ARE WE ON TOP OF AQUATIC WEEDS? WEED PROBLEMS, CONTROL OPTIONS AND CHALLENGES

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Are we on top of aquatic weeds? Weed problems, control options, and challenges

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ABSTRACT

Several floating, submerged, emergent, and shoreline aquatic plants are among the world's worst weeds. Leading candidates for this dubious distinction are the floating weeds *Eichhornia crassipes*, *Pistia stratiotes*, and *Salvinia* spp., submerged weeds *Ceratophyllum demersum*, *Egeria* spp., *Hydrilla verticillata*, *Myriophyllum* spp. and *Potamogeton pectinatus*, rooted, shallow-water plants such as *Ludwigia* spp., *Polygonum* spp., *Typha* spp., several grass species and some wetland shrubs and trees. Some species of planktonic, filamentous, and macrophytic algae are also regarded as problems. Collectively these aquatic weeds impact the economic and societal well-being of communities. Their effects on human and environmental health are particularly complex and difficult to manage regardless of the economic status of the affected communities. Among the control practices used are manual, mechanical, physical, chemical, and biological controls. Successful management of recurrent aquatic problems requires consistent, long-term control efforts that are co-ordinated and administered on a regional basis (county, state, or national).

Are we on top of aquatic weeds? Yes, in some countries and situations, but serious challenges exist in many parts of the world due to lack of financial resources and administrative infrastructure to manage the weeds and/or the limited choice of control methods. How can we do better? There should be continued vigilance to prevent introduction of new invasive species, coupled with concerted, persistent efforts to control and maintain problematic weed species at acceptable levels. The problem of aquatic weeds and their control is not likely to improve in the near term, given the high cost of mechanical and chemical controls, increasing regulatory restrictions on the use of chemical herbicides, limited options for safe and effective chemical herbicides, and under-utilisation of biological control. To get on top of aquatic weed problems, it is urgently needed to develop and utilise biological control as a key component of aquatic weed management programmes. It is equally important to invest in discovery and development of newer and safer chemical herbicides for aquatic use.

INTRODUCTION

This presentation attempts to answer the question posed in the title, "Are we on top of aquatic weeds?" Simply put, aquatic weeds are manageable, but at a considerable cost and co-ordination of efforts. The challenge is to control these weeds 1) in a cost-effective manner that society can afford, 2) by using the most effective and safe methods available, 3) causing minimal adverse side-effects, 4) with public acceptance of the control practices, and 5) in a sustainable manner that reduces recurrent costs and promotes environmental balance. In reality, the problems posed by aquatic weeds are exacerbated in many parts of the world (e.g. African countries, Brazil and others; see Charudattan *et al.*, 1996; Fernandez, 2000; Marcondes *et al.*, 2000; Pitelli, 2000; Thomaz, 2000). This is largely due to the limited number of effective tools available for control, governmental restrictions on the use of chemical herbicides, emergence of several native and non-indigenous weeds as new weed problems, and increasing and recurrent cost of aquatic weed control. Agencies charged with aquatic weed management are required to consider the environmental and human consequences of control methods, their cost-effectiveness, and societal affordability. Combined with the variety of weed problems, sites, and user needs, weed-control decisions become highly complex and challenging. With this backdrop, the following discussion will highlight some aquatic weed problems, pros and cons of the commonly used control methods, an example of an effective management programme that is in place, and key elements for a successful long-term management programme.

WEED PROBLEMS

In their highly influential book, "The World's Worst Weeds: Distribution and Biology," Holm *et al.* (1977) listed just ten aquatic weeds, including the three most notorious weeds, *Eichhornia crassipes* (water hyacinth), *Pistia stratiotes* (water lettuce) and *Salvinia auriculata*, later identified as *S. molesta* (water fern, giant salvinia, or the Kariba weed). In the quarter century since this book was published, the number of world's worst aquatic weeds has grown to about three dozen (Table 1). Collectively, these weeds cause serious problems in nearly all countries, affecting almost all uses of water bodies such as for aquaculture, commercial and subsistence fishing, drinking and household consumption, hydropower generation, irrigation, transport, and recreation. The more invasive species among these weeds affect biodiversity by replacing native flora and fauna, often causing irreversible changes to habitats. An increase in insect-borne human diseases and poisonous snakes are other serious problems. Loss of aesthetic value of waterfront communities due to weed growth is also an important concern. Dead biomass from large weed infestations increases the rates of sedimentation and eutrophication and reduces water depth. Excessive algal blooms can render the water undrinkable, impart an unpleasant odour to fish, deplete oxygen levels, and cause fish kills (Pieterse, 1990).

Some aquatic weeds are unique to a few regions of the world (e.g. *Crassula helmsii* in the United Kingdom, *Egeria* spp. in Brazil), but a few species (e.g. *E. crassipes, P. stratiotes, S. molesta* and *Myriophyllum spicatum)* have become nearly global in their distribution, causing similar types of problems in every location. *E. crassipes* has been reported as a problem from some 50 countries and *P. stratiotes*, likewise, has been reported as a weed from about 44 countries (Holm *et al.*, 1979). *M. spicatum* (Eurasian water milfoil) causes problems in many temperate countries, occurs in 45 of the 50 states and the District of Columbia in the USA and three Canadian provinces (Engel & Crossan, 2000). *S. molesta,* the notorious Kariba weed, has recently become established in western Texas and western Louisiana, USA, (Jacono, 1999).

Table 1: A list of important aquatic weeds

Botanical name	Common name	Family	Plant type
Alternanthera philoxeroides	Alligator weed	Amaranthaceae	Mat-forming
Azolla spp.	Azolla, water fern	Azollaceae	Floating
Brachiaria spp.	Signalgrass	Poaceae	Emergent, grass
Ceratophyllum demersum	Coontail	Ceratophyllaceae	Submerged
Chara spp.	Muskgrass	Characeae	Submerged
Crassula helmsii	Australian swamp stonecrop	Crassulaceae	Submerged, mat-forming
Eichhornia crassipes	Water hyacinth	Pontederiaceae	Floating
Egeria spp.	Egeria, elodea	Hydrocharitaceae	Submerged
Hydrilla verticillata	Hydrilla	Hydrocharitaceae	Floating
Hydrocotyl spp.	Water pennywort	Apiaceae	Mat-forming
Ipomoea spp.	Water spinach, swamp morning-glory	Convolvulaceae	Emergent, mat-forming, wetland shrub
Lagarosiphon major	Lagarosiphon	Hydrocharitaceae	Submerged
Lemna spp.	Duckweed	Lemnaceae	Floating
Ludwigia spp.	Water primrose, primrose willow	Onagraceae	Emergent
Monochoria spp.	Monochoria	Pontederiaceae	Emergent
Lythrum salicaria	Purple loosestrife	Lythraceae	Emergent
Melaleuca quinquenervia	Melaleuca, paper-bark	Myrtaceae	Wetland tree
Myriophyllum spp.	Parrot's feather, Eurasian water milfoil	Haloragaceae submerged	Emergent, mat-forming,
Nitella spp.	Nitella, stonewort	Characeae	Submerged
Nuphar luteum, *Nyphaea* spp.	Water lilies	Nymphaeaceae	Emergent
Panicum repens	Torpedo grass	Poaceae	Mat-forming, grass
Paspalum spp.	Paspalum	Poaceae	Mat-forming, grass
Phragmites spp.	Reed	Poaceae	Emergent
Pistia stratiotes	Water lettuce	Araceae	Floating
Polygonum spp.	Smartweed, knotweed	Polygonaceae	Emergent
Potamogeton spp.	Pondweed	Potamogetonaceae	Submerged
Sagittaria spp.	Arrowhead, duck potato	Alismataceae	Emergent
Salvinia molesta	Giant salvinia, Kariba weed	Salviniaceae	Floating
Scirpus spp.	Bulrush	Cyperaceae	Emergent
Spartina spp.	Cord grass, marsh grass	Poaceae	Emergent, grass
Sphenoclea zeylanica	Gooseweed	Sphenocleaceae	Emergent
Spirodela polyrhiza	Giant duckweed	Lemnaceae	Floating
Typha spp.	Cattail	Typhaceae	Emergent
Utricularia spp.	Bladderwort	Lentibulariaceae	Submerged
Vallisneria spp.	Eelgrass, tape grass	Hydrocharitaceae	Submerged
Vossia cuspidata	Hippo grass	Poaceae	Emergent, grass

Aquatic weeds share some common characteristics that contribute to their success as weeds such as their prolific growth rates, high seed-output, multiple modes of propagation including clonal and sexual propagules (by vegetative fragments, tubers, turions, and rhizomes), and high vegetative and physiological plasticity that imparts intense competitiveness and environmental fitness (Spencer & Bowes, 1990; Langeland, 1996). These traits contribute to the difficulty and complexity of aquatic weed management.

Many aquatic weed problems are caused by a single, dominant species, but presence of subdominant species is typical in many water bodies. These species often proliferate and fill the niche when the dominant species is controlled. For example, vast infestations of water hyacinth in large African lakes provide a habitat for the establishment of floating islands consisting of different grasses and other aquatics (*Cyperus papyrus*, *Echinochloa* sp., *Ipomoea aquatica, Leersia* sp., *Phragmites* spp., *Typha* sp., and *Vossia cuspidator).* These floating islands move back and forth with the water hyacinth mats, and when freed from the surrounding water hyacinth, they aggregate in large masses to create problems of their own (de Graft Johnson, 1996).

Floating weeds, such as *E. crassipes, P. stratiotes,* and *S. molesta,* cause problems by partially or completely blanketing large and small bodies of water, interfering with the normal use of water. They increase water loss through the dual actions of evaporation and transpiration. They also can have differential effects on submerged plants by promoting plant species that are tolerant of shade and changes in water chemistry, especially pH and dissolved oxygen, while having a detrimental effect on more sensitive species (Janes *et al.*, 1996). Field and laboratory studies in Florida, USA, indicate that uncontrolled growth of water hyacinth can have an adverse effect on native bulrush (*Scirpus californicus*) communities, leading to their local elimination (Thayer & Joyce, 1990). Deposition of organic matter is another undesirable effect of floating weeds. For example, Joyce (1985) estimated that *E. crassipes* could add as much as 11,650 kg/ha/yr of sediment from natural turnover of older growth as well as plants killed by control treatments.

The problems caused by floating weeds can be best illustrated by *E. crassipes,* which continues to be one of the world's worst weeds. The problems caused by this invasive weed are now most severe in countries of Africa and Asia, but many countries in the Americas are also affected. For instance, in Mexico, more than 40,000 ha of reservoirs, canals, and drainage systems are infested with this weed (Gutiérrez *et al.*, 1996). The current *E. crassipes* problems in the African continent are best illustrated by the situation in Uganda. *E. crassipes* has been present in Africa, particularly in the River Nile, since the 1870s but was not reported as a major problem until the 1980s (Orach-Mesa, 1996). The problem demanded massive control efforts in the early 1990s when 90% of the Ugandan side of Lake Victoria coastline was covered by the plant. Bordered by Kenya, Tanzania, and Uganda, Lake Victoria is the second largest lake in the world with a surface area of almost 96,000 km^2. Several communities live around the lake, which provides fish for food, drinking and irrigation water, a means of transportation, and energy. All of these uses were affected by *E. crassipes* infestation (Lindsey & Hirt, 1999). The weed has also contributed to an increase in disputes between local communities, reduced the supply of clean potable water, constrained water extraction, irrigation, and transportation, reduced fish catches, decreased available landing sites, increased vector-borne diseases, reduced tourism, displaced communities from Lake Victoria, decreased biodiversity, and affected power production at the hydroelectric plant at Jinga, thereby interrupting the power supply to the capital of Kampala (Twongo & Balirwa, 1995).

Submerged aquatic macrophytes (e.g. *Egeria* spp., *H. verticillata*, *M. spicatum* and others), as a group, are particularly difficult and costly to manage. They pose the most serious problems for lake management (Clayton, 2000). The type of submerged aquatic weed community in a lake typically is influenced by the depth, turbidity, age, sediment composition, bottom topography, water transparency, and nutrient concentrations of the water body (Clayton, 2000). Submerged species such as *C. demersum, Egeria* spp., *H. verticillata, Potamogeton* spp., *Ranunculus* spp., and others cause serious problems also in irrigation channels in temperate regions by reducing water flow. These plants can growth very rapidly in shallow canals, and their control is complicated by the need to avoid herbicide carryover to irrigated crops as well as the poor efficacy of herbicides in fast-moving water due to dissipation and insufficient contact/absorption. In hydropower reservoirs, the loss of revenues due to reduced energy production, damage to turbines, intakes, and protection screens, and recurrent weed-control costs are a primary consideration. In some hydropower systems, disruption of power production due to aquatic weeds could run into millions of dollars per month. In addition, the indirect costs of control methods on the environment and surrounding communities are also an important consideration. Generally, in these situations, the effect of control options on fish protection, insect control, and water quality must be also factored into to the choice and timing of control methods (Pitelli, 2000; Thomaz, 2000).

Shoreline weeds, especially cattails, grasses, and sedges, which are rooted emergent plants, are common in many lakes and rivers, and canals. In the tropics, where seasonal drought and the prevalence of highly turbid waters generally are the norm, floating and rooted emergent plants are more common than submerged aquatic weeds. Among the rooted emergent plants *Typha* spp. (cattail), *Phragmites* spp. (reed), and grasses are important weeds in irrigation and drainage canals. These perennial, shallow-water plants can grow in large clonal masses and obstruct water flow. Because of their capacity for rapid regeneration from rhizomes, mechanical restoration of canals at regular intervals and chemical control are commonly practised, despite the high cost of these methods and temporary results (Da Silva *et al.*, 2000).

CHALLENGES

Cost of control

Aquatic weeds cost millions of dollars in lost revenues and control costs. The direct and indirect cost in human suffering in less affluent nations and subsistence communities is immeasurable in monetary terms. Aquatic weeds, especially submerged species, are costly to manage, and many communities and even some countries cannot afford the high and recurring cost of control. In the USA as a whole, about $100 million is spent annually for the control of non-indigenous aquatic weed species (U.S. Congress, Office of Technology Assessment, 1993). About $15 million is spent every year in the state of Florida, USA, to control *E. crassipes, P. stratiotes,* and *H. verticillata.* It is estimated that nearly $100 million was spent in Florida in the 1990s to suppress water hyacinth and water lettuce ($27 million) and *H. verticillata* ($72 million) (Schardt, 1998). Presently, nearly two-thirds of the 26,500 ha of water in the Kissimmee Chain of lakes and 95% of the 10,925 ha of Lake Istokpoga in Florida, USA are covered with *H. verticillata*. The lost revenues from the recreational use of these lakes due to excessive weed growth are estimated at $10 million/year (Schardt, 1998).

The cost of eradicating *H. verticillata* from 192 km of irrigation canals in the Imperial Valley, California, USA, by using a combination of 120,000 triploid grass carp (*Ctenopharyngodon idella*) over a six-year period, chemical herbicide applications, concrete lining to improve water management efficiency, and labour was $5,300,000 (Stocker, 1993). The estimated cost of a proposed control programme for *M. spicatum* with the herbicide fluridone in approximately 14.5 ha in the Adirondack Park, New York, USA, is $14,757/ha for a total cost of $215,000 (Hu, 2001). Thus, the cost of herbicidal control of aquatic weeds is quite large, and communities may find it difficult to fund control programmes.

Non-indigenous vs. native species

With increasing global trade and rapid transport, non-indigenous, invasive weeds are emerging as a major concern in many parts of the world. According to Simberloff *et al.* (1997), an estimated 5,000 introduced plant species have escaped and now exist in natural ecosystems in the USA compared with about 17,000 native species. In Florida, of the approximately 25,000 alien plant species imported mainly as ornamentals for cultivation, more than 900 have escaped and become established in surrounding natural ecosystems. Similarly, of the 3,000 plus plant species introduced into California, many have escaped into the natural ecosystems (Simberloff *et al.*, 1997; Hall, 1998). According to Babbitt (1998), non-indigenous weeds are spreading and invading approximately 1,800 ha/day of the U.S. wildlife habitats. One of these is the wetland weed *Lythrum salicaria* (purple loosestrife), which, since its introduction in the 19th century, has spread to most of the states in the USA, changing the basic structure of the wetlands in its path. However, this weed may soon be successfully managed by biocontrol insects (Malecki *et al.*, 1993). The wetland tree species, the Australian *Melaleuca quinquenervia* (melaleuca), is another example of an invasive species that has displaced native trees, shrubs, and other vegetation types, along with populations of some associated native animal species in South Florida, USA (Simberloff *et al.*, 1997).

While many of the world's worst aquatic weeds are introduced species, native species have also become problematic in some parts of the world, prompting the frequently asked question: "how do native species become problematic in their own native habitats where they are expected to be under control by indigenous, co-evolved natural enemies and plant competition?" The answer is in the fact that water is a dynamic and unstable medium and most aquatic plants are genetically programmed to multiply and fill an available niche when conditions become favourable. This can be seen as a recurrent theme in many countries where ageing of man-made reservoirs or an increase in eutrophication due to anthropogenic causes have triggered sudden increases in populations of native aquatic plants to problematic levels. Plants that were hitherto kept under check by co-evolved natural forces (herbivores, diseases, and plant competition) adapt to the increased nutrient levels, and those with invasive tendencies become dominant. The present situation in several Brazilian hydropower reservoirs, affected by *Egeria densa* and *E. najas,* is a good example (Nachtigal & Pitelli, 2000). Generally, when native plants become problematic (e.g. *Typha* spp., *Phragmites* spp., *Pontederia cordata* and others), the potential for conflicts of interest increases. Some of these plants may be viewed as economically and environmentally beneficial by some while as a nuisance by others.

Control vs. perceived benefits of aquatic weeds

Most would agree that excessive aquatic weed growth is unacceptable, but some level of aquatic macrophyte presence is necessary for the health of water bodies. However, it is almost always difficult to reach a consensus on how much macrophyte density is desirable in a given body of water. Agencies charged with aquatic weed management as well as scientists debate this point, often reaching conflicting conclusions. A useful review of the issues involved and how this complex topic may be addressed has been provided by Chambers *et al.* (1999). The primary reason for the divergent views on this aspect of aquatic weeds is that these plants have beneficial values as well, sometimes even when they are present at nuisance levels. They can add aesthetic value to water resources, are widely used as aquarium and aquascape plants, provide ecological balance, and can promote waterfowl and fish populations (Joyce, 1990). Some weeds like *E. crassipes, Typha* spp., and grasses that generate enormous volumes of biomass have been tried as a resource for industrial or hand-crafted products, including animal-feed supplements, soil conditioners, composts, paper, biogas, and handicrafts (Virabalin *et al.,* 1993; Pandey & Srivastava, 1996; Anonymous, 2000b). However, these uses require a steady supply of aquatic weeds, and maintenance of supply sources is generally incompatible with the need to control these weeds.

Aquatic plants provide cover for micro- and macrofauna that are part of the food chain, provide shade and shelter for small fish and fingerlings of game fish, improve dissolved oxygen levels, cycle nutrients, reduce turbidity, and provide food and shelter for birds and animals. For instance, aquatic plants can increase waterfowl abundance by providing shelter, nesting sites, and food. In turn, herbivory by birds and other fauna can contribute to a significant reduction in aquatic weed biomass (Van Donk & Otte, 1996). Grazing by black swan is credited with maintaining *H. verticillata* canopy consistently 1m below the water surface in two New Zealand lakes (Hofstra *et al.*, 1999).

Fish in particular are vitally interdependent on aquatic plants, which are key moderators of this interrelationship (Petr, 2000). Aquatic plants regulate nutrients, planktons and macro-invertebrates and even determine the carrying capacity of some fish species (references in Petr, 2000). Both spatial distribution and relative abundance of plants must be considered when instituting weed control programmes. because optimal aquatic plant densities are needed to maintain good fish diversity and productivity. Aquatic macrophytes have been shown to contribute to an increase in fish abundance, particularly in areas that were previously lacking in sufficient amount of plant cover, although the evidence for this is not clear. There are data showing an increase in fish populations following infestation of some large water bodies by invasive plants. For example, fish densities increased in Currituck Sound, North Carolina, USA (approximately 900 km^2 in size) from 1,000 in size to more than 15,000 fish/ha following the establishment of *M. spicatum* in the 1970s (Borawa *et al.,* 1979). Shireman *et al.* (1981) found high fish densities of 13,000 to 205,000 fish/ha in areas infested with submerged plants in Orange Lake, Florida, USA. On the contrary, Hoyer & Canfield (1996) examined 56 Florida lakes and found no strong predictable relationships between the abundance of aquatic macrophytes and the abundance of largemouth bass (*Micropterus salmoides*) among Florida lakes of <300 ha in size. Maceina (1996) suggested that the size of the water body may influence the relationship of largemouth bass populations to aquatic vegetation and this interrelationship among aquatic plant density, size of water body, and fish population should be considered in weed-control decisions.

CONTROL METHODS

Manual removal; mechanical control by various types of mechanical harvesters; physical control by the use of shading devises such as dyes and shade films, burning, and water-level fluctuations; chemical control by using herbicides; and biological control are the principal methods of weed control used.

Manual and mechanical: Extensive use of human labour is common in less-affluent countries, although the results can be quite discouraging when dealing with a weed like water hyacinth that can double in plant numbers in just six to 18 days under some tropical and subtropical conditions (Gopal, 1987). Removal of aquatic weeds with mechanical devices has been used for a number of years in many countries. Draglines, mechanised shovels, harvesters with various types of saws and choppers, and harvester-conveyer-dumper combinations have been used (Gallagher & Haller, 1990). Triturators (=chopper boats) are used in water bodies where the environmental consequences of allowing the chopped biomass to sink and rot *in situ* are not an issue (Gutierrez *et al.*, 1996).

In general, mechanical control methods are extremely inefficient, often requiring repeated cuttings to tackle weed populations that quickly rebound (Lindsey & Hirt, 1999). Plants fragmented by mechanical harvesting can re-grow from the fragments, promote weed reestablishment, and worsen the weed problem (Sidorkewicj *et al.*, 2000). Fragments may also float and clog downstream structures, such as water intakes. Furthermore, the equipment will require frequent maintenance and costly replacement parts, which, unless available locally, could tie-up weed-control operations for days and weeks. Generally, the harvested biomass must be physically removed from the water body and dumped on land. Access to dump sites and availability of equipment (barges, dump trucks, etc.) and cost of such operations should also be factored into the control costs (Haller, 1996b).

In a study conducted in New York State, USA, on the effects of suction-harvesting and benthic barriers on *M. spicatum*, it was found that both native plants and *M. spicatum* were removed but both re-established rapidly (Boylen *et al.*, 1996). Although this short-term management substantially reduced the amount of *M. spicatum* with negligible impact on the restoration of the native plant community, *M. spicatum* was not eradicated. To be effective, it was necessary to repeat the harvest every two to three years (Boylen *et al.*, 1996). The need for repeated harvesting was also indicated in a study conducted in Argentina on *Potamogeton illinoensis* (Armellina *et al.*, 1996). This plant re-grew rapidly after a single spring cutting, but failed to regrow after two additional cuttings later in the season. Similarly, more than one cutting was necessary for effective control of *Egeria densa, Lagarosiphon major* and *Ceratophyllum demersum* in some New Zealand hydropower lakes, but in others a single cutting was sufficient (Howard-Williams *et al.*, 1996).

Because most harvesters cut only the surface biomass of submerged plants, the plants typically re-grow and the biomass rebounds quickly, necessitating repeated cuttings. To tackle this problem, Unmuth *et al.* (1998) designed a harvester that could cut the vegetation close to the sediment surface. Using this experimental device, they were able to keep 46% of the treated deep channels clear of weeds for three years following a single cut, whereas only 4% of the treated shallow channels could be kept weed-free during this period. Thus, refinement in harvester design is possible, but the harvester designs should be carefully matched with the operational site and weed-control objective (Haller, 1998).

Typically, the cost of mechanical control is quite high, limiting the applicability of this method to a few situations where cost is not the primary consideration. For example, the cost of mechanical control of water hyacinth in the USA ranges from $2,000 to $3,000/ha and requires 15 h/ha to complete (Haller, 1996a; 1996b), and the cost for *H. verticillata* is approximately $2,500/ha (Langeland, 1996). The cost of suction-harvesting of *Myriophyllum spicatum* in Lake George, New York, USA, was projected to be $1.58/m^2 or about $15,800/ha (Eichler *et al.*, 1993). Besides, the cost of currently available harvesters specially designed to fit the operational needs is also quite high, running into several thousands of dollars in capital outlay.

Mechanical harvesting can have strong negative impacts on the environment since the process is non-selective. Harvesters not only remove the target weeds but also native plants and numerous micro- and macrofauna (e.g. fish, snails, frogs, etc.) that become entangled in the vegetation being removed by the harvester. Several authors have documented significant losses in juvenile fish and other creatures due to harvest (Mikol, 1985; Engel, 1990; Booms, 1999). Haller *et al.* (1980) estimated that in Orange Lake, Florida, USA, a loss of $6,000 in replacement value of fish resulted during an evaluation of mechanical harvesting as a management method. In addition, mechanical harvesting can leave unpredictable effects on resulting species richness (Best, 1993). From a weed management perspective, a desired species composition may be difficult to achieve following mechanical control.

Monahan & Caffrey (1996) found that some forms of mechanical weed removal more severely impacted macro-invertebrate communities than others. The land-based mowing-bucket method caused the greatest reduction in *Asellus aquaticus*, a major component of fish diet and a dominant organism in Irish canal locations studied. However, populations of this organism recovered rapidly after treatment and there was no adverse effect on the fish species. As an added safeguard, it was recommended that no more than 50% of the vegetation in any one section should be removed in any one period, thus leaving refuges and plentiful food for the fish.

Physical: Burning exposed vegetation and water-level fluctuations have been tried for aquatic weed control. Plants can be exposed to freezing (winter) or hot and dry (summer) conditions and allowed to die and decay. Short-term summer draw-down was found to be useful in controlling *H. verticillata* (Poovey & Kay, 1998). The natural water-level fluctuations of lakes and ponds, such as during periods of drought, could be availed of to dredge and remove or burn the dead vegetation and accumulated organic sediments. This process can be used to rejuvenate and return highly sedimented lakes and ponds to renewed health. However, draw-down is not possible in all water bodies; size and topography, user needs, and logistical considerations may limit the applicability of this method.

Dyes specifically designed to screen or shade portions of the sunlight spectrum (red-orange and blue-violet) required by underwater aquatic plant and algae for growth have been developed and registered in the USA. Aquashade®, a blend of blue and yellow dyes can be used to inhibit photosynthesis in submerged bottom growth. If applied early in the season, growth of submerged plants may be prevented completely. The product is effective at depths of 0.6 m or greater but not in shallow waters. It is used at the rate of 1 ppm concentration, and is labelled for use in non-potable waters (Applied Biochemists, 2001). Cost and public acceptance (due to colouration of water, potential for skin and eye irritation, etc.) are two issues that should be considered.

Various types of bottom-covering materials such as sand-gravel mixture, polyethylene, polypropylene, synthetic rubber, burlap, fibreglass screens, woven polyester, and nylon film have all been used with varying degrees of success, generally providing fairly quick results. Some of the products in the market are claimed to provide weed control for up to one to three years following placement. However, it is difficult or impossible to use bottom barriers on a large scale. The materials are generally costly, the installation is labor-intensive, and the barriers have limited durability. The control will be only as good as the coverage; so, complete control may not occur. Decomposition of plant material and deleterious effects of bottom-covering on aquatic micro- and macrofauna are other negative aspects of this method (Western Aquatic Plant Management Society, 2001).

Chemical: Chemical herbicides enable control of aquatic weeds quickly and efficiently, albeit temporarily. Nonetheless, chemical control is the predominant and dependable means of aquatic weed management. The present generation of aquatic herbicides is generally safe when used according to the labelled directions. However, several negative features of chemical control must be considered in decisions to use this method of control. The cost of controlling some weeds, especially to poor or small communities or less-affluent countries, could be daunting. Although some weeds can be chemically managed to keep lakes and ponds weed-free for several months or even years, re-growth of the weeds is a common problem. Any re-treatment should take into account the magnitude of the weed problem, economics of additional herbicide application, and potential for cumulatively exceeding the permissible residue levels. Misuse of herbicides, deliberate or due to a lack of understanding of proper use, as well as worker protection, are frequent concerns. Misuse can damage the surrounding habitats. Even proper use of herbicides can cause nutrients to be released from decaying vegetation into the water and trigger temporary algal bloom, depress oxygen level, and cause fish kill, especially during hot months. The amount and persistence of chemical residues in treated waters and the increase in the amounts of organic matter that sediments are two other problems. Many herbicides and algaecides require either waiting periods of several hours or days before the water can be used; more stringent restrictions may apply if the water is used for drinking, irrigation, recreation, or fishing. This will inevitably disrupt the use of the treated water.

Another serious issue is the potential shrinking of the already short list of herbicides registered for aquatic use. Presently, chemical pesticides are facing unprecedented scrutiny and restrictions due to regulations such as the Food Quality Protection Act and the Clean Water Act in the USA. In many countries, herbicide use in multi-use waters is banned or severely restricted. Presently, a critical issue facing submerged aquatic weed control is the extremely limited choice of herbicides. Coupled with this, the prospects of resistance build-up to a widely used herbicide, fluridone (Macdonald *et al.*, 2001), raises a new level for concern. Hitherto, herbicide resistance has not been a problem in aquatic weed control. A reason for this paucity of chemical herbicides for aquatic weed control is said to be due to the relative high cost of development and registration of new products, estimated to be around \$15 to 30 million. The aquatic weed market is relatively small (\$20-25 million/year) compared to typical markets for major crops such as corn (*Zea mays*; \$1 billion/year) (Haller, 1998). Furthermore, compared with pesticides used on land, regulations concerning pesticides used in water are more stringent due to the vulnerability of aquatic habitats to damage from pesticide residues and side-effects of control operations. Consequently, this added burden is also a disincentive to develop new products for aquatic weed control.

The method of herbicide application is dependent upon the herbicide formulation and the target weed species. Treatment of large areas requires the use of mechanical sprayers, spreaders, or bottom-injectors mounted on boats or helicopters. The cost of equipment, fuel, and labour and availability of trained applicators and managers to apply the chemicals in a safe and effective manner should also be factored into control programmes. In this regard, the Center for Aquatic and Invasive Plants, Florida Agricultural Experiment Station, University of Florida, USA, offers an annual training course that can be used to gain practical training and educational credits.[1]

The amount a herbicide applied will vary with the product used, and several characteristics of the water body, weed, and other aquatic plants present must be known in order to apply proper amounts. Application of chemical herbicides in moving waters poses problems of rapid dilution and dissipation of the herbicide resulting in sub-optimal contact-time (Getsinger *et al.*, 1990; Fox & Haller, 1992; Fox *et al.*, 1994). The problem can be partly solved by using higher concentrations of herbicides (Green & Westerdahl, 1990; Lembi & Chand, 1992; Netherlands *et al.*, 1993; Van & Vandiver, 1994), slow-release formulations (Murphy & Barrett, 1990), or by timing and split applications (Fox & Haller, 1992). The necessity to assure optimal contact-time is also an issue with potential microbial herbicides, as shown by our studies on *H. verticillata* (Smither-Kopperl *et al.*, 1999).

Herbicide registrations and products vary in different countries[2]. It is extremely important to understand and use herbicides in a manner that is consistent with the labelled uses and directions. The following herbicides are most widely used for aquatic weed control: 2,4-D, copper, diquat, glyphosate, fluridone, and endothall. 2,4-D (2,4-dichlorophenoxy acetic acid), a member of the phenoxy family of herbicides, is one of the most widely used herbicides in the world. A major use of this non-selective herbicide is to control aquatic weeds, as foliar sprays for floating and emersed weeds and in granular form for submersed weeds. Various formulations of 2,4-D are sold around the world. Copper sulfate and chelated coppers are widely used as non-selective, fast-acting, contact herbicides or algicides. Copper compounds are widely used for algae control but certain groups of phytoplanktonic algae are more tolerant to copper. Moreover, copper can build-up in sediments, can be toxic to fish and invertebrates, and the algae could build-up of resistance. Diquat (1,1'-ethylene-2, 2'-bipyridylium dibromide salt) is a contact herbicide that can be used for the control of emersed and submersed weeds and filamentous algae. Glyphosate (*N*-(phosphonomethyl)glycine), labelled for aquatic use as Rodeo (Monsanto, USA), is also a systemic, translocated, non-selective herbicide used for the control of several floating, emergent, and shoreline weeds. This chemical has a short half-life of <25 days and low mobility in soil, is readily adsorbed to soil and rapidly degraded through microbial activities. It is not effective on submerged plants or on buried roots and tubers. Fluridone (1-methyl-3-phenyl-5-[3-(trifluoromethyl)phenyl]-4(1*H*)-pyridinone), registered as Sonar (SePro, USA), is a slow-acting systemic herbicide used to control *H. verticillata, Egeria*, spp., *M. spicatum*, and other underwater plants. Fluridone controls most submersed and immersed weeds and,

[1] Aquatic Weed Control Short Course. (http://conference.ifas.ufl.edu/aw.).

[2] Products named here are registered in the USA; product names and registrations vary in different countries.

being a systemic, translocated herbicide, it kills plants slowly over a 30 to 90 day period. The slow action of fluridone is an advantageous feature since rapid weed decomposition and the resultant oxygen-depletion problem can be avoided. However, the need for application of an adequate concentration and provision of sufficient contact-time impose some complexity to the use of this chemical. The recent confirmation of the emergence of fluridone-tolerant *H. verticillata* in the USA (Macdonald *et al.,* 2001) is an emerging issue of concern. Edothall (7-oxabicyclo[2.2.1]heptane-2,3-dicarboxylic acid), as dipotassium salt (Aquathol (Elf Atochem, North America), is a fast-acting non-selective contact herbicide. It can destroy vegetative parts of the plant but not the roots. Amine salt of endothall (Hydrothol 191 ; Elf Atochem, North America) is a rapidly acting non-selective contact herbicide that can be used also as an algicide. Endothall formulations vary considerably in their safety to fish and weed control spectrum; some more than others are toxic to fish (compiled from Ahrens, 1994 and product labels available on the Internet).

Biological: Biological control can be an economically sustainable, environmentally safe, long-term option to manage certain targeted aquatic weeds in multi-use waters. Invasive aquatic weeds that colonise vast areas of water bodies in monotypic stands are ideal targets for biological control. However, biological control is not meant to eradicate a target weed, but merely suppress the weed populations substantially, allowing native species to return. When used in an integrated approach with other control techniques, biological agents can stress their host plants, making them more susceptible to other controlling forces. Two forms of biological control are practised: 1) introduction of non-native organisms that function in a self-maintaining, host-density dependent manner with their target weeds (the classical or inoculative biocontrol strategy) and 2) augmentation or manipulation of indigenous organisms that, with human intervention, can be made to incite weed-suppression (the augmentative, inundative, or bioherbicide strategy). In both cases, the objective is to use organisms that can significantly curtail the growth and reproduction of the target weeds without adversely affecting non-target organisms.

The most widely used biocontrol organisms with a proven record of success are fish and insects (Table 2). Herbivorous snails, the Ampulariids, have been tested, but they have not shown good effectiveness or safety to merit consideration as biocontrol agents for aquatic weeds (Cowie, 2001). Based on the author's own work and those of others, several fungal plant pathogens have been shown to be capable of controlling *E. crassipes, Egeria* spp., *H. verticillata*, and *M. spicatum* under experimental conditions (Charudattan, 1990; Shearer, 1998; Nachtigal & Pitelli, 2000). Some indigenous pathogens also play a significant natural role as interactive factors with insect biocontrol agents and increase the levels of biotic stress (Charudattan, 1986). However, technological and regulatory difficulties in developing and registering these agents, coupled with the problem of inconsistent performance of some of these agents in large-scale field trials have so far precluded their practical use in aquatic weed management programmes. (Charudattan, 1996; 2000). Research is continuing to address these problems.

Table 2. Notable examples of aquatic weeds managed fully or partially by biological control agents [a]

Weed	Agent(s) most responsible for success	Country(~ies) where most successful [b]
Alternanthera philoxeroides	*Agasicles hygrophila* (beetle)	Australia, USA
Eichhornia crassipes	*Neochetina eichhorniae* and *N. bruchi*(weevils)	Australia, India, Kenya, Sudan, Thailand, Uganda, USA, Zimbabwe
Lythrum salicaria	*Galerucella calmariensis* and *G. pusilla* (beetles)	Canada, USA
Pistia stratiotes	*Neohydronomous affinis* (weevil)	Australia, Zambia, Zimbabwe
Salvinia molesta	*Cyrtobagous salviniae* (weevil)	Australia, Fiji, Ghana, India, Kenya, Namibia, Papua New Guinea, South Africa, Sri Lanka, Zambia
Several submerged weeds	*Ctenopharyngodon idella* (fish, carp)	USA, several countries in Europe, the Middle East, and Asia

[a] See Julien & Griffiths, 1998, for details of insect agents released, field performance of agents, country of origin of agents, key references, and other information.
[b] "Success" represents a general recognition that the weed is no longer a major problem.

Non-native biocontrol organisms that are introduced from a different country or continent must be thoroughly tested for their safety to non-target organisms and habitats. For non-native insects and pathogens used in this manner (classical or inoculative strategy), there are well-established testing protocols to avoid introductions of unsafe organisms. Extensive regulatory oversight is exercised before classical biocontrol organisms are used against aquatic weeds. Because of the extensive testing requirement to assure host specificity, introduction of classical biocontrol agents is a slow process that requires years of research. It is estimated that the cost of developing and deploying a single classical biocontrol agent is between $4 and $6 million and the process requires between 3.5 and 20 scientist-years (Center *et al.*, 1997). On the other hand, biocontrol programmes can yield enormously favourable returns on investment. For example, Thompson *et al.*, (1999) have calculated a return of 27 units of benefit from each one unit of investment in research and development of a public-funded biological control programme for *L. salicaria*. Comparative figures for chemical and mechanical control of aquatic weeds are not available, but Pimentel *et al.*, (1993) project a smaller 1:4 return for all chemical pesticides, including herbicides, used in crop protection. Teague & Brorsen (1995), based on 1991 figures, estimate a return of $4.16 per every $1.00 spent on chemical pesticides in agriculture. Thus, based on cost-benefit considerations, biological control certainly ranks higher than other forms of aquatic weed control.

Despite solid scientific and empirical foundations of biological control, it is difficult to assure success in every case. Even after careful research and testing, many classical biological control agents fail to provide a level of control desired by different stakeholders. This could be due to the inability of the organism(s) to establish permanently and spread, inadequate capability to suppress the weed populations, or a number of other factors related to the weed, the organism, or the environmental (Julien & White, 1997). Moreover, not all weeds are likely to be easy targets for biocontrol. *H. verticillata,* for instance, has not been adequately controlled in the USA even after nearly ten years following the release and establishment of four non-native agents, *Bagous affinis* and *B. hydrillae* (tuber weevils; Coleoptera: Curculionidae) and *Hydrellia pakistanae* and *H. balciunasi* (leaf-mining flies; Diptera: Ephydridae) and the presence of a native or naturalised moth, *Parapoynx diminutalis* (Lepidoptera: Pyralidae). Likewise, as stated above, the fungal pathogens tested so far have not proven consistently effective in controlling submerged weed targets in field trials.

Use of the herbivorous fish, the Chinese grass carp, *Ctenopharyngodon idella* (Cypriniformes: Cyprinidae) represents a unique type of biological control in that the fish is a non-native species and a generalist feeder lacking host-specificity. Among the several herbivorous fishes that have been evaluated for the control of aquatic weeds, the grass carp is the most widely used and highly effective agent. A native of north-eastern Asia, this fish has been used in many countries for aquatic weed management since the 1960s (Opuszynski & Shireman, 1995; Sutton & Vandiver, 1995). The initial fear that this fish may reproduce in North American waters, establish, and adversely affect water quality, plant and animal biodiversity (especially the native fishes), and the sport fishing industry, was allayed through the introduction sterile triploid grass carp. The use of the triploid as a non-selective biological control agent for submersed aquatic weeds is regulated in the USA under a permit system (Sutton & Vandiver, 1995). Since the carp is edible, it may be doubly beneficial to use it as a weed-control agent and a food source in resource-poor, weed-afflicted communities. An important consideration in using this fish is the stocking rate; at high stocking rates grass carp can eliminate all submersed vegetation, increase water turbidity, shoreline erosion, and planktonic blooms, and affect other micro- and macrofauna.

In general, grass carp prefers submerged aquatic macrophytes, including important submerged weeds such as *H. verticillata, Chara* spp., *Najas guadalupensis, E. densa, Potamogeton* spp., *C. demersum*, *Myriophyllum* spp., and *Vallisneria,* floating weeds *Wolffia* spp., *Lemna* spp., *Spirodela* spp., and *Azolla caroliniana,* and grasses and cattails. The floating and emergent plants *E. crassipes, P. stratiotes, Nymphaea* spp., and *Nuphar luteum* are least preferred (Sutton & Vandiver, 1995). The triploid grass carp, when used at proper stocking rates, provides excellent control of several submerged weeds (Opuszynski and Shireman, 1995; Sutton & Vandiver, 1995). As a non-selective herbivore, grass carp can be used to manage several aquatic plants collectively to maintain plant coverage at empirically determined levels. It can also be used in combination with chemical control, as well as other control methods. The cost of aquatic weed control with the triploid grass carp in Florida, USA, ranges from about \$50 to \$620 per hectare (Wattendorf, 2001).

A. philoxeroides (alligatorweed), *E. crassipes* (water hyacinth), *L. salicaria* (purple loosestrife), *Pistia stratiotes* (water lettuce), and *S. molesta* (giant salvinia or Kariba weed) are examples of weeds that have been managed principally or to a considerable extent by insect biocontrol agents (Julien & Griffith, 1998). One of the early successes in biological control occurred when populations of *A. philoxeroides* throughout the southeastern USA were brought under substantial control following the introduction of three agents, *Agasicles hygrophila* (flea beetle; Coleoptera: Chrysomelidae), *Arcola malloi* (=*Vogtia malloi*; moth; Lepidoptera: Pyralidae), and *Amynothrips andersonii* (thrips; Thysanoptera: Paleothripidae) (Buckingham, 1994; Julien & Griffiths, 1998). These biocontrol agents were subsequently released at different times into Australia, New Zealand, Peoples Republic of China, and Thailand. The levels of control afforded by these agents vary depending on the latitude, season, and relative wetness of sites. Generally, these insects have provided good to excellent control in wetland and aquatic sites in tropical and subtropical latitudes, but not in the temperate fringes of the subtropics or in drier upland sites (Buckingham, 1994; Julien & Griffiths, 1998). Nevertheless, since the 1970s, alligatorweed has been downgraded from being one of the worst aquatic weeds in the world to one that is manageable. Further work is needed to find biocontrol agents that are effective on this weed in upland sites and cooler latitudes.

In the case of *E. crassipes*, published literature and anecdotal evidence indicate that biological control has been a key to the overall success of management programmes directed at this weed in several parts of the world (Center, 1994; Cordo, 1996; Julien *et al.*, 1996). However, in many tropical and subtropical regions, the weed grows at rates that far outstrip the ability of existing biological agents to control this plant. Furthermore, at sites where this weed must be controlled rather quickly and completely, biological control cannot be effective. Further improvements in biological control may be possible, and recent efforts to research and utilise additional agents are promising (references in Charudattan, *et al.*, 1996). Co-ordination of control efforts, regional co-operation among countries affected by this weed, choice of suitable control methods for integration, and a sustained commitment to a control strategy are essential for long-term success in the management of this global menace.

Success of biological control of *E. crassipes,* attributed to the effects of several introduced insects, principally two introduced weevil species, *Neochetina eichhorniae* and *N. bruchi* (Coleoptera: Curculionidae), has been reported from several sites in Australia, Benin, India, Sudan, and Papua New Guinea (Julien & Griffiths, 1998). The most recent, and perhaps the most dramatic success, has occurred in Lake Victoria in East Africa where nearly complete control was seen in two years after the release of some 142,000 weevils at 30 sites (Anonymous, 2000a). Several publications have presented evidence to the effectiveness of biological control of *E. crassipes* at various sites; these publications provide a more detailed accounting of water hyacinth biocontrol than presented here (Center, 1994; Julien *et al.*, 1996; Charudattan *et al.,* 1996; Hill *et al.*, 1999). However, what is not clear from these publications is whether the dramatic reductions in *E. crassipes* populations seen soon after the first releases at new sites (i.e., "the initial crash in weed population") will be repeated at every location. It is also not clear whether *E. crassipes* populations will rebound from the initial crash to reach stable levels that are acceptable from a weed-control standpoint. Opinions vary. For instance, Haller (1996a) and Ferriter *et al.,* (1997) have argued that *E. crassipes* populations in Florida, USA, would rebound if chemical herbicide applications are halted and that biocontrol agents alone would not keep the populations from rebounding. Biocontrol workers on the other hand concede that more could be done to improve the level of biological control seen in several countries by introducing additional agents (Center, 1994; Cordo, 1999). A Pan-African programme, currently underway, aims to develop an indigenous fungal pathogen as a bioherbicide that could be used concurrently with the insect agents to enhance the levels of biological control (Den Breeÿen, 2000; Bateman, 2001).

Worldwide, *E. crassipes* biocontrol has been a good model of an effective programme, and the insects have played a key role in this success. A network of scientists, governmental agencies, and private organisations collaborate to extend this biocontrol programme to new areas (Julien *et al.*, 1996) and to continue research and utilisation of additional agents and methods (Cordo, 1999). A protocol for mass rearing of *Neochetina* spp. has been developed that could be easily adopted anywhere to set up an insect-rearing and distribution network

(Julien *et al.*, 1999).

L. salicaria, an herbaceous wetland perennial of European origin, has spread and degraded wetlands in temperate North America. Mature plants can reach heights of up to 2m with 30-50 stems and produce >2 million, small, easily dispersed seeds per plant. Seedling densities can approach 10,000-20,000 plants/m^2. *L. salicaria* is now reported to occur in all states in the USA except Alaska, Arizona, Hawaii, Florida, Louisiana, New Mexico, and South Carolina (USDA, NRCS, 2001) and all Canadian provinces. Small but dense infestations in irrigation canals can impede water flow. In small areas, the weed could be managed with chemical herbicides, water-level manipulation, mowing or cutting, and burning. However, large infestations over vast natural areas, where the weed is most damaging to native plants and wildlife, can be managed only by biological control because chemical and mechanical controls are not feasible on such large scales. Realising this, a biological control programme was initiated and by the early 1990s several host specific insect species from Europe were released in the USA and Canada (Thompson *et al.*, 1999). Of these, two leaf-feeding beetles, *Galerucella calmariensis* and *G. pusilla* (Coleoptera: Chrysomelidae) and a flower-feeding weevil, *Nanophyes marmoratus* (Coleoptera: Curculionidae) are showing great promise (Blossey, 2001). A network of co-operators from academia, private, and public groups help disperse these insects and gather post-establishment efficacy data. The insects are reared and provided by co-operating scientists. Results coming from several locations in the USA and Canada attest to a high level of success in controlling *L. salicaria* solely by these biological control agents (e.g. Van Sickle, 2000). Thus, the prospects for long-term success of this biocontrol campaign seems assured and the estimation of 27 units of benefit to every unit of cost, as proposed by Thompson *et al.*, (1999) appears to be clearly within reach.

P. stratiotes, a floating weed, is reported to be under variable levels of biological control at many sites in Australia, Botswana, Ghana, Papua New Guinea, South Africa, USA, Zambia, and Zimbabwe (Julien & Griffiths, 1998). Two arthropods, *Neohydronomus affinis* (Coleoptera: Curculionidae) and *Spodoptera pectinicornis* (Lepidoptera: Noctuidae) are credited with this biocontrol. Although, it is clear that these agents have not performed consistently in all locations, there is good documentation to prove that *N. affinis* has successfully controlled the weed in large perennial rivers of South Africa (Cilliers *et al.*, 1996). Chemical control is used to control the weed in shallow, seasonally flooded water bodies where the discontinuous presence of the weed precludes the build-up of the biocontrol agent.

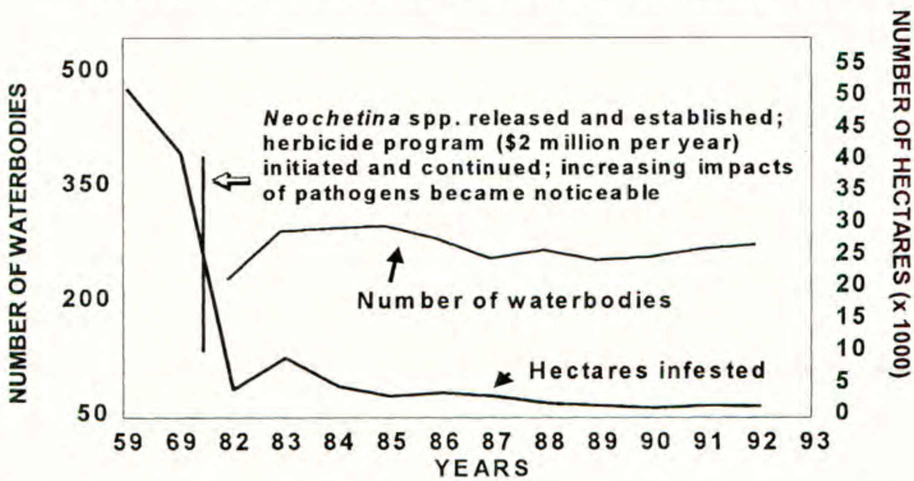
The South American weevil *Cyrtobagous salviniae* (Coleoptera: Curculionidae) has provided good to spectacular levels of control of *S. molesta* at several sites in Australia, Fiji, Ghana, India, Kenya, Malaysia, Namibia, Papua New Guinea, South Africa, Sri Lanka, Zambia, and Zimbabwe (Thomas & Room, 1986; Julien & Griffiths, 1998). For instance, in Zimbabwe, the weevil was established in two reservoirs comprising 16 ha in the north-west of the country (Chikwenhere & Keswani, 1997). Within two years after introduction in these reservoirs, the weevil provided 99% control of the weed at a cost-benefit ratio of 1:10.6 over a four-year period. The cost of this biocontrol campaign was estimated at $5 to $6/ha, representing one-fourth of the cost of chemical control and physical removal. The success of this weevil in Australia and Papua New Guinea, where the weed was completely controlled by *C. salviniae*, was reviewed by Thomas & Room (1986), who concluded that *C. salviniae* provides cost-effective, environmentally sound, and apparently permanent control of *S. molesta* in these two countries. Thus, in comparison with chemical control and physical removal, biocontrol is a more viable method for long-term control of *S. molesta*. Unlike *C. salviniae,* three other insects, *C. singularis* (Coleoptera: Curculionidae), *Paulinia acuminata* (Orthoptera: Pauliniidae), and *Samea multiplicalis* (Lepidoptera: Pyralidae) have failed to establish or are unable to provide adequate control of this weed.

EFFECTIVE MANAGEMENT OF WATER HYACINTH - A MODEL

Until a few years ago, *E. crassipes* occupied as much as 51,000 ha in several public waters in Florida, USA; it now occurs in only about 2,000 ha of these waters (Figure 1). This is clearly an example of a highly successful, co-ordinated programme of aquatic weed management. The water bodies that were covered in this programme are those that the State of Florida manages as per legislative mandates. Regular surveys are conducted to catalogue aquatic plants and rank them according to their abundance. These surveys have established that since the early 1970s, *E. crassipes* has gone from being the number one aquatic weed to one of minor importance. Opinions vary as to the cause of this dramatic reduction in *E. crassipes* infestation. Three biological control insects, *Neochetina bruchi, N. eichhorniae,* and *Niphograpta albiguttalis* (Lepidoptera: Pyralidae), were released into Florida in the 1970s (Center, 1994). Several localised impacts of indigenous and/or naturalized insects and microbial pathogens became a common occurrence during this period (Charudattan *et al.*, 1978), and a legislatively mandated, continuous, chemical control programme was installed in 1976 (Schardt, 1997). Prior to this, a chemical control programme was in place but funding was on an ad hoc basis. It is not possible to attribute the sharp drop in *E. crassipes* populations that occurred between 1960-1970 (Figure 1) to the chemical control programme or the biological agents due to lack of studies that could have quantified the relative contributions of these factors. Some, like Ferriter *et al.*, (1997), contend that this success resulted from a sustained chemical control programme termed "maintenance control."

"Maintenance control" is defined in the Florida statutes as a method for the control of non-indigenous aquatic plants in which control techniques are utilised in a co-ordinated manner on a continuous basis in order to maintain the plant population at the lowest feasible level as determined by the Florida Department of Environmental Protection (Schardt, 1997). As originally envisioned, maintenance control was to be an integrated weed management approach to water hyacinth control, but as currently practised it consists primarily of chemical control. Studies by Center *et al.*, (1999) have shown that *E. crassipes* at sites left undisturbed for several years benefited from intense effects of biocontrol agents (i.e., small plants, heavily stressed from insect and microbial attacks) whereas sites subjected to the maintenance control programme did not share these beneficial effects. However, accumulated stress from insect biocontrol agents, mainly the *Neochetina* spp. weevils, at the unmanaged sites rendered the plants less suitable for the weevils and consequently had lower weevil populations than at chemically managed sites. The *E. crassipes* plants in the latter sites, representing rebounding populations, were healthier and supported higher weevil densities (Center *et al.*, 1999). These results are consistent with biocontrol theory in that the weevil densities were lower in the unmanaged sites that became resource-limited as a result of biocontrol (i.e., smaller consumable biomass). In the chemically managed sites, the rebounding plants provided plentiful food on which a robust population of weevils could build-up. However, repeated chemical applications might have other adverse effects the weevil populations. For example, Chikwenhere & Vestergaard (2001) found that *N. bruchi* weevils from sites in Zimbabwe that were regularly treated with chemical herbicides had higher levels of infection by the fungal pathogen *Beauveria bassiana* compared with sites without chemical applications. Some chemicals are likely to be more incompatible with biocontrol agents than others; therefore, a case-by-case study should be performed to arrive at the best possible approach to integration of control methods. Improperly timed applications of chemicals could eliminate the food source for developing insect colonies and interfere with the normal development of the insects (e.g. development of wing-muscle and the ability of the weevils to disperse from herbicide-treated plants; see Buckingham & Passoa, 1984). Therefore, ill-timed application of chemical herbicides that disrupt the normal seasonal build-up of biocontrol agents will diminish the long-term benefits of the biological control programme.

Area of Water hyacinth Infestation in Public Waters and Number of Waterbodies Infested by this Weed in Florida, 1959 to 1993



Compiled from data published by the Bureau of Aquatic Weed Control, Tallahassee, Florida, USA

On the positive side, Joyce (1985) calculated that maintenance of *E. crassipes* at less than 5% coverage in a water body can significantly reduce the annual herbicide usage, reduce organic deposition, prevent depression of oxygen concentrations, and enhance the killing effects of winter freezes on the weed. Thus, the maintenance control programme can reduce the amounts of chemicals used over time.

Unlike the success of the *E. crassipes* programme in Florida, maintenance control of *H. verticillata* has not been effective. Infestations of *H. verticillata* have increased in Florida's public waters from about 5,000 ha in 1982 to about 40,000 ha in 1994. Schardt (1997) ascribes this inability to contain the spread of *H. verticillata* to insufficient funding of the maintenance control programme, although $1.5 to $5.5 million per year in public funds has been spent in this programme to control hydrilla. It should be noted that, unlike *E. crassipes* upon which the biocontrol agents are highly effective, the *H. verticillata* biocontrol agents (referred to above) have not been effective on this weed. It could be argued that biological control is the foundation that allows maintenance control to be effective; in the absence of effective biocontrol agents, it may not be possible to control *H. verticillata* with chemical herbicides alone. The presence of fluridone-tolerant *H. verticillata* in the USA (Macdonald *et al.*, 2001) simply makes matters worse.

KEY ELEMENTS FOR SUSTAINABLE, LONG-TERM MANAGEMENT OF AQUATIC WEEDS

Several key elements should be included in any long-term aquatic weed management programmes. It has been said that aquatic weed control, by necessity, should be local, but the management policies and administration should be co-ordinated and applied on a broad region-wide basis (Mitchell, 1996). Co-operation and co-ordination of efforts by several governmental and private agencies and the public are required to assure success. Aquatic weeds do not recognize political boundaries, and control efforts mounted in one region may be thwarted if there is a steady influx of weeds and weed propagules from neighboring areas. Although many countries have laws and regulations to prevent unauthorized introductions of invasive species including plants, new weed invasions do occur at regular frequency. Therefore, preventing establishment and re-establishment of weeds before they reach problematic levels should be a stard operating procedure. Early and timely intervention rather than a belated reaction should be part of this standard. A technical corps trained in the latest aquatic weed control techniques should be on hand. Experience should be drawn from prior research conducted in other regions of the world in designing action plans. It may be expedient to adopt successful models of weed control programmes from elsewhere rather than invest in all new indigenous programmes. Known ecological impacts of weeds and control methods gathered from other regions should be taken into consideration in assessing the potential local impacts of control methods (Stocker, 2000).

Since prevalence of aquatic weeds is associated in most cases with human activities, such as creation of large reservoirs or irrigation canals, the public's interests must be fully factored in any control operations. In situations where nutrient influx is the primary cause of water-quality deterioration, attempts should be made to stop or mitigate the influx of nutrients, especially phosphorus. The public must also be educated in ways to monitor, preserve, and protect water bodies and assured a sense of ownership of *their* water resources. The Florida LAKEWATCH programme in the USA (Florida LAKEWATCH, 2001) and the Working for Water Programme in South Africa (Working for Water Programme, 2001) are two good models of public stakeholder involvement in monitoring and protecting water resources from various threats including aquatic weeds.

Control strategies should include all appropriate and effective methods of control. Biological control should be the centrepiece of management programmes for non-native invasive species. Integration of biocontrol with other applicable techniques should be achieved in a manner that maximises the effectiveness and benefits of biocontrol. There is an urgent need to develop new chemical herbicides, particularly for submerged aquatic weeds. Under the dictates of the Food Quality Protection Act (USA), there is a window of opportunity to discover and develop newer, safer compounds as reduced-risk herbicides. In this regard, micro-organisms, which are an excellent source of novel compounds, should be explored.

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