrations during growth. Oecologia 70, 426–432.
Sand-Jensen, K., Riis, T., Vestergaard, O., Larsen, S.E., 2000. Macrophyte decline in Danish lakes and streams over the last 100 years. J. Ecol. 88, 1030–1040.
Santamaria, L., 2002. Why are most aquatic plants widely disturbed? Dispersal, clonal growth and small-scale heterogeneity in a stressful environment. Acta Oecol. 23, 137–154.
Simberloff, D., Gibbons, L., 2004. Now you see them, now you don't! Population crashes of established introduced species. Biol. Invas. 6, 161–172.
Srivastava, R.C., 1995. Kinetics of fresh water hyacinth digestion in semi-continuous operation. Chem. Eng. J. 56, B109–B113.
Stiers, I., Crohain, N., Josens, G., Triest, L., 2011. Impact of three aquatic invasive species on native plants and macroinvertebrates in temperate ponds. Biol. Invas. 13, 2715–2726.
Thiébaut, G., Muller, S., 1999. A macrophyte community sequence as an indicator of eutrophication and acidification levels in weakly mineralised streams in north-eastern France. Hydrobiologia 410, 17–24.
Thiébaut, G., Muller, S., 2003. Linking phosphorus pools of water, sediment and macrophytes in running waters. Int. J. Limnol. 39, 307–316.
Thiébaut, G., 2005. Does competition for phosphate supply explain the invasion pattern of *Elodea* species? Water Res. 39, 3385–3393.
Ulén, B., Tonderski, K.S., 2005. Cold climate phosphorus uptake by submerged aquatic plants in a sewage treatment free water surface wetland. J. Environ. Sci. Health A 40 (6/7), 1177–1190.
Van de Haterd, R.J.W., Ter Heerdt, G.N.J., 2007. Potential for the development of submerged macrophytes in eutrophicated shallow peaty lakes after restoration measures. Hydrobiologia 584, 277–290.
Van Donk, E., Gulati, R.D., Iedema, A., Meulemans, J.T., 1993. Macrophyte-related shifts in the nitrogen and phosphorus contents of the different trophic levels in a biomanipulated shallow lake. Hydrobiologia 251, 19–26.
Van Donk, E., De Deckere, E., Klein Breteler, J.G.P., Meulemans, J.T., 1994. Herbivory by waterfowl and fish on macrophytes in a biomanipulated lake: effects on long-term recovery. Verh. Int. Verein Limnol. 25, 2139–2143.
Van Donk, E., Otte, A., 1996. Effects of grazing by fish and waterfowl on the biomass and species composition of submerged macrophytes. Hydrobiologia 340 (1–3), 285–290.
Van Nes, E.H., Scheffer, M., Van den Berg, M.S., Coops, H., 2002. Aquatic macrophytes: restore, eradicate or is there a compromise? Aquat. Bot. 72, 387–403.
Van Valkenburg, J., Roijackers, R.M.M., Leonard, L., 2011. *Cabomba caroliniana* Gray in The Netherlands. In: Bohren, C., Bertossa, M., Schönenberger, N., Rossinelli, M., Conedera, M. (Eds.), 3rd International Symposium of Environmental Weeds and Invasive Plants. Abstracts. 2–7 October 2011. Monte Verità, Ascona, Switzerland. Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Available at: http://www.wsl.ch/epub/ewrs
Verbrugge, L.N.H., Van Der Velde, G., Hendriks, A.J., Verreycken, H., Leuven, R.S.E.W., 2012. Risk classification of aquatic non-native species: application of contemporary European assessment protocols in different biogeographical settings. Aquat. Invas. 7, 49–58.
Willby, N.J., 2007. Managing invasive aquatic plants: problems and prospects. Aquat. Conserv. Mar. Freshw. Ecosyst. 17, 659–665.
Winfield, I.J., Onoufriou, C., O'Connell, M.J., Godlewska, M., Ward, R.M., Brown, A.F., Yallop, M.L., 2007. Assessment in two shallow lakes of a hydroacoustic system for surveying aquatic macrophytes. Hydrobiologia 584 (1), 111–119.
Wolff, P., 1980. Die Hydrilleae (Hydrocharitaceae) in Europa. Göttinger Floristische Rundbriefe 14, 33–56.
Zehnsdorf, A., Korn, U., Pröter, J., Naumann, D., Seirig, M., 2011. Western waterweed (*Elodea nuttallii*) as a co-substrate for biogas plants. Agric. Eng. 66 (2), 136–139.