Biological and Integrated Control of Water Hyacinth, *Eichhornia crassipes*

Proceedings of the Second Meeting of the Global Working Group for the Biological and Integrated Control of Water Hyacinth, Beijing, China, 9–12 October 2000

***Editors*: M.H. Julien, M.P. Hill, T.D. Center and Ding Jianqing**

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Address of Welcome

Good morning, ladies and gentlemen

On the occasion of this splendid autumn season in Beijing, it is a great pleasure for all of us to greet the opening of the Second Global Working Group Meeting for the Biological and Integrated Control of Water Hyacinth, held under the auspices of the International Organization of Biological Control (IOBC). On behalf of the Biological Control Institute of the Chinese Academy of Agricultural Sciences, please allow me to extend our warm congratulations. I sincerely wish the meeting a great success.

As is known to all, water hyacinth is one of the most dangerous weeds in the world, causing great damage to agriculture, aquatic production, tourism and the environment in over 40 countries including China. Currently in China, water hyacinth grows in 17 provinces, and millions of dollars are spent on its control every year. Although China has made great efforts and achieved remarkable progress in the biological and integrated control of water hyacinth, the weed is still spreading into new regions at an alarming speed. As this working group meeting provides a good opportunity for mutual exchange of information and experiences in the field of water hyacinth control among the delegates and scientists from various countries, I am sure that a successful meeting will not only promote the research work on water hyacinth control in China, but also help advance research activities on global water hyacinth control into a new phase. Therefore, it is essential that the working group meeting be held regularly so that scientists and experts from different countries and regions can get together and cooperate in finding good solutions to the worldwide problem of water hyacinth.

Finally, I'd like to wish everyone a nice stay in China.

Thank you.

Professor Yang Huaiwen,
Director of the Biological Control Unit,
Chinese Academy of Agricultural Sciences

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Editorial

These are the papers presented at the Second Global Working Group Meeting for the Biological and Integrated Control of Water Hyacinth, held in Beijing, China in October 2000 under the auspices of the International Organization for Biological and Integrated Control of Noxious Animals and Plants (IOBC). The meeting brought together 31 delegates from 11 countries with the common purpose of identifying suitable biological and integrated control options for water hyacinth.

These proceedings represent the current status of work on water hyacinth worldwide and include new research initiatives, overviews of water hyacinth implementation programs in various countries and a proposal for a mechanism to facilitate the dissemination of information on water hyacinth through a clearinghouse. The papers, which were each refereed by at least two of the editors, were presented under a series of themes. The salient points from each of the papers were then summarised at the end of the theme session. These summaries are included in the proceedings. Nevertheless, much of the discussion that occurred at these workshops is not recorded here. The address list appended to the proceedings will, it is hoped, stimulate further interaction between the delegates. We are very grateful to the Australian Centre for International Agricultural Research (ACIAR) for supporting the preparation and publication of these proceedings.

One of the roles of this working group is to identify further research needs on water hyacinth. From the presentations and discussions the following ideas emerged as requiring further investigation.

- The impact of cold climates on the success of biological control. Investigation of the thermal tolerance of the natural enemies used was suggested, and of the value of collecting biological control agents from climatically similar localities. Also, studies of the impact of releasing large numbers of healthy, fertile females through the winter to obviate the lag time in population build-up of the weevils following cool winters were suggested.
- The use of plant competition studies between water hyacinth and other aquatic plants as an indicator of how effective particular agents are.
- The compatibility of the different control options that could be used in integrated management.
- The compatibility of each biological control agent with each of the herbicides likely to be used and their surfactants.
- The selection of suitable locations and undertaking of integrated management of water hyacinth where biological control is the base technique. This has been done in South Africa in a temperate climate (Jones, these proceedings). The Kafue River, where various agents are established but control has not been successful, offers an opportunity in the tropics.
- Identification and conduct of surveys for additional natural enemies (both insects and pathogens) in new areas in the region of origin of water hyacinth.
- The interactions between the insect natural enemies with the pathogen natural enemies.

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- The development of mycoherbicide for water hyacinth. It is hoped that the IMPECCA project (Bateman, these proceedings) will achieve this goal.
- Quantification of the contribution of *Orthogalumna* to biological control in the field. Studies in Malawi may be the first step in this.
- Quantification of the impact of *Eccritotarsus* in the field.

The workshop closed with a general meeting of the working group (the participants). During the meeting it was suggested that a mission statement for the working group be developed and this was done (see below). It was also decided that the next meeting should be held in Uganda on the shores of Lake Victoria in early August 2002.

Mission Statement

The mission of the IOBC Working Group for the Biological and Integrated Control of Water Hyacinth is to promote better management of water hyacinth through:
- facilitation of interactions,
- dissemination of information, and
- identification of research needs.

This will be achieved by:
- holding a meeting every 2 to 3 years,
- publishing the meeting proceedings, a water hyacinth newsletter and maintaining web site, and
- supporting activities that contribute to better management of water hyacinth.

Meeting participants

Front row (left to right): Wu Zhenquan, Chen Ruoxia, Joseph Ndunguru, Gasper Mallya, Raghavan Charudattan, Fu Weidong, Ding Jianqing, Peter Mjema and Xia Shanlong.

Back row (left to right): Lu Qingguang, Wang Qinghai, Sun Junmao, Ma Ruiyan, Tom Moorehouse, Tom McNabb, Eric Gutiérrez, Garry Hill, Yahia Fayad, Ted Center, Roy Bateman, Lius Navarro, Harry Evans, Richard Shaw, Godfrey Chikwenere, John Wilson, Roy Jones, Mic Julien, Andrew Mailu and Martin Hill.

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Biological Control of Water Hyacinth with Arthropods: a Review to 2000

M.H. Julien*

Abstract

Water hyacinth, native to the Amazon River, invaded the tropical world over the last century and has become an extremely serious weed. The search for biological control agents began in the early 1960s and continues today. Six arthropod species have been released around the world. They are: two weevils, *Neochetina bruchi* and *N. eichhorniae*; two moths, *Niphograpta albiguttalis* and *Xubida infusellus*; a mite *Orthogalumna terebrantis*; and a bug *Eccritotarsus catarinensis*. The mite and *X. infusellus* have not contributed to control and the bug is under evaluation following recent releases in Africa. The two weevils and the moth *N. albiguttalis* have been released in numerous infestations since the 1970s and have contributed to successful control of the weed in many locations. It is timely to assess their impact on water hyacinth and, to help in planning future strategies, to identify the factors that contribute to or mitigate against successful biological control. Although the search for new agents continues, and as a result biological control will likely be improved, this technique alone is unlikely to be successful in all of the weed's habitats. It is important that whole-of-catchment management strategies be developed that integrate biological control with other control techniques. The aims of such strategies should be to achieve the best possible control using methods that are affordable and sustainable; hence the need to develop strategies using biological control as the base component.

WATER hyacinth apparently became a problem in the USA following its distribution to participants in the 1884 New Orleans Cotton Exposition. By the early 1900s it was widespread in the southern states. During the same period it spread through the tropics of other continents and now reaches around the world and north and south as far as the 40° latitudes (Center 1994). More recently it spread into the many waterways of Africa and has expanded rapidly, probably in response to high nutrient conditions, to cause serious problems. To combat the problems caused by the weed, efforts to control its spread and to reduce its biomass have been many and varied and include weed management methods such as physical removal, application of herbicides and release of biological control agents. Utilisation of the weed for commercial and subsistence purposes has also been widely considered. It is now generally recognised that physical and chemical controls have very limited application in most countries because of their high cost and low sustainability. Utilisation has never developed into sustainable activities other than localised cottage industries or to support very poor communities in subsistence existences such as the production of biogas. Only small amounts of water hyacinth can be utilised in such activities, which should never be confused with control. Neither should the potential for utilisation prevent the implementation of control strategies (Harley et al. 1996; Julien et al. 1996). The cost of water hyacinth to communities far outweighs the benefits that might occur through utilisation. In general, even when the weed is successfully managed there is likely to be sufficient present to support the small-scale utilisation activities that persist.

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The one control technique that continues to show promise, can be developed further, is affordable, environmentally friendly and above all sustainable, is biological control. The remainder of this paper is a review of the activities and results of biological control of water hyacinth using arthropods, and includes a discussion of the attributes and limitations of this technique. A review of biological control of water hyacinth using pathogens is presented separately in this volume (Charudattan 2001).

Exploration for Natural Enemies

Surveys for natural enemies of water hyacinth for use as biological control agents began in 1962 and have continued until recently. A brief chronology, summarised largely from Center (1994), follows.

- Mr A. Silveira-Guido conducted the first surveys in Uruguay in 1962 to 1965. He found the moth *Xubida* (*Acigona*) *infusellus*, two weevil species *Neochetina eichhorniae* and *Neochetina bruchi*, the mite *Orthogalumna terebrantis* and the grasshopper *Cornops aquaticum*, among other species.
- Biology and host range studies were conducted on a number of these agents at the USDA-ARS laboratory at Buenos Aires. This laboratory was set up in 1962 to work on alligator weed and from 1968 studies focused largely on water hyacinth.
- During 1968 surveys were conducted by F. Bennett and H. Zwölfer of CIBC, now CABI Biosciences, in Guyana, Surinam and Brazil. To the list of species they added the petiole-tunnelling moth *Niphograpta* (*Sameodes*) *albiguttalis*, the petiole-boring flies *Thrypticus* spp., and an unnamed mirid bug.
- D. Mitchell and P. Thomas conducted surveys in Uruguay, Brazil, Guyana and Trinidad but did not extend the list of known phytophages.
- Bennett surveyed the West Indies, Belize and Florida USA in the late 1960s and found *O. terebrantis* and the stem-boring moth *Bellura densa*.
- Surveys were also carried out in India in the early 1960s by Rao, and in Indonesia in the mid 1970s by Mangoendihardjo and Soerjani.
- In 1969 R. Gordon and J. Coulson conducted surveys in Florida, Louisiana and Texas, USA, and found *O. terebrantis* and *B. densa*.
- In 1981 Bennett surveyed Mexico, finding *X. infusellus, N. eichhorniae, C. aquaticum* and *O. terebrantis.*
- In 1989 Stephan Neser, PPRI, collected the mirid *Eccritotarsus catarinensis* in Santa Catarina State, Brazil (Hill et al. 1999). This may have been the bug recorded by Bennett and Zwolfer during their 1968 surveys in Guyana, Surinam and Brazil.
- In 1999 a survey was conducted by M. Hill, PPRI South Africa, H. Cordo and T. Center, USDA-ARS, and H. Evans and D. Djeddour, CABI Biosciences, into the upper reaches of the Amazon River in Peru (M. Hill, pers. comm. 1999).

The native range of water hyacinth is widely referred to as South America. Using the variations in flower morphology, Barrett and Forno (1982) suggested that it was more accurately the Amazon Basin. Recent surveys suggest that the centre of origin for water hyacinth may be the upper reaches of the Amazon River and its tributaries. The reasons are that the widest diversity of fauna associated with the plant has been found in that area, and the floating habit of the plant probably evolved to withstand rapid fluctuations in water level that occur in the upper Amazon River (T. Center and M. Hill, pers. comm. 1999).

The range of surveys provided lists of fauna related to the weed. From these lists arthropods and pathogens have been selected for further studies. The selection process relies initially on the observations and judgment of the surveying scientists. The host ranges of those selected are observed in the field and studied in the laboratory. Those showing a narrow host range are then subjected to host-specificity tests to determine the safety of releasing them in the exotic range of the weed. The listing and selection of potential agents is a continuous process that occurs while surveys continue and as new information becomes available about the fauna. The most recent list was presented to the last International Organisation for Biological Control Water Hyacinth Workshop in 1998 (Cordo 1999), where three levels of priority were assigned to groups of potential agents. The first priority group listed the four agents that have been released for some time. They are: the weevils *N. eichhorniae* and *N. bruchi*; the moth *N. albiguttalis*; and the mite *O. terebrantis*. The second priority group included agents that have recently been released—*E. catarinensis* and *X. infusellus*—and others recently or currently under study including *C. aquaticum, B. densa*, the moth *Paracles* (*Palustra*) *tenuis* and the flies *Thrypticus* species. The third priority list included a list of nine organisms (eight insects and a mite) about which little is known. The second and third priority lists may change as a result of the recent and proposed surveys in Peru.

Biological Control Agents

Six arthropod biological control agents have been released around the world (Table 1). Five are insects (two weevils, two moths and a sucking bug), and one is a mite. The two weevils, *N. bruchi* and *N, eichhorniae*, and one of the moths, *N. albiguttalis*, have been released widely since 1971 in 30, 32 and 13 countries, respectively, while the others, the mite *O. terebrantis*, the moth *X. infusellus* and the bug *E. catarinensis,* have been released in fewer countries: 2, 3 and 6, respectively. The mite was first released in 1971 while the other two were first released in 1996.

Neochetina bruchi

Biology

Small whitish eggs are laid into the petioles, often into insect chew holes, singly or several together. Eggs hatch in about seven days and don't hatch below 15ºC. Larvae tunnel inside the petioles towards the base and into the crown where they often feed on developing axillary buds. A number of larvae may feed in the same petiole or crown and they may move between petioles. Larvae have three instars and development takes about 33 days, the rate of development being temperature and nutrient dependent. Final instar larvae exit the crown and move to the roots and construct a circular cocoon using excised root hairs, attached to a larger root. Pupal development takes about 20 days. Adult beetles are 4–5 mm long and tan brown in colour. They are nocturnal and remain concealed in the crown of the plant. They feed externally on the epidermal tissues of the leaves, forming characteristic feeding scars. Adults also feed preferentially on the narrow upper part of the petiole of the first and second leaves. Most eggs are laid within five weeks of emergence, and between about 300 and 700 eggs have been recorded per female. Adults may live to nearly 100 days. The generation time has been recorded at between 72 and 96 days. The optimum temperature for feeding and oviposition is about 30°C. High temperature and low humidity may decrease egg production and reduce adult survival, while low temperature, probably below about 15°C, arrests development, prevents population increase and decreases survival (Cordo and DeLoach 1976; Julien et al. 1999)

Damage

The damage caused by this insect and by *N. eichhorniae* (see below) is similar. Adult feeding scars, when numerous, debilitate the plant by removing extensive proportions of epidermal tissue thus increasing water loss and exposing the plant to attack by pathogens. Extensive feeding around the upper petiole may girdle the petiole and kill the lamina above. Larval tunnelling in the lower petiole and crown damages tissues and buds, initially preventing flowering. As damage increases, plant growth rate is reduced and the production of new leaves and new stolons is reduced. Plant size (height, weight, size of leaves, size of stolons) declines. Internal damage to plant tissues results in rotting of the lower petioles, waterlogging of the crown and gradual sinking of the plant so that the crown is several centimetres below the surface of the water. In time the plant dies, most sinking, though some may remain as a floating mass. The process from release of the weevils to plant death takes years, the duration depending on a combination of factors, such as temperature, nutrient status of the weed, climate, hydrology of the catchment, and number of healthy insects released.

Releases

The first recorded release was in 1974, in the USA. *Neochetina bruchi* was recorded in Mozambique in 1972 but there is no record of how it got there. It has been released in 30 countries, is not known to be established in four and recent releases in three others are under evaluation (Table 2). This weevil is contributing to control of the weed in 11 countries where the initial releases were made between 1974 and 1996. It is established and under evaluation in four other countries and, unfortunately, there are no post-release assessments for seven countries. *Neochetina bruchi* was distributed within Argentina in 1974 and in Bolivia (year unknown) to areas where the weed had become a problem (Julien and Griffiths 1998; Julien et al. 1999). It was released in The Republic of Congo in 1999 (IITA 2000), and in Egypt (Fayad et al. 2001) and Rwanda during 2000 (Moorhouse et al. 2001).

Neochetina eichhorniae

Biology

This insect's small whitish eggs are more slender and softer than those of *N. bruchi*. They are laid singly beneath the epidermis of the leaves, petioles and ligules. Eggs hatch in about 10 days and will not hatch at temperatures below 20°C. Larvae have three instars and tunnel inside petioles towards and into the crown. A number of larvae may exist in the same petiole or crown where they damage axillary buds. The rate of development of larvae is dependent on temperature and nutrition and takes 60–90 days. Construction of a cocoon, about 5 mm diameter, and pupal development

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Table 1. Countries (total 34) where biological control agents have been released on water hyacinth and the dates of initial releases. Data modified from Julien and Griffiths (1998)

	Neochetina bruchi	*Neochetina eichhorniae*	*Niphograpta albigutallis*	*Eccritotarsus catarinensis*	*Orthogalumna terebrantis*	*Xubida infusellus*
Australia	1990	1975	1977			1981; 1996[f]
Benin	1992	1991	1993	1999[h]		
China	1996	1996		2000[a]		
Congo	1999[h]	1999[h]				
Cuba	1995					
Egypt	2000[b]	2000[b]				
Fiji		1977				
Ghana	1994	1994	1996			
Honduras	1989	1990				
India	1984	1983			1986	
Indonesia	1996	1979				
Kenya	1995	1993				
Malawi	1995	1995	1996	1996		
Malaysia	1992	1983	1996			
Mexico	1995	1972				
Mozambique	1972	1972				
Myanmar		1980				
Nigeria	1995	1993				
Panama	1977		1977			
Philippines	1992	1992				
PNG	1993	1986	1994			1996
Rwanda	2000[d]	2000[d]				
Solomon Islands		1988				
South Africa	1989	1974	1990	1996		
Sri Lanka		1988				
Sudan	1979	1978	1980			
Taiwan	1993	1992				
Tanzania	1995	1995				
Thailand	1991	1979	1995			1999
Uganda	1993	1993				
USA	1974	1972	1977			
Vietnam	1996	1984				
Zambia	1997[c]	1971; 1996	1971; 1997[g]	1997[c]	1971	
Zimbabwe	1996	1971	1994	1999[e]		
Totals	30	32	13	6	2	3

a. Ding et al. (2001).
b. Fayad et al. (2001).
c. M. Hill (pers. comm., 2000).
d. Moorhouse et al. (2001).
e. G. Chikwenhere (pers. comm., 2000).
f. Failed to persist after releases in 1981 and was imported and released again in 1996 (Julien and Stanley 1999).
g. Initial releases did not establish and it was released again in 1997 (M. Hill, pers. comm. 2000).
h. IITA (2000).

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Table 2. *Neochetina bruchi*: status of releases for each country. Data modified from Julien and Griffiths (1998)

		Established				Control			
	Year released	No	Unknown	Under evaluation	Yes	No	Yes	Under evaluation	Unknown
Panama	1977		✓						
Philippines	1992		✓						
Taiwan	1993		✓						
Zambia[a]	1997		✓						
Congo[d]	1999			✓					
Egypt[b]	2000			✓					
Rwanda[c]	2000			✓					
Malaysia	1992				✓	✓			
Benin[d]	1992				✓		✓		
Australia	1990				✓		✓		
India	1984				✓		✓		
Kenya	1995				✓		✓		
PNG	1993				✓		✓		
Sudan	1979				✓		✓		
Tanzania	1995				✓		✓		
Thailand	1991				✓		✓		
Uganda	1993				✓		✓		
USA	1974				✓		✓		
Zimbabwe	1996				✓		✓		
China	1996				✓			✓	
Malawi	1995				✓			✓	
Mexico	1995				✓			✓	
South Africa	1989				✓			✓	
Cuba	1995				✓				✓
Ghana	1994				✓				✓
Honduras	1989				✓				✓
Mozambique	1972				✓				✓
Nigeria	1995				✓				✓
Indonesia	1996				✓				✓
Vietnam	1996				✓				✓

a. M. Hill (pers. comm., 2000).
b. Fayad et al. (2001).
c. Moorhouse et al. (2001).
d. IITA (2000).

are similar to that for *N. bruchi.* Adults are 4–5 mm long, slightly smaller than *N. bruchi*, and are coloured mostly grey. They feed nocturnally and hide in the crown during daylight. Adults feed externally on the epidermal tissue of the leaves and upper petioles producing feeding scars indistinguishable from those caused by *N. bruchi* feeding. The generation time is longer than for *N. bruchi*, 96–120 days. Adult longevity has been recorded at 140 and 300 days and eggs per female at 5–7 per day and 891 total (Cordo and DeLoach 1976; Julien et al. 1999). *Neochetina eichhorniae* is less dependent on good quality plants for development than *N. bruchi*. Consequently, the relative abundance varies between sites; more *N. eichhorniae* at sites with lower quality water hyacinth, and vice versa.

The two *Neochetina* species can be readily distinguished in the adult stage. In *N. bruchi* two dark marks on the elytra are equal in length, are relatively short and are located midway along the elytra. The elytra furrows are broader and have comparatively shallow curvature. New adults have scale coloration that forms a 'v' on the elytra. This mark fades with age. In comparison, the two elytra marks on *N. eichhorniae* are longer, not equal in length and tend to occur closer to the front of the elytra. The elytra furrows are narrow with strong curvature. There is no 'v' pattern on the elytra (Julien et al. 1999).

Damage

This weevil damages water hyacinth in a similar way to *N. bruchi* (see above). An important difference is that *N. bruchi* populations develop better under eutrophic conditions (Heard and Winterton 2000) and, in polluted waterways, may complement the damage by *N. eichhorniae*.

Releases

The first releases were in 1971 in Zambia and Zimbabwe. Thereafter it was released in another 32 countries (Table 3). This insect is established in all but six countries and three of these were recent releases and are under evaluation. It contributes to control the weed in 13 countries where releases were made between 1971 and 1995. It is being evaluated in two others and there is no post-release information about control from seven countries. *Neochetina eichhorniae* was distributed in Bolivia (year unknown) to areas where the weed had become a problem (Julien and Griffiths 1998; Julien et al. 1999). It has been released in The Republic of Congo in 1999 (IITA 2000), and in Egypt (Fayad et al. 2001) and Rwanda during 2000 (Moorhouse et al. 2001).

Niphograpta albiguttalis

Biology

Eggs are creamy white, 0.3 mm diameter and are laid singly or in small groups in leaf tissue, particularly at injury and feeding sites. Hatching occurs in 3–4 days. The five larval instars develop over 16–21 days. Larvae feed externally initially and after one or two days they tunnel into the petiole and feed below the epidermis causing characteristic 'windows'. As larvae grow they tunnel deeper into the petiole tissues and into the central rosette of the plant. They may move between petioles and several larvae may feed in the same petiole. Larvae are rarely found in older, tougher plants or petioles, but prefer younger, tender material, characteristic of the small bulbous plants that grow on the edge of water hyacinth infestations. Pupation occurs in a chamber chewed in a relatively undamaged portion of petiole with a tunnel leading to the leaf epidermis where a thin window is left for protection across the emergence exit. Pupation occurs within a white cocoon and takes about 5–7 days. The adult moves up the emergence tunnel and exits through the 'window' in the epidermis. Adults are 6–10 mm long with a wingspan of 17–25 mm. Colour is variable from golden yellow to charcoal grey, with brown, black and white markings. Mating occurs soon after emergence and oviposition begins soon afterwards. Some 70% of eggs are laid during the second and third nights and moths live for 4–9 days. Females lay 370 eggs on average. The life cycle takes 21–28 days. For greater detail see Bennett and Zwolfer (1968), DeLoach and Cordo (1978), Center (1981) and Harley (1990).

Damage

Early larval tunnelling causes necrosis and waterlogging of internal tissues. Small, dark spots occur on the surface of the petiole. Larger larvae cause severe, internal damage causing petioles and leaves to wilt, turn brown and rot. When damage destroys the apical bud, growth is prevented and ramet death occurs. However, axillary buds may continue to develop and, unless attacked by the moth, will replace the dead ramet. The adult moths disperse rapidly, up to 4 km per day. Severe local damage to water hyacinth may occur, but overall the damage is patchy as adults tend to oviposit on healthy young, tender plants. Quantifying the impact of this moth on weed populations is extremely difficult. Its role in biological control is thought to be in slowing the rate of expansion of mats by reducing new growth along the expanding edges. It could also play an important role in reducing the rate of invasion by preferentially attacking rapidly growing plants that are typical of invasion and regrowth areas.

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Table 3. *Neochetina eichhorniae*: status of releases for each country. Data modified from Julien and Griffiths (1998)

		Established				Control			
	Year released	No	Unknown	Under evaluation	Yes	No	Yes	Under evaluation	Unknown
Philippines	1992		✓						
Taiwan	1992		✓						
Vietnam	1984		✓						
Congo[3]	1999			✓					
Egypt[a]	2000			✓					
Rwanda[2]	2000			✓					
Fiji	1977				✓	✓			
Indonesia	1979				✓	✓			
Mexico	1970				✓	✓			
Sri Lanka	1988				✓	✓			
Australia	1975				✓		✓		
Benin	1991				✓		✓		
India	1983				✓		✓		
Kenya	1993				✓		✓		
Nigeria	1993				✓		✓		
PNG	1986				✓		✓		
South Africa	1974				✓		✓		
Sudan	1978				✓		✓		
Tanzania	1995				✓		✓		
Thailand	1979				✓		✓		
Uganda	1993				✓		✓		
USA	1972				✓		✓		
Zimbabwe	1971				✓		✓		
China	1996				✓			✓	
Malawi	1995				✓			✓	
Ghana	1994				✓				✓
Honduras	1990				✓				✓
Malaysia	1983				✓				✓
Mozambique	1972				✓				✓
Myanmar	1980				✓				✓
Solomon Islands	1988				✓				✓
Zambia	1971	✓							
	1996				✓				✓

a. Fayad et al. (2001).
b. Moorhouse et al. (2001).
c. IITA (2000).

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Releases

This moth was first released in Zambia in 1971 and has been released in a total of 13 countries (Table 4). It is established in six countries, contributes to control in two and is being evaluated in three others. Although not deliberately released there, this insect has been recorded in Cuba.

Eccritotarsus catarinensis

Biology

Eggs are inserted into the leaves just below the surface. Four nymphal instars are gregarious and feed on the surface of the laminae with the adults. Nymphs are pale, while adults, which are 2–3 mm long, have dark bodies and pale wings with dark markings. The development of the immature stages (egg to adult) takes 22 days and adults live for about 50 days (Stanley and Julien 1999; Hill et al. 1999).

Damage

Feeding by the nymphs and adults of this small, sucking bug causes chlorosis of the laminae. With severe damage, photosynthesis and therefore growth and reproduction of the weed could be reduced.

Releases

E. catarinensis was recently studied in South Africa and Australia. It was released in South Africa in 1996 (Hill et al. 1999). It has also been released in Malawi in 1996 (Julien and Griffiths 1998), Zambia in January 1997 (Hill 1997), Zimbabwe in May 1999 (G. Chikwenhere, pers. comm. 2000), Benin in June 1999 (O. Ajuonu, pers. comm. 2000), and in China during the spring of 2000 (Ding et al. 2001). It was not released in Australia because of its potential to damage native *Monochoria* species (Stanley and Julien 1999). It is well established in South Africa and is being evaluated. However, it appears not to have established in Malawi (M. Hill, pers. comm. 2000). This insect has been imported into Thailand for study but has not yet been released into the field.

Xubida infusellus

Biology

Eggs are 0.52 mm by 0.87 mm long and are deposited in groups in an elongated gelatinous mass up to several centimetres long. Eggs hatch after 6 days. Larvae enter the laminae or petiole and tunnel downwards, eventually entering the rhizome. There are 7–10 instars and the development of larvae takes about 48 days. The final instar larvae are about 25 mm long.

Table 4. *Niphograpta albigutallis*. Status of releases for each country. Data modified from Julien and Griffiths (1998)

		Established				Control		
	Year released	Unknown	Under assessment	No	Yes	No	Yes	Under evaluation
Ghana	1996	✓						
Zimbabwe	1994	✓						
Panama	1977	✓						
Malawi	1996		✓					
Benin	1993			✓				
PNG	1994			✓				
Zambia	1971			✓				
	1997[a]	✓						
South Africa	1990[a]				✓			✓
Sudan	1980				✓	✓		
Australia	1977				✓		✓	
USA	1977				✓		✓	
Malaysia	1996				✓			✓
Thailand	1995				✓			✓

a. Hill (1997).

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They move from the rhizome into a petiole where they tunnel to the surface. From the inside of the plant the larvae cover the exit hole with a silken window and then pupate in the tunnel below the window. The pupae are about 20 mm long, do not have a cocoon and require 9 days to develop to adults. The adult emerges from the petiole through the window. Mating occurs on the first night of emergence and most eggs are deposited in the second and third nights. Oviposition is not restricted to water hyacinth and may occur on other plant species, on pots and cage material. The number of eggs masses per female (4–26) and number of eggs per female (180–684) are quite variable. Females live for 4–8 days. Development from egg to adult is completed in about 64 days. This moth is susceptible to diseases, and variations in recorded biology may be due to variations in the disease status of the colonies that were studied. For greater detail see Silvera Guido (1971), DeLoach et al. (1980), and Sands and Kassulke (1983).

Damage

This moth attacks the older, slender petiole form of the weed and should complement the damage caused by the moth *N. albigutallis,* which prefers to attack young, tender plants, typified by the short, bulbous growth form. Young larvae of *X. infusellus* tunnelling inside the petiole may girdle the petiole causing the portion above the girdle to wilt and die. Feeding by larger larvae in the lower petioles and rhizome severely debilitates the plant and destroys apical meristems. Under caged conditions, damage by larvae destroys plants.

Releases

This moth was first released in Australia in 1981 where it persisted for up to 13 months at two locations before the demise of water hyacinth at those sites as a result of human activity or drought. *X. infusellus* was imported into Australia again for further study and released in Australia and Papua New Guinea (PNG) during 1996. Populations have persisted at one site in Australia for over three years with no apparent impact on the plants. Adults were recorded at a release site in PNG on several occasions up to 18 months after release, suggesting that the moth was established (Julien and Stanley 1999). However, no further assessments have been conducted in PNG since 1998.

Orthogalumna terebrantis

Biology

Eggs are placed in small holes in the surface of leaves and hatch in 7–8 days. The ensuing larvae are less than 0.24 mm long. Thereafter, three nymphal stages occur, the final stage being up to 0.5 mm long. Development of larvae and nymphs requires 15 days. For details see Cordo and DeLoach (1975, 1976) and Del Fosse et al. (1975).

Damage

The nymphs of this sucking mite form galleries between the parallel veins of the laminae from which adults emerge. High populations of the mite cause leaf discoloration and desiccation. Although this mite has infested various populations of water hyacinth for considerable periods it has not contributed to control of the weed.

Releases

O. terebrantis was first released in Zambia in 1971 and in India during 1986. It is present in Mexico, Cuba, Jamaica, the southern USA and South America, and has spread from Zambia to Malawi, Mozambique, South Africa and Zimbabwe (Julien and Griffiths 1998). The impact of the mite, along with other agents, is being studied in Malawi (M. Hill, pers. comm. 2000).

Potential Agents Recently Considered or Currently Being Studied

A resurgence of interest in better management of water hyacinth, partially in response to the serious and increasing water hyacinth problems in Africa, resulted in renewed interest in the studies of known potential agents and the search for new agents. For example, recent studies were conducted and releases were made of *X. infusellus* and *E. catarinensis* (see earlier). Other insect species have recently been assessed and rejected as insufficiently host specific, while others are currently being studied. They include the following.

- The moth *B. densa* Walker has been rejected because it attacks taro, *Colocasia esculenta* (L.) Schott. (Center and Hill 1999).
- The moth *P. tenuis* has been rejected as it developed on a range of plants over several families (Cordo 1999).
- The grasshopper *C. aquaticum* is currently under study in South Africa to clarify its host range (Oberholzer and Hill 2001).
- *Thrypticus* species flies are being studied in Argentina. Until recently this group of flies was thought to have low priority because of suspected wide host acceptance. Current studies have identified a number of species within the group, one or more apparently specific to water hyacinth (Cordo 1999).

Factors that Affect Establishment of Biological Control Agents

After identifying host-specific natural enemies that are suitable for introduction and release, the next most important step is establishing the agent(s) in the field. For those countries that release known agents, establishing the agent is the first and most important step. Successful establishment is a prerequisite to control. The researcher can influence some issues that affect establishment, and lack of attention to these can limit or prevent progress. They include: site selection, obtaining and maintaining healthy colonies of agents for mass rearing, rearing and releasing healthy and fecund individuals, and, depending on the dispersal capacity of each agent, repeated and multiple releases. These issues are discussed by Wright (1997a,b) and Julien et al. (1999) for *Neochetina* species.

The Impact of Biological Control on Water Hyacinth Infestations

Of the six organisms that have been released, four (the two *Neochetina* weevils, the moth *N. albigutallis* and the mite *O. terebrantis*) have been released either widely or for long periods (Table 1). The two weevils have provided excellent control in some habitats and have contributed much less or not at all in others. It is more difficult to assess the effects of the moth. Its impact on populations of the weed is insidious, and hard to quantify. It targets new, tender plants, typically those on the edge of expanding mats, regrowth plants or those plants involved in early invasion. The damage caused by the moth is unlikely to control serious infestations of the weed. However, it appears to complement the actions of other control methods, both biological and non-biological, by reducing spread and invasiveness. The fourth organism, the mite, has been established for about 30 years in Africa and USA. It has failed to contribute to control in its own right, but there is conjecture that it may debilitate the weed and therefore may contribute to control in the presence of other factors.

Where biological control of water hyacinth is demonstrably successful it has been a result of the activities of either *N. eichhorniae* or *N. bruchi* or both. It is timely to assess the factors that have influenced the successes and to try to identify the factors that have restricted or prevent control occurring. Such information may help in future management of the weed. It may assist in making and testing predictions about impact and control and in deciding how to develop integrated management strategies.

Successful biological control has occurred in various locations in the following countries: Argentina, Australia, India, USA, PNG, Zimbabwe, the three Lake Victoria countries (Uganda, Tanzania, Kenya), South Africa and Thailand (Harley 1990; Julien et al. 1999; Hill and Olckers 2001). The attributes of most of these locations are as follows.

- They are subtropical or tropical areas.
- The weed mostly grew as a monoculture and not as an understorey plant.
- The weed was free to sink once damaged and was not supported by other growth; nor were the roots resting in mud beneath water.
- The mats were stable for long periods so that insect numbers could build up.
- The weed was not subjected to regular removal by periodic or annual flows and so insect density increased unabated to damaging levels.
- In some instances, the action of wind and waves assisted the rate of damage and sinking of mats, e.g. Lake Victoria, Uganda. It is probable that control would have occurred regardless, although the level of control may have been less. In other locations, the lack of the additional stresses on the damaged plants imposed by wind and wave buffeting may limit control (Hill and Olckers 2001).
- In other instances, the reduction in plant growth and stature, resulting from insect attack, caused mats to disintegrate into smaller components that could be flushed from lagoons via narrow channels and hence to the ocean, e.g. lagoon of the Sepik River. This flushing-out accelerated the rate of removal of water hyacinth from the system, but it is likely that the heavily damaged plants would have been destroyed and sunk anyway, as occurred at other impounded locations, e.g. Lake Phayao, Thailand and Crescent Lagoon, Australia (A. Wright, pers. comm. 2000).

High nutrient status of the plant may influence the rate of control in tropical areas by allowing rapid increase in insect populations. High nutrients may work against control in temperate regions where the insect activity is curtailed by cool winter conditions. As spring and summer approach, the weed is able to rapidly outgrow previous damage before insect populations have time to increase. Once insect populations reach high proportions there is insufficient time in the remaining summer period to significantly damage the weed populations. Even if mat collapse occurs at the

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end of the season, the seed would not have been depleted (plants flower within six weeks of germination) and reinvasion is inevitable. In such situations, appropriate intervention with other methods might provide control.

Disruption of biological control by inappropriate use of herbicides is another reason for failure. This may occur where infestations are at important locations and require immediate removal, in which case biological control is inappropriate. It also occurs when managers or politicians become frustrated waiting for biological control to become evident. In many situations, planned strategies could utilise biological control to reduce the weed in the source area over the long-term while shorter-term controls are used to reduce the problem at the critical points. When biological control becomes effective, three or more years after release of the weevils, the water hyacinth at the source will be reduced and hence the need to apply short-term controls downstream should decline, e.g. Pangani River, Tanzania.

Conversely, it is important to identify the factors that may militate against control. These include the following.

- Locations that experience temperate climates where periods of low temperature reduce or stop weevil population increase and allow the weed to recover, e.g. areas in South Africa (Hill and Olckers 2001).
- High nutrient status of the water in temperate regions. See discussion above.
- Catastrophic reductions of the weevil populations by periodic or annual floods. The weed populations can recover much faster than the insect populations and hence control is prevented.
- Catastrophic reductions in the weed biomass and insect populations because of drought. The insect populations are driven to local extinction in the absence of the host plant, whereas the water hyacinth population continues with seedling growth after rain (Hill and Olckers 2001).
- Sudd formation that prevents damaged water hyacinth from sinking and provides a floating receptacle for seeds and a seedling bed.
- Shallow water where roots are embedded in mud and debris that may limit pupation, prevent damaged plants from sinking and encourage the growth of other plant species e.g. *Melaleuca* forest swampland in Australia (A. Wright, pers. comm. 2000) and shallow inlets of Lake Kyoga, Uganda (J. Ogwang, pers. comm. 1999).
- The uptake of heavy metals by water hyacinth may reduce fecundity of the weevils that feed on those plants (Jamil and Hussain 1993).
- Inappropriate application of other control methods may restrict the impact of biological control. Herbicide applications or physical removal may eliminate establishing populations. They may limit increase of established populations and reduce establishing populations by killing plants that support the insects. Application of some chemicals to the weed may directly affect some control agents.

Interactions between the many environmental factors affect survivorship and population dynamics of each biological control agent and hence the level of damage and control. As a consequence, for each control agent, there is likely to be a range of control outcomes, from areas where excellent control is achieved to those where biological control may have no impact. For those locations where water hyacinth continues to grow at greater than acceptable levels, management should aim to make best use of the cheapest and most sustainable control method, normally biological control, in synergy with other available tools—herbicides, physical removal, manipulation of flows, and reductions of nutrient input.

Biological control is being developed through the search for new organisms to assist control in those locations where less than satisfactory control can be achieved with the current agents. There is room to improve biological control and this is proceeding with the research being conducted by USDA-ARS, ARC-PPRI and CABI Bioscience. However, it is unrealistic to think that biological control on its own will solve all water hyacinth problems. Hence, there is a need to develop integrated management strategies. This means selecting the most appropriate control techniques available and implementing those techniques so that they complement each other in time and space. The objective should be to obtain the best level of control that is affordable and sustainable while considering environmental impacts. Since affordability and sustainability are major considerations in the management of most water hyacinth problems, biological control should be the base component of all strategies.

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Biological Control of Water Hyacinth by Using Pathogens: Opportunities, Challenges, and Recent Developments

R. Charudattan*

Abstract

There is good justification to renew concerted efforts to develop pathogens for biological control of water hyacinth (*Eichhornia crassipes*, (Mart.) Solms-Laub.). Among the most promising pathogens are *Uredo eichhorniae*, suitable as a classical biocontrol agent, and *Acremonium zonatum, Alternaria eichhorniae, Cercospora piaropi*, *Myrothecium roridum*, and *Rhizoctonia solani,* which are widely distributed in different continents, as bioherbicides. Other, less widely distributed pathogens, notably species of *Bipolaris, Drechslera,* and *Fusarium,* may hold promise, but further studies are needed to confirm their usefulness. Ongoing studies on the biology of *U. eichhorniae* are expected to help resolve the biocontrol potential of this rust fungus in the near future. It is also anticipated that recent advances in bioherbicide technology, and previous experience with pathogens of water hyacinth, will enable development of effective bioherbicides. Success in this effort will require the use of highly virulent pathogens and pathogen strains as well as novel formulations that help to counter water hyacinth's ability for rapid growth under different site conditions and assist the pathogen to overcome environmental limitations. In Florida, USA, our aim is to develop a bioherbicide that could be used in integration with the existing suite of introduced arthropod biocontrol agents and improve the overall effectiveness of the biological control strategy under different weed-control scenarios. In this attempt, unlike in previous unsuccessful attempts, we are aided by the availability of a large and diverse collection of highly virulent pathogen strains to choose from, the facility to formulate effective pathogens in newer materials to assure consistency of performance, the ability to integrate dual and multiple pathogens, and a 'biofriendly' posture of regulatory agencies toward the development and registration of bioherbicides. Results from our ongoing field trials suggest the feasibility and commercial potential of our current approach.

THERE are several good reasons to consider pathogens as biocontrol agents: pathogens can cause significant reductions in water hyacinth biomass, especially following natural disease outbreaks, after severe insect attacks, or when used as inundative bioherbicide agents (Charudattan et al. 1985; Shabana et al. 1995b). Published accounts of natural declines in water hyacinth populations following natural disease outbreaks further confirm the potential of pathogens in limiting water hyacinth populations (Martyn 1985; Morris 1990). Controlled experimental studies have confirmed the potential of *Acremonium zonatum, Alternaria eichhorniae,* and *Cercospora piaropi* to control (i.e. reduce weed biomass) water hyacinth (Martyn and Freeman 1978; Charudattan et al. 1985; Shabana et al. 1995b). In addition, it has been well proven that pathogens can be successful as classical or inundative (bioherbicide) agents. Currently, worldwide about 15–20 weeds are biologically controlled with pathogens (Rosskopf et al. 1999). Therefore, there is clear justi-

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fication to explore pathogens fully and fairly as agents of biological control of water hyacinth. In this effort, we will be starting with the benefit of past attempts that have helped to lay the foundation through surveys and characterisation of host–pathogen systems. It is now imperative to take steps to turn this early empirical knowledge and success into practical utilisation of pathogens in weed-management programs. Clearly, with some pathogens, such as the rust fungus *Uredo eichhorniae,* further studies are needed to understand the biology and biocontrol potential of the agents before they can be used. Nonetheless, the current state of knowledge and experience give us the optimism to assert that pathogens can succeed in practice, especially when used in integrated weed control systems rather than as stand-alone control options.

Opportunities and Challenges

Development of a pathogen or pathogens for use in operational weed management systems is long overdue. In this regard, the present timing and opportunities may be the best we can ever expect. For instance, there is renewed interest in developing additional biological control agents to supplement those already in use. There is an urgent need for effective controls for water hyacinth in countries of Africa and Asia. Support, in the form of funding initiatives, is also evident, as in the case of the recently formed Pan-African mycoherbicide program. Despite these optimistic signs, the most important lesson learned from earlier attempts should not be forgotten: that foliar pathogens generally do not have the capacity to kill water hyacinth plants completely and quickly unless they can be used in conjunction with efficacy-enhancing formulations and adjuvants, low doses of chemical synergists, and/or insect biocontrol agents. Bioherbicides were regarded as biological substitutes for chemical herbicides and therefore as stand-alone products. There was little technological sophistication in the bioherbicide products; usually fresh fungal inoculum was used without formulations devised to protect the inoculum from adverse environmental conditions or to improve its performance. Improvements in efficacy of foliar pathogens are now possible through a number of recently developed formulations such as hydrophilic polymers, emulsions, surfactants etc. (Shabana et al. 1997; Green et al. 1998; Boyetchko et al. 1999). Several pathogens can be combined and used in a 'multiple-pathogen strategy' (Chandramohan et al. 2000) to improve the level of weed control, minimise or prevent development of host resistance, overcome age-related host resistance, assure consistency in bioherbicide performance, improve environmental latitude of activity, and so on. It is also possible to 'customise' the pathogen mixture depending on the types of pathogens available for use in a given country or region.

Among the challenges, we must address the pervasive perception among aquatic weed managers that biological control does not provide *quick and acceptable* levels of control and that biological control is inadequate under conditions that promote rapid expansion of water hyacinth mats. Given the general consensus of this working group that the overall effectiveness of biological control should be (could be) improved, we should aim to develop a pathogen or pathogens that can provide *quick and assured* levels of biological control. Accordingly, we should explore all potentially useful pathogens. In this respect, both classical and bioherbicide strategies should be pursued.

As we renew our efforts to develop pathogens, we should remember the following.

- Localised pathogens, fungi and bacteria that have not been previously explored, may be useful. Therefore, further surveys, especially in the African continent and the Neotropics, and thorough evaluations of the pathogens found, should be a part of our plans.
- Technological innovations should be developed to overcome micro-environmental conditions surrounding the plant that are non-conducive for disease development.
- Water hyacinth plants growing under conditions that promote rapid growth will result in the plant outgrowing the rate of progress of foliar diseases. Consequently, soon after a bioherbicide application, the disease pressure will wane, turning even a disease with polycyclic potential into a monocyclic disease. Therefore, the ability of water hyacinth plants to grow at rapid rates under different site conditions is a challenge that must be factored into the design of bioherbicides.

To address the dual challenges of rapid host growth rate and environmental constraints and to assure biocontrol effectiveness, the pathogen (specifically a bioherbicide) may be applied with low rates of a registered chemical herbicide. Alternatively, the bioherbicide formulation may contain an adjuvant (e.g. a phytotoxic compound or a registered chemical herbicide at low rates). Multiple applications of the bioherbicide may be also used, but the economics of multiple applications would have to be assessed. Also, bioherbicide applications may be timed to maximise the impacts of insect agents and thus increase the level of biotic stress. Novel formulations should be developed that help to prolong humidity on the leaf surface, protect the pathogen against solar irradiation, and/or promote leaf penetration by the pathogen. Combinations of two or three different pathogens may be used to increase the level of damage and consistency of performance, as has been tried under experimental conditions, most recently by Den Breeÿen (1999) and Vincent and Charudattan (2000). An approach that is quite applicable but has not been tried is the use of several strains of a pathogen (e.g. *C. piaropi*), each having different levels of virulence, fitness, phytotoxin production, and other desirable traits.

It is fair to say that, despite several field surveys in the past two decades, no *new and highly* promising pathogens have been added to the list of known, prospective biocontrol agents. However, this statement is not meant to imply that there may be no additional pathogen candidates left to discover, but rather it is an assessment of the current situation. For example, of the nearly 70 fungi and bacteria recorded on water hyacinth (Barreto and Evans 1996; Charudattan 1996), only about 15 have been adequately tested and confirmed to be highly virulent pathogens. Of these, three fungal pathogens, *Acremonium zonatum, Alternaria eichhorniae,* and *Cercospora piaropi (= C. rodmanii)*, have been studied intensively as biocontrol agents and shown to be effective in controlling water hyacinth under experimental conditions (Martyn and Freeman 1978; Charudattan et al. 1985; Shabana et al. 1995b). This leaves a large number of other reported fungi and bacteria that remain to be assessed for their biocontrol potential. Thus, for now, the choice of pathogens for biological control is limited to *Uredo eichhorniae,* as a classical biocontrol agent, and as bioherbicide agents, *A. zonatum, A. eichhorniae, C. piaropi (= C. rodmanii), Myrothecium roridum,* and *Rhizoctonia solani.* Several other, less widely distributed pathogens, such as species of *Bipolaris, Drechslera,* and *Fusarium,* may hold promise, but they need to be studied further to confirm their potential.

A Synopsis of Highly Virulent and Useful Pathogens

The following are brief descriptions of virulent pathogens that are leading candidates for further development.

Acremonium zonatum

This fungus causes an easily identified necrotic zonate leaf spot characterised by spreading lesions, most noticeable on the upper laminar surface (Fig. 1). On the lower surface, which is normally protected from direct sunlight, the area directly under the spot may have a sparse, spreading layer of white fungal (mycelial) growth. Each spot may be small (2 mm diameter) to large (> 3 cm diameter) and the spots may coalesce, covering most of the lamina. The zonate pattern may not be evident in new infections when most spots are small. This disease has been reported from Australia, USA, and many countries of Asia, Central America, and South America. It is often associated in the field with infestations of the water hyacinth mite *Orthogalumna terebrantis*. This pathogen is represented by several highly virulent strains such as the ones found in Mexico by Martinez Jimenez and Charudattan (1998).

Alternaria eichhorniae

Two species of *Alternaria, A. eichhorniae* and *A. alternata,* have been recorded on water hyacinth. One or both of these species have been reported from Australia, Bangladesh, Egypt, India, Indonesia, and South Africa. *Alternaria alternata* appears to be a weak, opportunistic parasite, whereas *A. eichhorniae* is a highly virulent, host-specific pathogen of water hyacinth. *Alternaria eichhorniae* has been shown to have good potential as a bioherbicide agent (Shabana et al. 1995a,b; these proceedings). It causes discrete necrotic foliar spots (oblong, 2–4 mm long) surrounded by a bright yellow halo. Blighting of the entire leaf lamina can be induced by using mycelial inoculum and providing prolonged, 100% relative humidity (Fig. 2). In culture, *A. eichhorniae* produces several bright red compounds in culture, including bostrycin and deoxybostrycin that are phytotoxic to water hyacinth leaves (Charudattan and Rao 1982). The extent of naturally occurring variability in virulence in this pathogen is not clear. More details about this pathogen are given by Shabana (2001).

Cercospora piaropi (= *C. rodmanii*)

Symptoms caused by *Cercospora* spp. may be easily confused with those of many other foliar pathogens, including many opportunistic, weak parasites. Until now, two species of *Cercospora, C. piaropi* and *C. rodmanii*, have been recognised as pathogens of water hyacinth, but recently Tessmann et al. (2001) have merged the two species into an emended *C. piaropi. Cercospora piaropi* has been reported on water hyacinth from throughout the present range of the weed. This pathogen causes small (2–4 mm diameter) necrotic spots on laminae and petioles (Fig. 3). The spots are characterised by pale centres surrounded by darker necrotic regions. Occasionally, the spots may appear in the shape of 'teardrops' that coalesce as the leaf matures, causing the entire leaf to turn necrotic and senescent. In fact, the senescence is accelerated by the *Cercospora* disease, and the disease can rapidly spread across water hyacinth infestations, causing large areas of the weed mat to turn brown and necrotic. Under severe infections, the plant may be physiologically stressed, lose its ability to regenerate, become waterlogged, and sink or disintegrate.

Tessmann et al. (2000) compared 60 isolates of *Cercospora* species isolated from water hyacinth leaves showing symptoms of *Cercospora* infection which were collected from the USA, Mexico, Venezuela, Brazil, South Africa, and Zambia. They found the isolates to be variable in pigmentation in culture, spore morphology, and virulence. Virulence of the isolates was also variable: isolates ranged from being nearly avirulent to highly virulent and capable of causing leaf death. These traits were independent of the geographic origin of isolates. The isolates were then tested to see if the species concept based on conidial and cultural morphology and virulence, as used by Conway (1976) in his designation of *C. rodmanii* into a separate species, might agree with a species concept developed with the help of molecular markers.

Accordingly, members of a collection of isolates representing acquisitions from the USA (Florida and Texas), Mexico, Venezuela, Brazil, South Africa, and Zambia were compared on the basis of the DNA sequences of gene segments for beta-tubulin (*TUB2*), histone-3 (*H3*), and elongation factor-1-alpha (*EF1a*), corresponding to 380, 309, and 431 base pairs (bp), respectively. Eight of the isolates were also compared for the rDNA regions containing ITS1, ITS2, and the 5.8S gene. Extracted DNA was amplified by polymerase chain reaction using TUB2, H3, and ITS primer pairs selected from the literature. The combined phylogenetic relationships of *TUB2*, *H3*, and *EF1a* sequences done with phylogenetic analysis using parsimony did not support the species distinction between *C. piaropi* and *C. rodmanii*. Isolates representative of both species grouped into a single, well-supported clade (Tessmann et al. 2000).

Thus, the molecular evidence pointed strongly to a common phylogeny of *Cercospora* pathogenic to water hyacinth. This raises some important questions relevant to the use of *C. piaropi* for water hyacinth control. For instance, given the worldwide distribution of this pathogen and the molecular evidence pointing to a common origin of *Cercospora* isolates pathogenic to water hyacinth, should this pathogen be subject to plant quarantine restrictions? Would it not be advantageous to import and supplement native *C. piaropi* strains with more highly virulent strains from whichever continent or country they could be found? Perhaps a search for highly virulent strains (of any pathogen) should be an inherent priority for all mycoherbicide programs in order to ensure that only the best strains are used. These questions deserve to be considered.

Myrothecium roridum

This fungus causes a teardrop-shaped leaf spot (up to 1×5 cm), rounded on the side facing the petiole and tapering to a narrow point in the direction of the laminar tip (Fig. 4). Older leaf spots turn necrotic with dark brown margins, with the centre of the spot covered with discrete white and black conidial masses. Myrothecium disease of water hyacinth has been reported to occur in India, Malaysia, Indonesia, possibly Mexico, and some western African countries. Although this species is worldwide in distribution, the typical myrothecium disease has not been recorded on water hyacinth in the Americas. The occurrence of variability in virulence in this pathogen is therefore not clear. Some recent studies suggest that some *Myrothecium* species can be used as broad-spectrum bioherbicides against several weeds (Walker and Tilley 1997), a finding that has implications for the development of *M. roridum* for water hyacinth control.

Rhizoctonia solani

Disease symptoms caused by this fungus may resemble damage caused by a desiccant type of chemical herbicide (e.g. diquat). Symptoms consist of irregular, necrotic spots, and broad lesions (Fig. 5). Unlike chemical damage, the brown necrotic areas are usually surrounded by noticeable, thin, water-soaked margins of darker brown colour than the rest of the lesion. Rhizoctonia disease has been reported on water hyacinth from the southeastern United States, Brazil, Mexico, Panama, Puerto Rico, India, Malaysia, and Indonesia. This fungus is usually very aggressive and destructive, capable of rapidly killing water hyacinth plants. The extent of variability in virulence of *R. solani* pathogenic to water hyacinth is not clear, but isolates collected in the USA, Panama, and Brazil have been found to be extremely virulent (R. Charudattan, unpublished data; R.A. Pitelli, University of the State of Sao Paulo, Jaboticabal, Brazil, pers. comm.).

Figure 1. Zonate leaf spots caused by *Acremonium zonatum* (left) and naturally infected plants in the field (right)

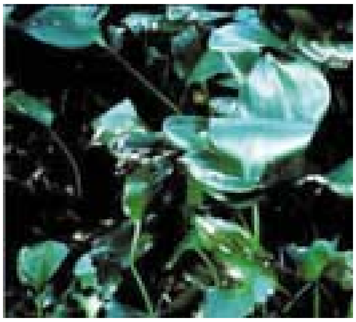

Figure 4. Teardrop-shaped foliar lesions and the extent of damage caused by *Myrothecium roridum*

Figure 2. Discrete necrotic leaf spots surrounded by yellow halo (left), symptoms developed when inoculated with spores (middle) or mycelium and kept under high humidity (right)

Figure 5. Blighting symptoms caused by *Rhizoctonia solani* on leaves (left) and whole plants (right). Picture on the right shows fungus-infected and uninfected control plants

Figure 3. Leaf spot symptoms caused *Cercospora piaropi*

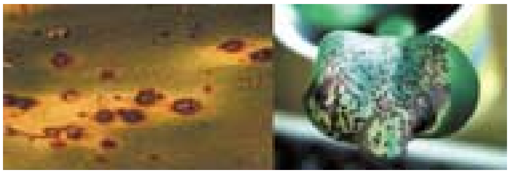

Figure 6. Water hyacinth leaves showing uredial pustules of *Uredo eichhorniae*

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Despite its high virulence and destructive capabilities, *R. solani* has never been seriously considered as a bioherbicide agent because of its reputed wide host range. However, this should not be a deterrent in today's regulatory environment which has permitted registration and commercial use of pathogens that do not possess high levels of host specificity (e.g. *Colletotrichum gloeosporioides* f.sp. *aeschynomene, Phytophthora palmivora*, and *Chondrostereum purpureum*).

Uredo eichhorniae

This rust fungus occurs in southern Brazil, Argentina, and Uruguay. It is known only in its uredial spore stage (Fig. 6). Because it is a rust fungus, it is likely to be highly host-specific and therefore a desirable classical biological control agent, but several aspects of its biology remain to be fully understood. For instance, since this fungus was first described from the Dominican Republic, a tropical island, it is unclear why it does not occur beyond its present range of distribution in the subtropical to temperate regions of South America. It is possible that it is adapted to slower growing plants of the temperate fringes of water hyacinth's distribution and its original finding in the Dominican Republic is an anomaly. Nevertheless, the occurrence of this pathogen only inside the native range of water hyacinth, but not outside (e.g. Asia, Africa, or Australia), is to be expected on the basis of ecological theory of coevolution of rust fungi.

Our earlier attempt to import *U. eichhorniae* into Florida was disallowed by U.S. regulatory agencies on the grounds that the full life cycle of this fungus was unknown. Stimulated by the current interest in deploying additional biocontrol agents, we have recently restarted research on the life cycle and biology of this fungus in collaboration with scientists from the Plant Protection Research Institute, Stellenbosch, South Africa and the University of the State of Sao Paulo at Jaboticabal, Brazil. The objective is to import the rust into quarantine at two locations outside its native range, one in the southern hemisphere (Stellenbosch, South Africa), the other in the northern hemisphere (Gainesville, Florida), to initiate epidemio-logical studies under controlled conditions. In this regard, South Africa, with its climatic, latitudinal, and hemispheric similarity to temperate South America, offers an eminently suitable location to conduct these studies.

As a first step in the evaluation of its biocontrol potential, we have initiated studies on the life cycle (i.e. spore stages, particularly the aeciospores and teliospores) and disease cycle of *U. eichhorniae* under field conditions. The biocontrol potential of this fungus will be determined by using fungicide(s) to block the effects of the rust disease in natural field populations of water hyacinth and comparing the growth rates of such fungicide-protected plants with rust-infected plants. These studies should help to establish the suitability of *U. eichhorniae* as a classical biocontrol agent and set the stage for its eventual release into the USA, South Africa, and elsewhere. The addition of this rust pathogen to the existing suite of biocontrol agents is likely to improve the prospects for a sustainable, long-term biological control of water hyacinth.

Recent Developments in Progress

With the above-mentioned concepts in mind, our current efforts in Florida are aimed at the development of a bioherbicide that can be used in combination with existing insect biocontrol agents. Our goal is a bioherbicide that will help to improve the overall effectiveness of the biological control system under different control scenarios. Our emphasis is on a knock back (reduce biomass) rather than a knock down (weed kill and biomass elimination) strategy. Specifically, we are evaluating two pathogens, *C. piaropi* and an isolate of *M. roridum* (isolated from begonia since no virulent isolate of this pathogen has been found on water hyacinth in the United States). The pathogens are being tested individually and in combination and applied with a surfactant, an invert emulsion, and/or a humectant gel. Applications are made to water hyacinth plants with and without natural populations of *Neochetina* spp. Results from field trials in progress indicate that a treatment with *C. piaropi* applied in the surfactant Silwet L-77 provided the best levels of biomass reduction and damage severity. The combination of the two pathogens was not significantly better than *C. piaropi* plus Silwet L-77, possibly because the isolate of *M. roridum* used is not a true pathogen of water hyacinth (Vincent and Charudattan 2000). Further, large-scale field trials are under way to develop a commercially feasible bioherbicide formulation.

Conclusions

It is a challenge to develop an effective bioherbicide that is acceptable for use in practical water hyacinth management programs. The challenge can be met, especially now, given the bio-friendly regulatory climate in the United States and other countries, and the availability of newer, innovative approaches to bioherbicide development and deployment. An assessment of the potential usefulness of *Uredo eichhorniae* as a classical biocontrol agent is in progress and the prospects for using this rust fungus on a global scale should be known in the near future.

Acknowledgments

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Water Hyacinth in China: Its Distribution, Problems and Control Status

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Abstract

Water hyacinth is one of the most important invasive alien plant species in China, into which it was introduced in the early 1900s. Now the weed is distributed in 17 provinces, and in Guangdong, Yunnan, Fujian, Zhejiang and Taiwan has become a bio-disaster. Compared with the situation in 1960, few people now use water hyacinth plants to feed pigs or ducks, or to make fertilisers. It poses a great threat to agriculture, fisheries, transportation and the environment. It is estimated that each year more than 100 million RMB yuan (US$12m) is spent on control of water hyacinth throughout China, but in most areas the weed remains vigorous and continues to spread. Chemical, mechanical and biological control, as well as integrated control strategies, have been employed to combat water hyacinth in more than 10 provinces. Two weevils, *Neochetina eichhorniae* and *N. bruchi*, which were introduced from Argentina and USA in 1995, have established and spread their populations in Zhejiang and Fujian provinces. The weevils greatly suppressed the plants around the release areas. In early 2000, a mirid, *Eccritotarsus catarinensis,* was introduced from South Africa but did not establish. A survey for pathogens of water hyacinth began in spring 2000 in southern China.

WATER hyacinth was introduced into China in the early 1900s. As an ornamental plant, it was first introduced into Taiwan in 1903 from Southeast Asia. In the 1930s it was introduced to the mainland (Diao 1989). But the first scientific record appeared for the mainland in 1954 in the book, 'Taxonomy Catalogue for China's Plants: Families and Genera' (Anon. 1954). In the 1950s and 1960s, water hyacinth was distributed widely into almost all provinces for animal food. After artificial transplanting and mass rearing and breeding, water hyacinth was distributed to further areas in the 1970s and began to cause damage in the 1980s. Increasing damage has been reported since the 1990s as nutrient levels increased in water bodies and the use of water hyacinth plants began to fall.

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Distribution

Water hyacinth is now distributed naturally in 17 provinces or cities in China. In several other provinces water hyacinth is still utilised but cannot overwinter. Water hyacinth causes damage in more than 10 provinces (Ding et al. 1995). Great damage has been reported in five provinces: Yunnan, Guangdong, Zhejiang, Fujian, Taiwan. Figure 1 maps the distribution of water hyacinth in China.

Problems Arising from Water Hyacinth

As in many other countries, in China water hyacinth has caused many economic, social and environmental problems. It blocks waterways, affects water transport for agriculture and tourism, covers lakes and rivers, lowers the dissolved oxygen in water bodies and

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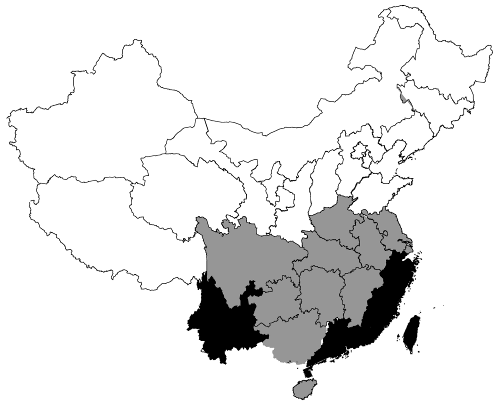

Figure 1. The distribution (shaded areas) of water hyacinth in China. Black areas are where damage is greatest.

reduces aquatic production. It also affects the irrigation of agricultural fields.

As an invasive alien species, water hyacinth has posed a great threat to biodiversity by competing with native plants for water, nutrients and space. At Caohai, Dianchi Lake, in Yunnan province, southwestern China, the plant diversity has been greatly reduced in the past 30 years because of the competition by water hyacinth and the increased water pollution. The number of water plant species at Caohai has fallen from 16 in 1960, 8 in 1970, 5 in 1980, to 3 in 1990 (Wu 1993) . The plants absorption of heavy metals causes a second water pollution problem after they die and sink. In rural areas, after control by harvesting, huge numbers of plants were always heaped together along the banks of rivers and allowed to decay, which greatly affected environmental quality (Wu 1993).

Water hyacinth has also caused a series of problems to local society in China. People have difficulty in their daily lives as it covers their rivers, ponds and lakes. The health of local people is threatened as water hyacinth provides a habitat for mosquitoes and flies. It is said that water hyacinth even creates a public security issue: dense and high water hyacinth plants provide a nice place for criminals to hide.

Utilisation of Water Hyacinth

During the 1950s–1970s, water hyacinth was widely used for animal food in China, as at that time, the economy in rural areas was very depressed and there was great shortage of food for animals. It was also used for fertiliser in a few areas. Some people even tried to make paper from water hyacinth plants. But since the end of 1980s, and the economy improved, the number of people seeking to use water hyacinth has fallen. The sole use of water hyacinth now, and in only a few places, is for feeding ducks. In some environmental institutes, water hyacinth is used as a test plant in the purification of polluted water.

Control Status

Manual removal has been employed in most areas in China in the past 10 years. It is estimated that more than 100 million RMB yuan (US$12m) was spent on artificial control of water hyacinth each year but the practice was neither economic nor effective. Mechanical control is used in only a few places, but it cannot provide long term control. In some areas, herbicides such as Roundup and paraquat were used, but they are prohibited in some places where the water is used by people and animals.

Biological Control

In China, biological control activities for water hyacinth were initiated in early 1995, when the Biological Control Institute (BCI) introduced two weevils *Neochetina eichhorniae* and *N. bruchi* from the USA and Argentina, respectively. Upon the request of the local government, host range tests for the two weevils were conducted in Kunming, Yunnan Province in 1995. Forty-six plant species from 23 families representing local economic, ornamental, and ecologically important plants (Ding et al. 1998) were tested. As they had done previously in the USA, Australia, India and other countries, host range tests showed the weevils attacked and completed their life cycles only on water hyacinth and they were safe to other local plant species.

After host-specificity tests, weevils were first released at four rivers in Wenzhou and Zhejiang provinces in September 1996. Some 1000 individuals of a mixture of the two weevil species were released at each river. The weevils established at all the four rivers within one year of release. At Lincun River, about 50% of water hyacinth plants were killed in late spring 1998, while a native grass, *Paspalum* spp., recovered and occupied the space where water hyacinth grew. Since then, the density of water hyacinth has varied seasonally between 10 and 50% of coverage of the water surface. By means of water flow, the weevils spread rapidly to water bodies up to 40 km from the release site by the summer of 2000 (Ding et al., unpublished data).

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In 1998, the weevils were distributed to Fuzhou, Fuqing and Fuan cities of Fujian Province where water hyacinth was a great disaster. They established quickly, as it was warmer than in Zhejiang Province. Significant control has been achieved at several release sites but no detailed survey results are available yet.

In the early summer of 2000, a colony of the weevils was introduced to Ningbo, another city of Zhejiang Province, where they were released in one river. There is some concern about the ability of the weevils to overwinter there. Located at around 30°N, Ningbo is in the north of Wenzhou and Fujian. In some years when it is very cold in winter, the water hyacinth plants die. In the next year, plants may regrow from seed. Hence, tests have been planned to see if the weevils can overwinter in Ningbo.

In 2001 the weevils will be introduced to Guandong Province which is one of the areas in China most seriously affected by water hyacinth damage.

Besides the weevils, a bug, *Eccritotarsus catarinensis,* was introduced into China in the early spring 2000 from the Plant Protection Research Institute (PPRI), South Africa but, for unknown reasons, had not established its population after 4 months. BCI will introduce it again later. Pathogen surveys have also been started in Fujian and Zhejiang provinces in May 2000. Several promising isolates have been screened.

Integrated Control

In order to control the weed rapidly, an integrated control system was developed from 1996 by BCI scientists. Several herbicides, e.g. Roundup (41% IPA salt of glyphosate) and Caoganlin (10% salt of glyphosate), were screened to supplement the activity of the weevils. Bioassay tests showed that Roundup and Caoganlin had almost no adverse effect on the adults, pupae, larvae and eggs of the weevils. The tests of integrating Roundup at different concentrations with weevils indicated that herbicides had to be used at a lower concentration than normal, so as to not kill the plants too rapidly and not deprive the insects of food and habitat. The details of those tests were reported in the first IOBC water hyacinth workshop in Zimbabwe in 1998 (Ding et al. 1999).

Prospect

Water hyacinth is still a big problem in South China (even a new disaster in some areas) although great efforts have been made to control it in the past 10 years. As more and more attention from central and local governments is paid to improvement of the environment, control of water hyacinth is becoming one of their objectives. Biological control will be employed in more and more areas, but more effort still needs to be made to make the public and government officials aware of the important role that biological control can play in the solution of the weed problem.

BCI research on the biological and integrated control of water hyacinth will focus on the following subjects in the next few years by means of national and international collaborations:

- Study of the factors influencing the level of control of water hyacinth achieved by weevils, including the nutrients in the water body, lower temperatures in winter, natural enemies of the weevils, competition from other aquatic plants such as *Paspalum* species etc.
- Distribution of the weevils into more areas and introduction of new insects from abroad. An agreement between the South African and Chinese governments has been signed for collaboration on water hyacinth over the next three years. BCI will obtain help from PPRI for the importation of new natural enemies e.g. *Eccritotarsus catarinensis.*
- Conduct of field tests of integrated control on a large scale. The results from the tests in 1996–1998 on integrating herbicides with weevils will be verified and amplified on a large scale in the field in South China so as to modify the integrated management system.
- Continuation of the survey of pathogens in South China and introduction of promising fungi from abroad. More effort will be put into pathogen studies. In BCI a pathogen laboratory has been set up for the study of control of the weed by this means. China's strong background on developing biopesticides and bioherbicides in the past 40 years should help the laboratory to make good progress in the near future.

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Biological Control Initiatives against Water Hyacinth in South Africa: Constraining Factors, Success and New Courses of Action

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Abstract

The success of biological control initiatives undertaken against water hyacinth in South Africa has been variable, despite the establishment of six natural enemy species (five arthropods and one pathogen) between 1974 and 1996. By contrast, successful biocontrol was achieved in a relatively short time frame (4 years) on Lake Victoria in Uganda and in Papua New Guinea, using only the two insect agents, *Neochetina eichhorniae* and *N. bruchi*. The variable results achieved in South Africa have so far been attributed to variable climatic conditions, eutrophication of the aquatic ecosystems and interference from integrated control operations. However, hydrological features, notably the size of the water body, and techniques for establishing agents, may also affect the degree of biocontrol. It is believed that biocontrol is more successful in larger water bodies where wind and wave action increase the mortality of agent-stressed plants. These considerations have prompted several courses of action in South Africa, notably: (i) mass-rearing and re-releases of agents that failed to establish at specific sites; (ii) evaluation of the impact of the combinations of agents already established; (iii) development of management strategies in which biocontrol can be appropriately integrated with existing control operations; and (iv) search for additional agents that are effective under more temperate conditions. The success of these initiatives will ultimately rely on the extent to which water authorities and policy-makers become educated about, and come to accept, the principles of biological control.

THE biological control program against water hyacinth in South Africa was initiated in 1973 and resulted in the release of the weevil *Neochetina eichhorniae* in 1974 (Cilliers 1991). Three agents have since been released, including another weevil *Neochetina bruchi* in 1989, the moth *Niphograpta albiguttalis* (= *Sameodes albiguttalis*) in 1990 and the mirid *Eccritotarsus catarinensis* in 1996 (Julien and Griffiths 1998; Hill and Cilliers 1999). In addition, two agents were inadvertently introduced: the pathogen *Cercospora piaropi*, which was first recorded in 1987, and the mite *Orthogalumna terebrantis*, recorded in 1989 (Cilliers 1991). Despite the high number of established agents (the highest of all the countries involved with this program), the success of these initiatives has been variable. Although several water hyacinth populations in South Africa have been significantly reduced through biological control, notably in the Eastern Cape Province (Hill and Cilliers 1999), the results overall do not compare with those obtained in Papua New Guinea (Julien and Orapa 1999) and more recently on Lake Victoria in Uganda (Cock et al. 2000).

Hill and Cilliers (1999) discussed several factors that have constrained the impact of the arthropod agents in South Africa. These include: (i) cold winters, which

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vastly increase the time taken to control the weed; (ii) highly eutrophic waters in which the weed thrives; (iii) periodic removal of the weed and natural enemy populations through flooding and drought; and (iv) interference from other control methods, notably herbicide applications. This situation has prompted several courses of action in South Africa, which include the search for additional natural enemies that are effective in cooler areas and the development of management strategies in which biocontrol can be appropriately integrated with existing control operations.

In this paper, we further discuss the above constraining factors and suggest two additional factors (viz. the size of the water body and techniques for establishing agents), which might also affect the biocontrol of water hyacinth in South Africa.

Factors Affecting the Efficacy of Biocontrol

Variable climatic conditions

Water hyacinth populations are subject to a wide range of climatic conditions in South Africa, including: (i) high altitudes (above 1500 m), temperate summer rainfall areas, where frosting occurs frequently during the colder months (May to August); (ii) coastal, Mediterranean winter rainfall areas, where frost is absent; and (iii) coastal, subtropical summer rainfall areas. Although all five arthropod agents have become established on water hyacinth throughout this climatic range, this is little doubt that the varying conditions affect their impact.

In the high elevation areas of South Africa (highveld), the plants and insects remain dormant for up to 5 months of the year (May–September). Despite this, there is some evidence that agent-induced stress inflicted on the plants during summer increases the mortality of the plants which suffer cold stress during the following winter (Cilliers and Hill 1996). However, plant populations increase rapidly with the onset of spring (late September and October) while the resurging insect populations, which have to regenerate from considerably lower numbers because of cold-induced mortality and low reproductive output, do not reach damaging levels until the end of summer (March and April), only to 'crash' during the following winter. Consequently, unlike the situation in tropical and subtropical areas, the agents persisting in temperate areas seldom reach the population densities required to severely stress the weed, and successful biocontrol thus takes considerably longer. Unfortunately, water authorities often regard such time lags as unacceptable and the water hyacinth mats are invariably subjected to other control methods, notably herbicide applications and mechanical removal, which further reduces the natural enemy populations (Center et al. 1999).

The Mediterranean climate typical of the Western Cape Province may also have had a negative impact on the agents, which appear to have been ineffective in this region. However, the reasons for this are unclear, as the effect of cool, wet and frost-free winters and hot, dry summers on the agent populations has not been determined. In addition, other factors such as flooding and eutrophication (see below) also limit the efficacy of biocontrol in this region.

By contrast, biocontrol has been considerably more successful in the coastal and subtropical areas of the Eastern Cape (EC) and Kwa Zulu-Natal (KZN) provinces. This has occurred in both integrated control programs, such as at Lake Nsezi on the Nseleni River near Richards Bay (KZN) (Jones and Cilliers 1999), and pure biocontrol programs, such as at New Year's Dam near Alicedale (EC) (Hill and Cilliers 1999). However, even in the subtropical areas of South Africa, eutrophication (see below) has hampered the efficacy of biocontrol.

Although not quantified, the range of climatic conditions under which water hyacinth occurs in South Africa certainly has an effect on the natural enemy populations and thus the degree of biocontrol. Whereas successful biocontrol usually takes 3–5 years in tropical areas (Harley 1990), it takes considerably longer (8–10 years) under more temperate situations. As a remedy, insect species that have short generation times and which are capable of rapid population increases during the 6-month growing season of water hyacinth in South Africa should be targeted for release. Such agents have already been identified in South America and include a petiole-mining dolicopodid flies *Thrypticus* spp., a delphacid *Megamelus* sp. and a dictyopharid *Taosa* sp.

Eutrophication of aquatic ecosystems

Many of the rivers and dams in South Africa receive run-off which is highly polluted with nitrates and phosphates arising from agricultural activities. These eutrophic waters enhance the growth of water hyacinth and other aquatic plant species, both native and introduced, to such a degree that aquatic weed problems should be regarded as a symptom of eutrophication. A positive implication for biocontrol is that natural enemy

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populations may proliferate because of higher quality host plants (Room 1990). Alternatively, the impact of the natural enemies may be negated by the extraordinary plant growth caused by rapid leaf production. This appears to be the case at Hammarsdale Dam (KZN) where both *N. eichhorniae*, established since 1989, and *E. catarinensis*, established since 1998, have reached very high population densities but appear to have had little impact on the weed population.

Although Hammarsdale Dam occurs in a warm-temperate area where the insects are not affected by frost, this seems to be negated by severe pollution. Indeed, during the summer months some 50% of the dam's inflow is made up of effluent from textile industries and a wastewater treatment plant and this increases to 100% of the inflow during winter. Eutrophic conditions ideal for water hyacinth populations to proliferate thus persist throughout the year. Current post-release evaluations at this site have indicated that, although the density of the weed population has not been reduced, the two agents appear to have reduced the size of individual plants. Other factors may thus have played a role at Hammarsdale Dam. One explanation is that the system may be too small for wind and wave action to continually disturb the weed mat and thereby enhance plant mortality (see below).

Four other agents have been released at Hammarsdale Dam— *N. bruchi* and *C. piaropi* in 1989 and *N. albiguttalis* and *O. terebrantis* in 1991—but none have become established. Possible reasons for this include inadequate release techniques (see below) and host-plant incompatibility in the case of *N. albiguttalis* which is poorly suited to the tall plants with elongated petioles typical of this site. Further releases of these species are under way.

The different agents established on water hyacinth have differing plant requirements. *Niphograpta albiguttalis* requires plants with actively growing, young tissue and is therefore unlikely to establish on plants growing under oligotrophic (i.e. unpolluted or unenriched) conditions. Heard and Winterton (2000) showed also that *N. bruchi* is more damaging than *N. eichhorniae* under eutrophic conditions. In addition, Jamil and Hussain (1993) showed that uptake of heavy metals by the two *Neochetina* species reduced female fecundity and might thus prevent their establishment in weed populations that have assimilated high concentrations of heavy metal pollutants. These considerations emphasise the importance of host plant quality when trying to establish agents on water hyacinth.

A strategy for the biocontrol of water hyacinth at Hammarsdale Dam should involve new approaches. These would include: (i) reducing the effluent inflow into the dam; (ii) releasing large numbers of the better-suited *N. bruchi* to ensure establishment; (iii) allowing sufficient time for biocontrol to be effective; and (iv) manipulating the water level in the dam to allow periodic flushing of the system.

Interference from herbicide control operations

In South Africa, the control of water hyacinth relies heavily on the application of herbicides, and this policy has been antagonistic to biological control for two reasons. Firstly, certain herbicide formulations used on the weed in South Africa, especially those with high surfactant content, cause high mortality in the natural enemies. Although *N. eichhorniae* was resistant to most herbicide applications, those that contained diquat as an active ingredient were toxic to the weevil (Ueckermann and Hill 2000). These authors also found that all herbicides tested, with the exception of one glyphosate-based product that contained no surfactants, were toxic to the mirid *E. catarinensis*. Secondly, herbicidal destruction of water hyacinth populations, especially in impounded systems, causes extensive mortality of the sessile immature stages and dispersal of the adult stages, when the weed mats start to sink. Re-infestation of these treated sites occurs via seed germination and isolated plants that were left unsprayed and the water hyacinth populations proliferate in the absence of natural enemies (Center et al. 1999).

Solutions to these problems, currently under investigation, include: (i) using herbicide formulations that are less toxic to the natural enemies; (ii) re-inoculating plants that are overlooked during herbicidal applications; and (iii) accepting the concept of leaving untreated 'reserves' to act as refugia for the agents. Ultimately, successful integrated control of water hyacinth in South Africa will rely on a change in the attitude of water authorities. This will entail their acceptance that the control of water hyacinth depends on reducing the level of nutrients flowing into the water bodies, allowing sufficient time for biocontrol to take affect and limiting the use of herbicides, particularly formulations that are damaging to the agents.

Hydrological features

The influence of hydrological features on water hyacinth infestations and subsequent biological control has often been underestimated. This is illustrated by three recent examples of successful biocontrol of water hyacinth, namely the lagoons of the Sepik River in Papua New Guinea (Julien and Orapa 1999), Lake Kyoga in Uganda (Ogwang and Molo 1999) and Lake Victoria in Uganda (Cock et al. 2000). All three systems comprise large, deep-water bodies with a wind fetch greater than 2 km (Clayton 2000). In these situations, the two weevil species reduce the size of the plants, the plants sit lower in the water and the weed mats loosen and fragment more easily. The mats are then further fragmented by wind and wave action, which also kills many plants and causes the mats to sink, as occurred at Lake Victoria (Ogwang, pers. comm.). Alternatively, the small mats may be flushed out of the system, as occurred down the Nile River off Lake Kyoga (Ogwang and Molo 1999) and down the Sepik River in Papua New Guinea (Julien, pers comm.).

In South Africa, many of the impoundments are small (< 100 ha), shallow (<10 m) basins and are therefore not subject to wind and wave action. Although the agents can inflict severe damage on the plants, with up to 30 adult weevils per plant in some areas, the lack of physical stress on the mats prevents them from breaking up and the plants from sinking. Furthermore, some areas in certain impoundments are too shallow (<0.3 m) for the plants to sink and the roots merely rest on the substrate, as occurred at New Year's Dam near Alicedale. Lack of wind and wave action, coupled with an inability to flush these impounded systems, has prevented the spectacular success observed in Papua New Guinea, Lake Victoria and Lake Kyoga from being repeated in South Africa.

South African river systems that are infested with water hyacinth but which have not been impounded, present a different problem for biological control. Most African rivers are prone to periodic flooding and drought, which cause unscheduled, sporadic removals of both weed and agent populations. This results in water hyacinth resurging from dormant seed banks and, in the absence of the agents, proliferating to reach pre-biocontrol levels. In these situations, redistribution of the natural enemies and close monitoring of the weed populations is necessary to restore biological control.

Techniques for establishing agents

The use of appropriate release techniques may prove critical in ensuring the establishment of natural enemies on water hyacinth. Establishment relies on the release of large, healthy populations of the agents onto healthy plants in the field. In South Africa, the release of the two weevil species as adults has mostly ensured establishment, while the pathogen, mirid, mite and moth are more likely to establish when individual plants, heavily infested with them, are placed into the weed populations. All releases must be made in sheltered areas that are protected from disturbance by both biotic or abiotic factors. Numbers released have also proved crucial, since large or multiple releases have a higher chance of ensuring establishment. Indeed, the very low numbers (less than 100) of *N. bruchi* released at several sites in South Africa may well explain its failure to establish in some areas and its poor distribution. Furthermore, the very large releases of *Neochetina* species carried out on Lake Victoria (greater than 100,000) appears also to have contributed to the spectacular success of biocontrol.

A series of dossiers on the rearing, release and monitoring of natural enemies for water hyacinth is being produced by CSIRO Australia. One has already been completed for the two *Neochetina* species (Julien et al. 1999), while others are either in press (e.g. that on the moths, *N. albiguttalis* and *Xubida infusella*) or in preparation (e.g. that on the mite, *O. terebrantis,* and the mirid, *E. catarinensis*). These publications will provide essential information on the techniques needed to ensure the successful establishment of agents for water hyacinth.

Successful Biocontrol: a South African Case History

One of the best examples of successful biocontrol of water hyacinth in South Africa is New Year's Dam, a 150 ha impoundment near Alicedale (EC). In 1990, when the weed mat covered some 80% of the dam, around 200 adult *N. eichhorniae* were released. The weevils became established, spread throughout the population and by 1994 had reduced the weed mat cover to less than 10% of the dam's surface area. The remaining plants were small (10 to 20 cm tall) and unable to sink because of very shallow water. *Niphograpta albiguttalis*, *O. terebrantis* and *E. catarinensis* were released in 1996 but failed to establish, possibly because of both incorrect timing of the release (middle of winter) and the very poor condition of the surviving plants. By 1998, the weed mat cover had increased to 80% of the water surface, but, with no further releases, *N. eichhorniae* once again reduced this to around 10% by 2000. This system is thus considered to be under biological control and three factors appear to have contributed to this.

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Firstly, the system is oligotrophic in that the sustaining catchment is fairly small, sparsely populated and does not support intensive agriculture or industry. Run-off into the dam is thus low in nitrates and phosphates and even before the introduction of the weevils, the plants were small (<35 cm) and nutrient-stressed. The weed's resurgence in 1998 may have been initiated by above-average rainfall in this semi-arid area, which significantly increased the nutrient input to the dam. A small resident weevil population, caused by the reduced weed mat and poor quality of the plants, allowed the resurging mat to temporarily 'escape' the weevils, which then took 2 years to respond and restore biocontrol.

Secondly, climate appears to have played a significant role in the success of the weevils. New Year's Dam is situated in a warm temperate region characterised by spring and autumn rainfall, summer temperatures of 20–35°C and winter temperatures that seldom drop below 10°C. Consequently, the life cycle of *N. eichhorniae* might be protracted during the winter months but their populations are not hit by frosts.

Thirdly, and most importantly, no other control methods have been employed at this site. The town of Alicedale, which obtains all its water from the dam, supports a small community, and the weed has never severely affected the quality or quantity of water. In addition, the infestation does not threaten any infrastructure and is not regarded as a source of infestation for other nearby catchments and rivers. Consequently, the national water authorities are under no pressure to control the infestation in the short-term and are thus prepared to allow biocontrol to operate in isolation.

Discussion

Problems with biological control of water hyacinth are presumably not unique to South Africa and are likely to be experienced elsewhere in the world. Although the biocontrol program in South Africa has been less successful than those implemented in other tropical areas of the world, it has, nevertheless, lessened the overall impact of water hyacinth. Besides the few situations where water hyacinth infestations have been significantly reduced, the plants have generally become smaller in size. Indeed, some 20 years ago plants of 1 m and taller were frequently recorded while today plants in mature stands seldom exceed 0.6 m on average (C. Cilliers, unpublished data). Smaller plants cause less-extensive mats, which pose less of a threat to infrastructure. In addition, the natural enemies reduce the rate of mat expansion after disturbances, notably flooding, manual removal and herbicide applications. As a result, water authorities are able to reduce the number of herbicide applications at many of the control sites, leading to considerable economic and ecological savings.

The success achieved at New Year's Dam has not been repeated elsewhere in South Africa and this has prompted several courses of action. Firstly, there are several sites where some of the agent species have failed to establish and these have been targeted for redistribution. Mass-rearing and re-releases are aimed at establishing the full suite of natural enemies at all sites throughout the country, to ensure that inappropriate release methods used previously were not the cause of non-establishment. Secondly, the impact of certain agents on the weed, notably *E. catarinensis*, *O. terebrantis* and *C. piaropi*, is unknown. Laboratory and field studies have been initiated to quantify the efficacy of these agents, both in isolation and in combination with the other species, and thereby facilitate the development of improved management strategies for water hyacinth. Thirdly, additional agents are under investigation, and recent surveys in northern Argentina (Cordo 1999) and the upper Amazonian region of Peru (H. Cordo et al., unpublished data) have revealed several species that might be suitable for release in South Africa. These include: (i) the grasshopper *Cornops aquaticum* which is very damaging but not suitably host specific (Oberholzer and Hill 2001), (ii) several species of the petiole-mining fly *Thrypticus*; (iii) the delphacid *Megamelus;* and (iv) the dictyopharid *Taosa*. These species have favourable attributes, notably the fact that, despite their tropical origin, they thrive in the cooler regions of Argentina (Buenos Aires province) suggesting adaptations to more temperate climates. In addition, all have short generation times (less than 40 days) and are thus capable of rapid population increases. These species may thus be suitable for release in the cooler areas of South Africa where rapid population increases during the summer months could cause more damage to water hyacinth populations than the agents currently established.

Although some 26 years have elapsed since the first release of a biological control agent against water hyacinth in South Africa, the program has remained very active in researching additional ways of controlling the weed. However, the emphasis has shifted from a purely biological to a more integrated management approach, which includes aspects of biocontrol, herbicide applications, manual removal, hydrological control and nutrient control. The

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success of this program will ultimately rely on the extent to which water authorities and policy-makers become educated about, and come to accept, the principles of biological control.

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Recent Efforts in Biological Control of Water Hyacinth in the Kagera River Headwaters of Rwanda

T. M. Moorhouse*, P. Agaba* and T. J. McNabb†

Abstract

As part of regional water hyacinth management activities in the Lake Victoria Basin that also involve Kenya, Tanzania, Uganda and several international partners, Rwanda is currently implementing efforts to rear and release the two *Neochetina* weevil species as biological control agents through coordination of training activities and training visits made to Uganda and Tanzania. Weevils for release in Rwanda have come from stocks maintained in Uganda.

The implementation of the biological control program within the Kagera River system of Rwanda is expected to further support the long-term control of water hyacinth in the Lake Victoria Basin by reducing water hyacinth biomass in source waters. Funding and technical support for the implementation of the biological control program for water hyacinth in Rwanda are being provided by Clean Lakes, Inc. through a two-year cooperative agreement with the United States Agency for International Development Greater Horn of Africa Initiative through the Regional Lake Victoria Water Hyacinth Management Program.

APPROXIMATELY 13 years ago water hyacinth was officially recognised as having invaded the world's second largest lake, East Africa's Lake Victoria. During the ensuing years various management activities have been implemented by Kenya, Tanzania and Uganda with support from several international partners and donor organisations. Recently, these countries and Rwanda have begun to coordinate management efforts through regional organisations such as East African Cooperation (EAC), the Lake Victoria Fisheries Organization, the Lake Victoria Environment Management Program, or through bilateral memoranda of understanding. Biological control efforts using the weevils *Neochetina eichhorniae* and *N. bruchi* began in late 1995 through release efforts initiated by Uganda that continue to date. Rwanda is currently implementing water hyacinth control through rearing and release efforts assisted by Clean Lakes, Inc. (CLI), under cooperative agreement funding from the United States Agency for International Development (USAID), and through coordination of training activities and visits carried out in Uganda and Tanzania. Weevil stocks maintained in Uganda are the source of weevils imported into Rwanda.

The Lake Victoria Basin water hyacinth infestation extends to its uppermost point within the Kagera River system to the headwaters of Mukungwa River tributary, located approximately 50 km northwest of Kigali, Rwanda (F. Orach Meza, pers. comm.). The Mukungwa River is joined by the Nyaborongo River, keeping the latter's name, until it merges with the

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Burundi's Ruvubu River system near Lake Rweru, along the Burundi border, to form the Akagera River, also known as the Kagera River (see Figure 1). The entire Mukungwa/Nyabarongo/Kagera river system to Lake Victoria is infested with water hyacinth, a length of over 500 km. Water hyacinth ultimately enters Lake Victoria in the form of mats torn away from the shoreline or as individual plants. There is at least one set of major waterfalls along the Rwanda/Burundi border at Rusoma, Rwanda, and a large swamp/lake complex along the Rwanda/Tanzania border of the Akagera River where water hyacinth becomes damaged or is caught in the swamp matrix, thus potentially reducing amounts travelling downstream. Downstream of this large swamp/lake system, which forms a large part of the Akagera National Park, the Akagera River changes direction to an easterly course, becomes shared by Tanzania and Uganda, and experiences a series of elevational drops near Kikagati, Uganda, where water hyacinth again becomes damaged by turbulent waters.

Below Kikagati at a point approximately 160 km from Lake Victoria, the river flattens and passes primarily through Tanzania where water hyacinth flourishes along river banks, growing toward the river centre to a width of about 2 m from the shoreline. Water currents and velocity prevent water hyacinth from growing much beyond that with the exception in some bends, inlets or sloughs, or during periods of drought or flood. Considering that all rivers have two banks, these 160 km of river therefore produce 320 km of linear shoreline growth potential for the weed to a width of approximately 2m, or a total of about 64 ha. It has been visually estimated by CLI staff that within 1 km of Lake Victoria the daily rate of weed flowing down the Kagera River ranges between 0.2 and more than 1.5 ha/day (average 0.75 ha/day or 300 ha/year), depending on seasonal river flow. Others have estimated weed flow rates at 3.5 ha/week or 0.5 ha/day (Twongo and Balirwa 1995). If a growth rate model of 1% per day were assumed, then these 64 ha growing along the shoreline would generate about 0.64 ha of new weed growth/day. This is equivalent, on average, to the estimated daily inflows documented by CLI staff in 1997 (unpublished data) and by Twongo and Balirwa (1995).

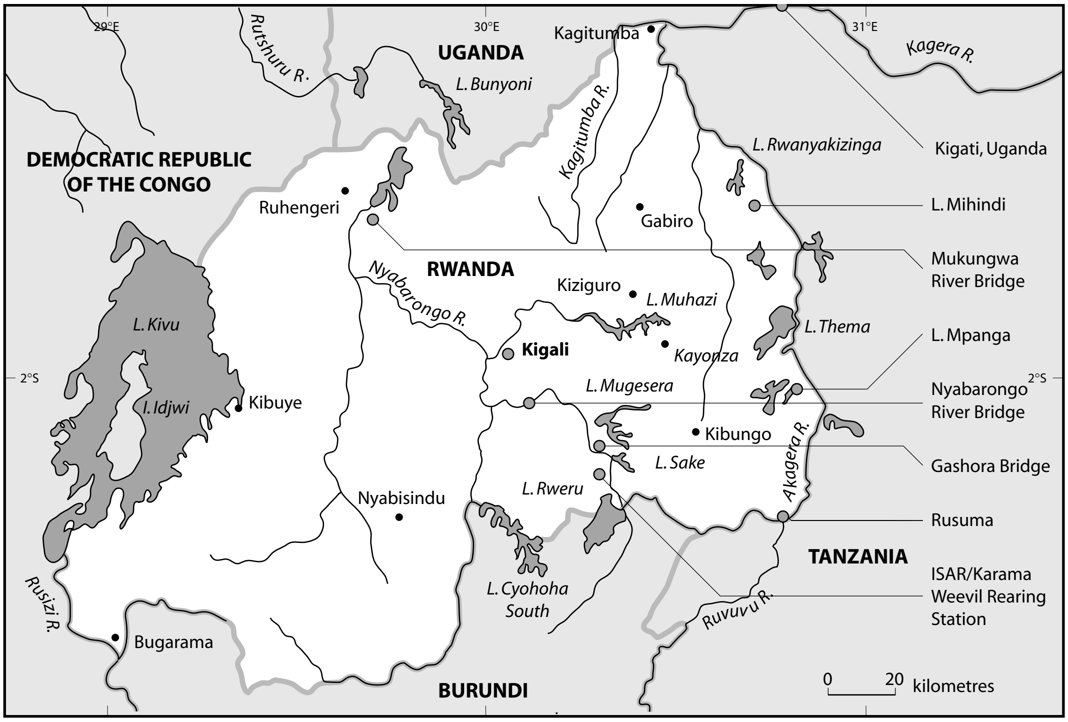

Figure 1. Rivers and lakes of Burundi and adjacent areas of the Lake Victoria Basin

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The Rwandan Biological Control Effort—a Summary

It was recognised that, in order to bring the water hyacinth under management within the entire Lake Victoria Basin, a cooperative effort should be encouraged between the countries concerned. Recommendations were made in various regional and EAC fora to include Rwanda and Burundi in efforts to manage water hyacinth in the lake basin. In 1997, the governments of Rwanda and Uganda signed a memorandum of understanding on common agriculture issues to cooperate on, among other things, water hyacinth management. Both governments committed their countries to full collaboration in management of the water hyacinth problem.

During a Uganda Agricultural Policy Committee meeting in July 1999, the Uganda National Agriculture Research Organization (NARO) sought support for Rwandans to be trained for implementing biological control of water hyacinth in the upper Kagera River watershed.

In August 1999, EAC adopted a regional strategy document on the control of water hyacinth and other invasive weeds in East Africa. This document covered the issue of water hyacinth control in the upper Kagera River.

In September 1999, CLI staff visited Rwanda to hold discussions with the Director General, Institut des Science Agronomique du Rwanda (ISAR), to explore interest in training and release programs for biological control of water hyacinth in the upper Akagera River watershed. While there, CLI staff visited the Nyabarongo River, a tributary of the Kagera River that flows south of Kigali, and reviewed the weed infestation.

During November 1999, the Secretariat of the EAC, in close collaboration with the United Nations Economic Commission for Africa, Kigali Sub Regional office, held a workshop in Entebbe on water hyacinth in the Lake Victoria Basin. One of the recommendations of the workshop was that a program for the biological control of water hyacinth should be implemented in the upper Kagera River.

Through a USAID cooperative agreement, CLI facilitated the training of Rwandan and Burundian government officials in November 1999. The training was led by Dr James Ogwang, head of biological control programs at NARO's Namulonge Agriculture and Animal Production Research Institute (NAARI) and by staff of the Uganda Ministry of Agriculture, Animal Industries and Fisheries/Water Hyacinth Unit (MAAIF/WHU).

In May 2000, MAAIF/WHU and CLI staff visited Rwanda, in cooperation with ISAR officials, to identify locations suitable for establishing the initial weevil rearing centre. Karama Animal Husbandry and Fisheries Unit, one of the ISAR branch locations in Rwanda, was selected because of its relative closeness to the Nyabarongo/Akagera River system. This unit is located in the southern part of the country, approximately 70 km southeast of Kigali in the Commune of Gashora on the shores of Lake Kilimbi.

In July 2000, MAAIF/WHU, CLI and ISAR officials erected two weevil rearing tanks at ISAR/Karama. The tanks were filled with water and water hyacinth.

In mid August 2000, the Rwanda Ministry of Agriculture, Livestock and Forestry issued an authorisation allowing the Director General, ISAR, to import water hyacinth weevils.

During 19–22 September 2000, ISAR/Karama weevil rearing facility and CLI staff travelled to the weevil rearing sites at Kyakairabwa (Bukoba) and Kyaka (Kagera River), Tanzania, to review and further strengthen weevil-rearing techniques and experience through observation and discussions with weevil-rearing technicians. On their return to Kampala, they proceeded to the village sometimes known as Goma (near Kasensero) to a point approximately 1 km upstream from the Kagera River outlet on Lake Victoria to observe water hyacinth growth. Weevil damage was noted on plants. The weevils present might have come from releases carried out by the Goma weevil rearing site, or have migrated upriver from Lake Victoria after releases carried out in the Bukoba, Tanzania area, or from upriver releases at Kyaka (quarterly releases since June 1998) under the support of the Lake Victoria Environment Management Project, or at Mulongo, Tanzania through support from the International Fund for Agriculture Development under the Kagera Agriculture and Environmental Management Program (KAEMP) (quarterly releases since 1999). The ISAR/CLI team understood that KAEMP had also made two weevil releases on the Tanzanian side of the Akagera River, opposite Rusoma, Rwanda, though no dates were given and details remain sketchy.

In September 2000, the Deputy Director – Research of the Ugandan NARO, issued a letter granting approval for Rwanda to export weevils from Uganda and gave permission for NAARI to collect and prepare weevils for transit to Rwanda.

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On 25 September, weevils were collected in cooperation with NARO from the NAARI weevil rearing tanks under the direction of the head of biological control programs and assisted by NAARI, ISAR, and CLI staff. The numbers of weevils collected for transport were as shown in Table 1.

In order to help monitor the efficacy of weevil releases, satellite images were scheduled for acquisition in late September or early October 2000, depending on cloud cover. IKONOS 1-metre PAN and 4-metre multispectral band data were to be collected in collaboration the United States Geological Survey–EROS Data Center. One image each will be acquired for the small lakes, Lake Mpanga and Lake Mahindi, in the Akagera River area of Akagera National Park (eastern Rwanda) at the upstream and downstream ends of the swamp/lake complex, respectively. While influences such as flooding, drought and pathogens may also lead to declines in water hyacinth, it is expected that these images will provide a baseline sample for tracking water hyacinth cover and distribution before and after weevil release. On-the-ground observations will be made along other sections of the river.

On 27 September 2000, ISAR and CLI staff travelled by air from Entebbe, Uganda to Kigali, Rwanda, with the consignment of *Neochetina* spp. Upon arrival in Kigali, they were met and transported to the ISAR Karama weevil rearing facility in order to inoculate the weevils into water hyacinth in previously established tanks. Approximately 800 weevils were placed in the water hyacinth plants of the two tanks. The two weevil species were deliberately mixed when placing them in the tanks. The Karama weevil rearing site is within 10 km of the Gashora Bridge on the Nyabarongo River, which is expected to become one of several weevil release sites within Rwanda.

On 28 September, approximately 25 weevils of each species were released in a small depression, Lake Kiruhura, in the Nyabarongo River floodplain, approximately 2 km east of the Nyabarongo River Bridge, 20 km south of Kigali. This seasonal lake, just over a hectare in area, lies approximately 200 m south of the Nyabarongo riverbank. It was about 60% covered with water hyacinth of estimated average height 30–40 cm. About 40% of the plants were in flower. As a result of drought in much of Rwanda at the time, rivers, pools, and depressions were experiencing very low water levels. It was expected, however, that the rainy season would commence shortly over the entire country, as rains had at release time been reported in the upper Mukungwa/Nyabarongo rivers of northern Rwanda.

Table 1. Numbers of water hyacinth weevils collected in Uganda in September 2000 for release in Rwanda

	Chevroned water hyacinth weevil (*Neochetina bruchi*)	Water hyacinth weevil (*Neochetina eichhorniae*)
Females	117	330
Males	127	280
Subtotal	244	610
Total	854	

Conclusion

Studies and evaluations of the effectiveness of the biological control program will continue, and updates will be provided as data become available. The next report on the campaign is scheduled for release in January 2001.

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Ongoing Activities in the Biological Control of Water Hyacinth in Egypt

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Abstract

As in many other tropical and subtropical countries, the aquatic floating weed water hyacinth causes serious problems to various types of water bodies in Egypt. The total infested area is estimated to be 487 km^2 covering most of the drainage and irrigation canals in different governorates of Egypt, and about 151 km^2 covering lakes. The total amount of water loss by evapotranspiration from water hyacinth infested areas was estimated to be 3.5 billion m^3 per year. This amount is sufficient to irrigate about a further 432 km^2 every year.

During the period 1978 to 1984, two weevils, *Neochetina eichhorniae* Warner and *N. bruchi* Hustache, were introduced into Egypt and studied under quarantine conditions. Host-specificity tests proved the safety of both weevils for release as biocontrol agents for water hyacinth. No authorisation for release was given until 1999, when a biological control program to be financed by the French Government was approved. In May 2000, 3004 weevils—1118 *N. eichhorniae* and 1886 *N. bruchi*—were collected from water hyacinth infested sites in Fort Lauderdale, Florida, and transferred to Egypt for rearing and multiplication in an aquatic weed greenhouse. Field releases of both species in Egypt began in August 2000.

WATER hyacinth, *Eichhornia crassippes* (Mart.) Solms (Pontederiaceae), was first recorded in Egypt by Simpson (1932). During the period 1978–1984, in cooperation with the United States Department of Agriculture, Fort Lauderdale, Florida, two weevil species, *Neochetina eichhorniae* Warner and *N. bruchi* Hustache, were introduced into Egypt and studied under quarantine conditions through a PL480 project. These beneficial weevils have been introduced and released in several countries in the world (Julien and Griffiths 1998), such as the USA (Perkins 1973; Center 1982), Australia (Wright 1979) and Sudan (Besher and Bennett 1985), to control water hyacinth. Host-specificity tests proved the safety of both weevils for release as biocontrol agents (Julien et al. 1999; DeLoach 1976; Fayad 1982, 1999). No authorisation for release in Egypt was given until 1999 when the Egyptian Ministry of Agriculture approved the introduction of the two *Neochetina* weevils for release on water hyacinth. A biological control program, financed by the French Government, started in January 1999.

In May 2000, 3004 weevils—1118 *N. eichhorniae* and 1886 *N. bruchi*—were collected from water hyacinth near Fort Lauderdale, Florida, USA. They were transferred to Egypt for rearing, multiplication and release in the northern lakes Mariout (Alexandria Governorate) and Edko (Beheira Governorate).

Methods

Construction of aquatic weed greenhouse and growing of water hyacinth

A light and temperature-controlled aquatic weed greenhouse of dimensions 15 × 7 m, containing 9 cir-

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cular water pools of 160 cm diameter and 100 cm depth each, were constructed in the Department of Biological Control, ARC at Giza. Water supply and drainage was provided to each pool. The greenhouse was quarantine secure and supplemented with a dressing room, bathroom and laboratory. The pools were filled with tap water to 80 cm depth and left for 3 days to remove any undesired dissolved gases before introducing water hyacinth plants collected from the River Nile or irrigation canals. Water hyacinth plants were washed thoroughly with tap water before placement in the pools.

Fifteen grams of a soluble NPK fertilizer containing micro nutrients (Polyfeed – Haifa Chemicals Ltd) plus 70 g nitrogen and 10 g iron, were added to each pool monthly or as required, as indicated by leaves turning yellow or a blue colour appearing on the roots. The temperature in the greenhouse was set at an average of about 27.8°C. Plants were washed daily using tap water to prevent aphid and mite infestations. Water was added to the pools whenever needed.

Collecting *Neochetina bruchi* and *N. eichhorniae* for introduction into Egypt

A collecting trip was made to Fort Lauderdale, Florida, USA, during the period 14–19 May 2000. Individuals of both *Neochetina bruchi* and *N. eichhorniae* were collected by handpicking from water hyacinth plants either from the shore or a boat. Collected weevils were kept in plastic containers provided with tissue paper and water hyacinth leaves. The containers were transferred to the laboratory, weevils separated into species and stored in the refrigerator at 10°C. Over 5 days, a total of 3004 weevils of both *Neochetina* species was collected. Samples from the collected weevils were taken, dissected and microscopically examined for insect-disease detection. Weevils were placed in screw-capped carton tubes for shipping, 200–300 weevils per tube. The tubes were stored in the laboratory at 18°C for 2 days then hand-carried to Egypt. Upon arrival, insects were inspected by quarantine officers at Cairo Airport then transferred to the quarantine room attached to the aquatic weed greenhouse and stored in a refrigerator at 10°C. The following day, the insects were examined and healthy weevils were placed on healthy water hyacinth plants placed in the 9 water pools in the greenhouse.

N. bruchi adults were released on water hyacinth in 6 pools, while *N. eichhorniae* were released in the other 3 pools. Each pool was allocated 200–250 weevils. The rest of the weevils were stored in the refrigerator at 10°C.

The pools were examined daily for feeding spots and symptoms of weevil activity.

Harvesting the weevils from water hyacinth plants in the greenhouse

The first generation started to emerge in the first week of August 2000. During the daytime, many adults were found on the floor of the greenhouse, driven out of the pools by overpopulation. These adults were collected. Furthermore, a metal ring net of 120 cm diameter was placed on the water hyacinth plants in the pool and pushed down to submerge them. Floating adults were then collected using a medium-size strainer. The weevils collected each day were counted and placed in square, plastic containers furnished with tissue paper and provided with fresh green water hyacinth leaves. A window of about 8 × 4 cm covered with wire gauze was made in the cover lid for ventilation. The containers were stored in the refrigerator at 10°C until release of the weevils.

Field release of *N. bruchi* and *N. eichhorniae*

Harvested weevils were transferred in an icebox to the release sites at Mariout and Edko lakes. Both lakes were chosen as they were heavily infested with water hyacinth. Airboats, rubber boats and sometimes narrow wooden fishing boats were used for transfer in the lakes. Release details are given in Table 1.

Results

Establishment of the weevils in the greenhouse

Feeding scars and weevil activities including mating and oviposition were observed 2 days after release. The damage to water hyacinth plants became more obvious each day, and new plants were added periodically or whenever needed. Leaf and petiole samples were taken, dissected and examined under the binocular microscope. Weevil eggs could be seen. Three weeks later, root inspection indicated the presence of different instar larvae attached to the plant roots. In late July, cocoons containing pupae were also found, attached to the submerged roots of the plants. In the first week of August, the first generation started to emerge, indicating success in rearing the introduced weevils under greenhouse conditions.

Release of *N. bruchi* and *N. eichhorniae* in Mariout and Edko lakes

Some 6573 adults of both *Neochetina* species were released in Mariout and Edko lakes (Table 1). Furthermore, water hyacinth plants supporting different *Neochetina* life stages were distributed on water hyacinth infestations at certain sites in the lakes.

Follow up of the establishment of the released weevils

Weekly visits to the release sites in each lake were conducted to determine the establishment and spread of the weevils. Many feeding scars were observed on water hyacinth leaves, suggesting the establishment of *Neochetina* weevils at the release sites in both Mariout and Edko lakes, but more time is needed to confirm this.

Discussion and Conclusion

Despite the studies conducted in Egypt since 1978 on the use of insects for the biological control of water hyacinth with results indicated the safety of releasing both *N. bruchi* and *N. eichhorniae* (Fayad 1982, 1999), no authorisation for release was given until 1999.

The success of rearing both weevils under greenhouse conditions and symptoms of feeding scars gradually increasing after releasing the weevils in both lakes are very promising signs. By introducing and releasing *N. bruchi* and *N. eichhorniae,* the authors announce that, in August 2000, Egypt joined other countries in applying biological control to water hyacinth. In combination with other control methods it is hoped to gain an acceptable level of water hyacinth control that keeps the population under the economic threshold. Several other known biocontrol agents have to be introduced. A search for, and study of, new agents needs to continue.

Acknowledgments

The authors wish to thank the French Government for financing the project entitled 'The biological control of water hyacinth in Egypt', which covered all travel expenses for collecting in the USA and participation in this working group meeting. Great appreciation is extended to the scientists of USDA at Fort Lauderdale, Florida, for their sincere assistance provided during the collecting trip on 14–19 May 2000.

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Table 1. Releases of *N. bruchi* and *N. eichhorniae* in Mariout and Edko lakes

Date of release	Site of release	No. of released adults		Total	No. of release sites
		N. bruchi	*N. eichhorniae*		
15.8.2000	Edko Lake	1395	692	2087	3
21.8.2000	Mariout	668	332	1000	3
		infested plants distributed			1
30.8.2000	Edko Lake	702	298	1000	3
		infested plants distributed			1
11.9.2000	Mariout	812	490	1302	3
19.9.2000	Edko Lake	787	397	1184	3
		infested plants distributed			2

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Progress with Biological Control of Water Hyacinth in Malawi

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Abstract

Water hyacinth appeared in southern Malawi during the late 1960s, and spread slowly northwards in the Lower Shire River, but in 1995 it was found in the Upper Shire River, just south of Lake Malawi. It is now present in most parts of the Shire River, and in a number of other locations, including the far north of the country. Biological control was initiated in 1995 under a UK Department for International Development-funded project, and is now being continued through a World Bank-funded project. About 200,000 *Neochetina* have been reared and released, mainly in the Shire River, but recently at other sites outside the Shire. The beetles are well established in the Shire, though establishment and subsequent population build-up has been faster in the Lower Shire than the Upper and Middle Shire. Water hyacinth infestation in the Shire River is now less than it was two years ago, but it is too early to conclude that this is the result of the biological control campaign. As new infestations appear elsewhere in the country, biological control agents will be released to limit build-up of the weed.

FISHERMEN in the southern tip of Malawi report that water hyacinth first appeared there in the Shire River in the 1960s, and suggest that it may have arrived from across the border during floods (Harley 1991; Chimatiro and Mwale 1998), a reasonable hypothesis given that it had been present in Zimbabwe and the Zambezi River for many years before its discovery in Malawi. It subsequently spread slowly northwards, and by 1980 was present at the southern end of Elephant Marsh (Blackmore et al. 1988) (near Makhanga; see Figure 1). By 1991 it had reached the northern end of Elephant Marsh, south of a Chikwawa (Terry 1991). In 1995 it was discovered in the Upper Shire River north of Mangochi, although surveys indicated it was not present between Lake Malombe and Chikwawa at that time (Hill et al. 1999), suggesting that it had been accidentally introduced to the Upper Shire.

The Shire River can be divided into four sections (Table 1), but only the Murchison Rapids section is unsuitable for the weed. As well as occurring throughout the Shire, water hyacinth is now present at a number of locations across the length of Malawi, including Blantyre, Lilongwe River, Salima, Nkhotakota, south of Nkhata Bay, and north of Karonga. There are unconfirmed reports from other locations, including the Songwe River along the northern border with Tanzania, so the weed is clearly now widely distributed. However, in most places outside the Shire River infestations are generally relatively small.

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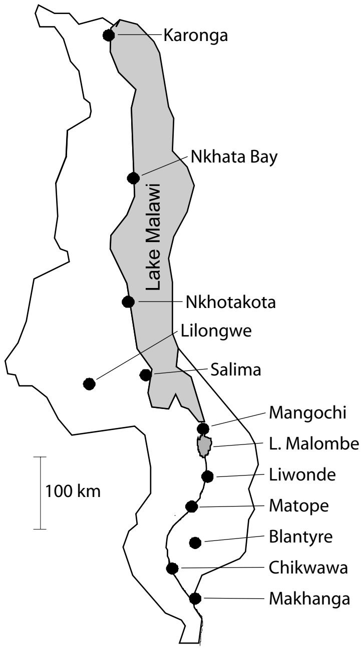

Figure 1. Map of Malawi showing places referred to in the text

A project was commenced in late 1995, funded by the UK Department for International Development (DFID), which focused on the Shire River. The project had four components: biological control, public awareness and community participation, socioeconomic evaluation of the problem, and assessment of the weed's environmental impact, and these were described at a workshop in Harare, Zimbabwe in 1998 (Hill et al. 1999). The project ran for a little over three years, after which there was a hiatus of nearly a year before a new project started, funded by the World Bank. The new project again has several components, but biological control remains the main thrust in the strategy for long-term control. In this paper we provide an update on progress with the biological control of water hyacinth in Malawi.

Methods

Rearing and release of biological control agents

Rearing tanks for *Neochetina* spp. were established at Fisheries Department facilities at Makhanga and rearing was started using *N. bruchi* and *N. eichhorniae* hand-carried from Zimbabwe in September 1996. Part of the initial importation was used to make small-scale releases. Tanks were set up at Mangochi in May 1997 using insects from the first harvest at Makhanga. Initially, both units had 10 tanks, but later 5 were added at Makhanga, and 10 at Mangochi, though the tanks at Mangochi have not been used for *Neochetina* rearing continuously.

Methods used were adapted from those used in South Africa. Rearing tanks were cylindrical, with a diameter of 265 cm and height of 67.5 cm, and so contained approximately 3000 litres of water. Each tank was placed on a concrete plinth, with drainage channels between tanks leading to a soakaway. Water levels were checked daily and topped up as required. Once a fortnight the water was replaced using water pumped from the river. At replacement 500 g of urea and 250 g fertiliser (NPK: 6-18-6 or other as available) were added to each tank. Dead leaves and plants were removed as necessary. Harvesting was undertaken about once a month, and harvested beetles were counted by species and sex then released.

Table 1. Sections of the Shire River (adapted from Crossley 1980, quoted Blackmore et al. 1988)

Section	Between	Gradient mm/km	Features
Upper Shire	Lake Malawi and Lake Malombe	~100	Fisheries
Middle Shire	Lake Malombe and Liwonde	16	Liwonde National Park
	Liwonde and Matope	96	Barrage at Liwonde
Murchison Rapids	Matope and Chikwawa	~5000	Hydroelectric power stations
Lower Shire	Chikwawa and southern border	250	Sucoma sugar plantation Elephant and Ndinde marshes (major fisheries)

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Eccritotarsus catarinensis and *Niphograpta albiguttalis* were imported in May 1997, May 1998, January 1999 and April 2000, hand-carried from South Africa. Initially, imported insects were released, but subsequently a part of each importation was released and part used to set up cultures in tanks at Mangochi.

The mite *Orthogalumna terebrantis* was already present on the weed in the Lower Shire, having accompanied the weed from the Zambezi where it was released in Zambia in the 1970s (Julien and Griffiths 1998). It was redistributed onto water hyacinth in the Upper Shire during 1996 and 1997 and is now well established on the weed throughout its range in the Shire River. Mite-infested leaves are being redistributed on new infestations of the weed as they are discovered.

Monitoring

Currently there are 14 sites at which the impact of biological control is being monitored, 3 in the Upper Shire, 3 in the Middle Shire, 5 in the Lower Shire, 2 on Lake Malawi, and 1 in Blantyre. Monitoring is undertaken once every 2 months, and on each occasion 30 mature plants are selected at random and the parameters listed in Table 2 recorded for each plant.

Results and Discussion

Rearing

Figure 2 plots the *Neochetina* harvested at the two rearing units. By mid 2000 the Makhanga unit had produced over 100,000 and the Mangochi unit about 90,000. Initial harvests at Makhanga were high as the tanks had been running for 8 months before harvesting commenced, so populations had reached high levels. During 1999, production was intermittent as the DFID project had ended and the new project had not yet started.

Table 4 shows that, at both units, there has been a slight excess of females in both species. At Makhanga, where the climate is hotter, slightly more *N. bruchi* have been produced than *N. eichhorniae*, while at Mangochi, almost two-thirds of production has been of *N. eichhorniae*. Rearing of both *Eccritotarsus* and *Niphograpta* has been unsuccessful: after 1–2 generations the populations in the rearing tanks have died out for reasons that are not clear.

Releases

The first releases of *Neochetina* were made in September 1996, from the first importation. The first

Table 2. Parameters recorded during impact monitoring

Parameter	Description
Longest leaf	The length of the longest petiole plus lamina on the plant
Root length	The maximum length of the root system
Lamina length for leaf 2	Leaf 2 is the second youngest/2nd most recently opened leaf.
Lamina width for leaf 2	At widest part of lamina
No. of leaves	Includes sick leaves but not leaves on any daughter plants
No. of ramets	The number of daughter plants attached to the sampled plant
No. of beetles	The numbers of adult weevils of the two species released
Leaf 2 scars	The number of weevil feeding scars on leaf 2
Leaf 2 mites	The mite damage score, using the system in Table 3
Leaf 2 pathogens	Damage caused by pathogens on leaf 2, using the same scale as for mite damage (Table 3)
Leaf 4 mites, pathogens	As for Leaf 2
Leaf 5 mites, pathogens	As for Leaf 2
Other agents	Presence/absence of *Eccritotarsus* and *Niphograpta*

releases of insects reared in Malawi were made in May 1997, and continued regularly until early 1999. Harvesting and thus releases during 1999 were intermittent, but with the start of the new project in late 1999, harvesting and releases have again continued regularly. Including the first releases, by mid 2000 over 190,000 weevils had been released. Figure 3 shows the proportion of insects released in different areas. Within an area a number of different release sites have been used.

Table 3. Mite and pathogen damage scores

Score	% of leaf occupied/damaged
0	0%
1	<5%
2	6–25%
3	26–50%
4	51–75%
5	75–100%

The rationale for the pattern of releases between the different areas is as follows:

- More releases have been made in the Upper Shire River as it was expected that populations would be carried downstream to the Middle and Lower Shire.
- During 1999, the time between the two projects, all of the weevils rearing at the Mangochi site were released in the Upper Shire.
- Establishment and build-up of populations in the Lower Shire have been faster than in the Upper and Middle Shire, requiring fewer releases.
- The first project focused on the Shire River. Since the start of the current project, releases have been made in Salima, Nkhotakota, and Chiwembe dam, Blantyre. The last site is only about 4 ha, but has large healthy plants due to pollution of the inflow (Limbe River).

Further releases are being made in the Middle Shire where establishment has been slow. No further releases are required elsewhere unless sites are discovered where the beetles are absent.

To date a little over 5000 *Eccritotarsus* have been released at sites in the Upper, Middle and Lower Shire and at Blantyre. About 800 *Niphograpta* have been released in the Upper and Middle Shire.

Table 4. Percentage of *Neochetina* spp. production by sex and species at the two rearing units

Unit	*N. bruchi*			*N. eichhorniae*		
	Male	Female	Total	Male	Female	Total
Makhanga	46.9	53.1	53.7	47.7	52.3	46.3
Mangochi	45.8	54.2	36.3	47.6	52.4	63.7

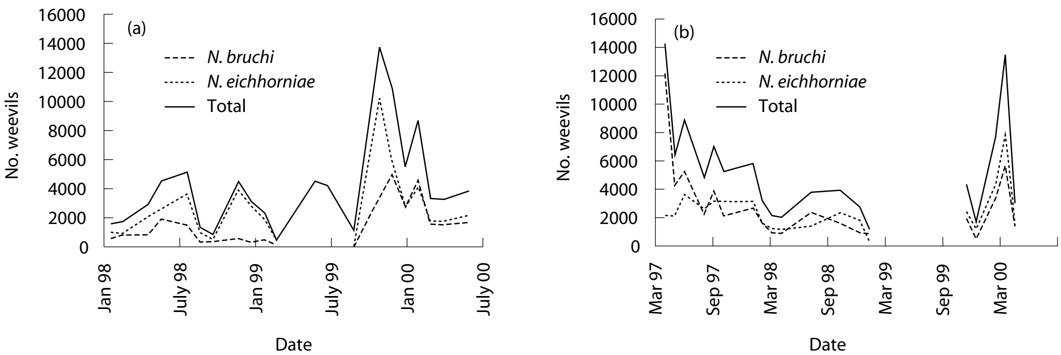

Figure 2. *Neochetina* harvesting at the two production units: (a) Mangochi; (b) Makhanga

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Monitoring

Here we present an example of the data-sets being collected. Figure 4 shows the mean number of weevil feeding scars on leaf 2 for one site each in the Lower, Middle and Upper Shire River.

The beetles are established at all monitoring sites. Damage by the weevils has increased in the Upper Shire in the last two years. In Lake Malombe and the Middle Shire, damage levels have remained low, while in the Lower Shire there has been a build-up to higher levels than in the Upper Shire. In recent months a reduction in weevil damage has been seen at some Lower Shire sites, and this appears to be associated with the reduction in plant height, though it may be a simultaneous response to an environmental variable rather than a causal link.

From 1998 to 2000 there has been some decrease in plant height, but this is not matched by a reduction in laminar area for leaf 2 or leaf number. If biological control is working, we would expect a general reduction in plant vigour and thus size.

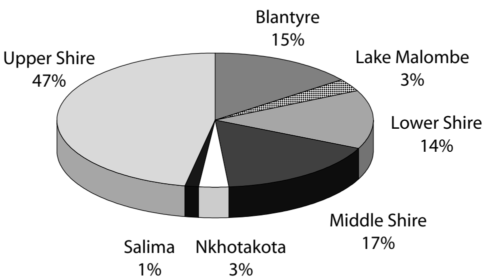

Figure 3. Releases of *Neochetina eichhorniae* and *Neochetina bruchi* in the Shire River.

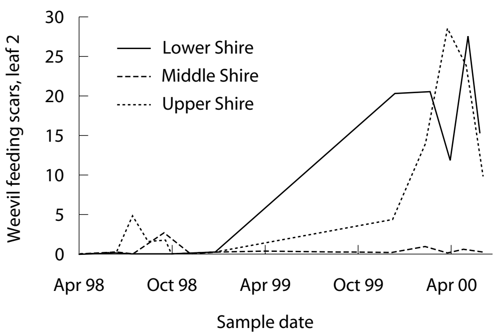

Figure 4. Weevil feeding scars at three monitoring sites in the Shire River.

Mite damage was generally higher in 1998 than subsequently, though there has been some increase in 2000. Interestingly, the same pattern has occurred for damage by pathogens, and this suggests that the mites may be facilitating infection by pathogens. However, both control agents may be responding to the same environmental conditions. No evidence has been found for establishment of either *Eccritotarsus* or *Niphograpta.*

At all the sites on the Shire River there appears to have been a reduction in the infestation of water hyacinth, and at one site in the Lower Shire monitoring has ceased as there is now so little water hyacinth present that monitoring is impractical. In the Upper Shire the reduction of the weed appears to have coincided with an increase in cover by the sedge *Pycreus mundtii*, and Rother and Twongo (1999) have suggested that the water hyacinth is stimulating a succession in which it is being replaced by *Pycreus* and *Ludwigia.*

Conclusion

Neochetina spp. are well established in most parts of the Shire River, and numbers at some sites have built-up to levels at which a significant impact can be expected on water hyacinth infestations. Hill et al. (1999) suggested that impact might become visible by 2000–2001, and certainly the population of water hyacinth in the Shire River is less than it was two years ago. Fishermen in the Lower Shire are crediting the weevils with this reduction, but while this is pleasing, more data need to be collected to confirm this view.

In other parts of Malawi, new infestations can be expected to occur. In some cases it may be possible for local communities to effect control by manual removal—there are already some cases of this reported. At the same time, the long-term strategy remains centred on biological control, and *Neochetina* spp. and *Orthogalumna* will be released on significant new infestations as they are reported. It is hoped that *Eccritotarsus* and *Niphograpta* will also become established.

As Julien and Orapa (1999) concluded, a successful biological program requires expertise, appropriate training and capacity building, staff and resources over an adequate period. We are confident that these ingredients are all present in the Malawi project, and so we are optimistic that the program will be a success.

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IMPECCA[1]: an International, Collaborative Program to Investigate the Development of a Mycoherbicide for Use against Water Hyacinth in Africa

R. Bateman*

Abstract

The IMPECCA Programme has been established to develop a mycoherbicide for the control of water hyacinth, using fungal isolates that have been found in Africa. Such a mycoherbicide could replace the use of broad-spectrum herbicides, which are used routinely at present, but have caused concerns about contamination to fish and degradation of water quality. In addition, a mycoherbicide might be more compatible with the use of insect biological control agents. The project will build upon existing studies of formulating water hyacinth fungi into mycoherbicides which have been carried out in Egypt and Zimbabwe, and expertise gained by CABI Bioscience during the development and commercialisation of mycoinsecticides.

One of the key outputs will be the strengthening of technical capacity and linkages within African national programs to undertake biological control of weeds. Scientists will carry out extensive exploration for pathogens of water hyacinth already present in Africa. These will be identified, characterised and assessed for suitability as the basis for a mycoherbicide; these studies will include molecular and chemotaxonomic identification of both fungal isolates and water hyacinth biotypes. Characteristics of a fungus isolate suitable for mycoherbicide development include: high pathogenicity, acceptable host specificity, low mammalian toxicity, and capacity for mass production and formulation. Candidate products will be laboratory and field tested for efficacy and compatibility with other (especially biological) control options. A water hyacinth management strategy will be proposed appropriate for local needs.

WATER hyacinth is perhaps the most pernicious aquatic weed in the world. Water hyacinth is generally the dominant plant when it occurs outside of its native range and is capable of suppressing or eliminating other species. It forms dense mats of vegetation in lakes and dams, and irrigation and flood channels, where it impedes boat traffic, increases eutrophication and harbours the mosquito vectors of malaria, encephalitis and filariasis (Forno and Wright 1981). The problems are most severe in developing countries, where human activities and livelihoods are closely linked to the water systems. Conventional methods of control rely mainly on mechanical/manual removal and chemical herbicides, which have generally been found to be inadequate and expensive measures to apply on a large scale. Herbicides have the added dis-

1. The International Mycoherbicide Programme for *Eichhornia crassipes* Control in Africa (the IMPECCA programme) is funded by Danida (Danish International Development Assistance) through the Environment, Peace and Stability Facility. This article contains the views of the author, which do not necessarily correspond to the views of Danida.

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advantage that they might have adverse environmental effects, and must be applied carefully and selectively. They also can interfere with or nullify the action of biological control agents present (Charudattan 1995). In recent years, attention has been given to using natural enemies to control the weed. Indeed, the only logical, long-term and sustainable solution to managing the weed is to employ an integrated approach, with special emphasis on biological control agents (Charudattan 1995).

As described in other chapters of these proceedings, biological control using insects such as *Neochetina* spp. has been highly successful in reducing water hyacinth populations in several countries in northern and central America and parts of Africa. The need for a range of effective management tools against this weed, including mycoherbicides, is illustrated by the waterways where water hyacinth remains a problem despite attempts to introduce insects for biological control (Hill and Olckers 2001; Charudattan 2001). Furthermore, several studies have demonstrated possible insect–pathogen interactions combining to cause a decline in water hyacinth populations (Galbraith 1987; Charudattan et al. 1978; Kasno et al. 1999). Mycoherbicides might therefore be used to augment other natural enemies.

Stages Required in the Development of a Mycoherbicide

Several research groups have identified promising microbial agents that might be used as biopesticides. However, this research has rarely resulted in the development of biopesticide products, which currently account for only a fraction of one percent of the global crop protection market (which is approximately US$3 $\times 10^{10}$). Although there is a long history of research on microbial control agents, it is not always appreciated that obtaining an active isolate is only the beginning of a series of activities necessary for implementing the use of a new mycoherbicide (O'Connell and Zoschke 1996). There are important issues to consider including: mass production (see e.g. Jenkins et al. 1998), delivery systems and 'laboratory to field' studies (Bateman 1998), strategies for use, registration and commercialisation.

Although focusing on 'downstream' processes of mycoherbicide development, the IMPECCA Programme will also carry out further surveys for pathogens for a limited period. Several isolates have already been collected that will act as standard isolates for comparison with newly collected material. The criteria for the selection of fungi were that:

- they must have been isolated in Africa;
- they must be widely distributed across the regions of Africa where water hyacinth is found; and
- they must be shown to have good pathogenicity to water hyacinth in laboratory or field studies.

In contrast, Evans and Reeder (2001) argue for a 'longer term' approach to the use of microbial agents, in which isolates are sought at the weed's centre of origin, for release as classical biological agents. However, the introduction of exotic pathogens is in its infancy and there is still a reluctance to the release of pathogens as biological control agents in many countries. As part of the inception phase of the IMPECCA Programme, the scientific collaborators have identified a short-list of fungal species that show most promise in their potential as mycoherbicides for water hyacinth control in Africa. In order of preference, they are:

1. *Alternaria eichhorniae*;
2. *Acremonium zonatum*;
3. *Cercospora piapori/C. rodmanii*;
4. *Rhizoctonia solani* and *Alternaria alternata*;
5. *Myrothecium roridum*.

Program of Activities and Progress to Date

Table 1 gives a possible sequence of activities for mycopesticide development, as identified by IMPECCA Programme scientists. The following major activities are in progress or are planned:

- Collection and preservation of pathogen isolates. Over 70 isolates have been collated by CABI Bioscience, and the most promising specimens will be accessioned at CABI Bioscience, UK. Isolate collection is being carried out in strict observance of the International Convention on Biodiversity, and a document has been prepared explaining IMPECCA Programme policy.
- Identification and characterisation of specimens:
  - morphological, molecular and chemotaxonomic identification of fungal isolates,
  - molecular identification of water hyacinth biotypes.

  Preliminary analyses of water hyacinth isolates from Africa, India and South America indicate a surprising degree of genetic homogeneity (Alex Reid, pers. comm.). However, we foresee the need

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Table 1. Major elements of mycoherbicide development

Issues	Process (may be repeated with new isolate)	Sequence
Survey for indigenous pathogens		1
Pathogen isolation and characterisation	Isolation	2
	Agreement on standard isolates	2
	Preservation of isolates	2
	Identification	3
	Assessment of pathogenicity	4
	Characterisation	5
Working methods	Formation of country networks	1
	Development of models as research tools	1
	Intellectual property issues	1
	Policy on publication	2
Biology	Key protocols: screening techniques/objectives	1
	Water hyacinth biology	1
	Water hyacinth–pathogen interactions/nutrient levels	9
	Persistence, horizontal transmission	10
Quarantine issues		2
Host range determination	For environmental safety	6
	Efficacy	6
Mass production	Laboratory (Petri dishes / bottles)	2
	Pilot plant	7
	Commercial	13
Toxicology	Mammalian safety tests (isolate assessment)	8
	Mammalian safety tests (registration)	12
	Ecotoxicology (includes host range data)	6–12
	Post control impact (succession of water hyacinth with other species) and changes in oxygen demand	10
Delivery systems	Storage	6
	Formulation	7
	Application	8
'Lab to field' studies	'Pre field trials' for efficacy	9
	Assessment of synergism (e.g. with *Neochetina* or chemicals/stressors)	9–11
Field testing	Small-scale field trials	10
	Large-scale field trials (operational effectiveness)	12
Strategy for use		10
Socioeconomic assessment		10
Product identification	Ideally one product (maximum 2) – registration is expensive!	11
Registration dossier		12

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to characterise approximately 100 samples before any firm conclusions can be drawn.

- Pathogen screening and selection for further mycoherbicide development on the basis of a *combination* of key criteria including;
  - virulence,
  - host range testing,
  - preliminary mammalian toxicity studies, and
  - an assessment of production and storage characteristics.

  A series of standard operating procedures for isolate collection, and assessment of virulence and host range testing, have been agreed or are in preparation. Preliminary observations confirm those of Shabana et al. (1995) that isolates of *Alternaria eichhorniae* appear to be the most promising. These and other useful techniques are being compiled in the form of IMPECCA Technical Guides.
- Development of a suitable delivery system (Fig. 1) that includes:
  - preparation of prototype formulations,
  - storage stability tests, and
  - selection of appropriate application equipment.

  The use of oil formulations has shown great promise for enhancing the efficacy of fungal agents that show potential as insecticides, fungicides and herbicides. Perhaps most importantly, the need for high humidity is overcome: Amsellem et al. (1990) showed that invert emulsions eliminated the need for a minimum inoculum threshold with *Alternaria cassiae* and *A. crassa*. Such formulations (where oil constitutes the continuous phase) are rather 'user unfriendly' being unstable and very viscous, so the use of less viscous vegetable oil suspension emulsions has been investigated by Auld (1993) and Shabana (1997). Bateman et al. (2000) discuss important criteria in the selection of application equipment for biopesticides, and argue that the equipment normally used for conventional pesticides is often most appropriate. Rotary atomisers fitted to aircraft for low volume spraying of chemical herbicides are a common method for water hyacinth control (Julien et al. 1999) and especially suitable for the application of oil-based formulations.
- Field testing and ecological evaluation. A preliminary model has been developed that describes water hyacinth phenology; this will later incorporate (and attempt to interpret) data on the impact of natural enemies and their interactions (Neils Holst, pers. comm.)
- Programme management, liaison with collaborating partners, donors and other projects; agreements, patents, subcontracts, promotion and publicity.

The IMPECCA Programme collaborates with the IOBC by publishing The Water Hyacinth Newsletter (editors: Rebecca Murphy and Martin Hill). News and progress will also be available on our World Wide Web page: <http//:www.impecca.net>.

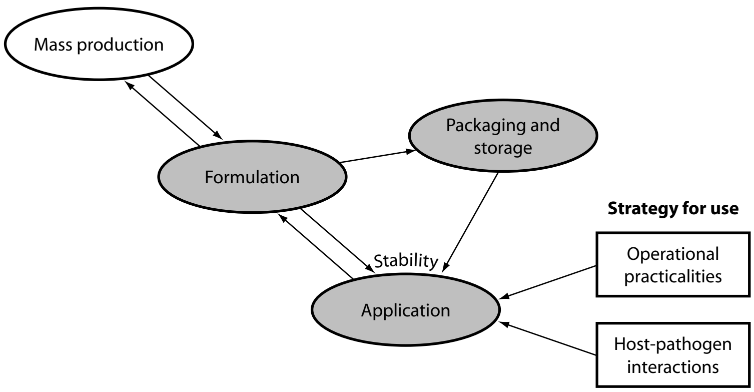

Figure 1. Delivery systems: successful biopesticide development is most likely to be brought about by considering all the various technical aspects of product development at an early stage. There are often important linkages between the mass production, storage and packaging processes. Formulation and application are likewise interdependent and governed by appropriate strategies for use of a microbial agent in the field.

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Collaborators

The main investigators of the IMPECCA Programme include:

1. CABI Kenya: Ignace Godonou, Christiaan Kooyman
2. CABI UK: Roy Bateman, Carol Elison, Harry Evans, Jane Gunn, Jeremy Harris, Nina Jenkins, Belinda Luke, Rob Reeder, Alex Reid, Sue Paddon, Emma Thompson
3. Danish Institute of Agricultural Science: Niels Holst (supervising PhD students: Sander Bruun and John Wilson)
4. Department of Research and Specialist Services, Zimbabwe: Bellah Mpofu, Lawrence Jasi
5. International Institute for Tropical Agriculture, Benin: Jürgen Langewald, Fen Beed
6. Plant Protection Research Institute, South Africa: Alana den Breeÿen, Cheryl Lennox
7. University of Mansoura, Egypt: Mahmoud Zahran, Mahomed El-Demerdash, Fathy Mansour, Yasser Shabana (from August 2001), Abdel-Hamid Khedr, Gamal Abdel-Fattah, Ibrahim Mashaly, S. El-Moursy

At the time of writing, the program has also established linkages with representatives from Kenya, Malawi, Rwanda, Tanzania and Uganda.

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Fungi Associated with *Eichhornia crassipes* (Water Hyacinth) in the Upper Amazon Basin and Prospects for Their Use in Biological Control

H.C. Evans and R.H. Reeder*

Abstract

Surveys were undertaken in 1998 and 1999 in the upper Amazon basin of Ecuador and Peru to collect and catalogue the mycobiota associated with water hyacinth in the river and lake systems. The results indicate that three groups of fungi, which occupy distinct niches on the plant, can be delimited: biotrophic fungi, colonising green leaf tissue, often without significant visible symptoms (e.g. *Didymella* and *Mycosphaerella*); necrotrophic fungi, causing prominent leaf lesions (e.g. *Leptosphaeria*, *Colletotrichum*, *Myrothecium*, *Phaeoseptoria* and *Stagonospora*); and fungi associated with and isolated from petioles previously invaded by coevolved insect natural enemies, such as *Taosa* and *Thrypticus* spp. (e.g. *Acremonium*, *Cephalosporiospsis*, *Cylindrocarpon*, *Cylindrocladium* and *Stauronema*). Some of these represent new host records, as well as undescribed taxa. A re-analysis of the mycobiota associated with water hyacinth worldwide reveals that most of the records originate from the USA and the Palaeotropics, where the plant is a major invasive species, and where, as a consequence, most research on its control has been concentrated. Fungal genera such as *Alternaria* and *Cercospora*, which traditionally have been favoured as biocontrol agents, seem to be absent or rare on *E. crassipes* in the Upper Amazon.

Introduction

EICHHORNIA *crassipes* (Mart.) Solms is native to the Neotropics but its precise centre of origin remains speculative. Based on style morphology, it has been suggested that the area of greatest genetic diversity lies in Amazonia (Barrett and Forno 1982); with natural spread from these to other regions of the South American continent, and human-vectored introductions into the Caribbean and Central and North America. Paradoxically, a search of the literature and unpublished herbarium records reveals that few fungi have been reported on water hyacinth in South America. For example, a detailed survey of the fungal pathogens associated with this host in the Brazilian State of Rio de Janeiro yielded only *Cercospora piaropi*, compared with four species recorded on the closely related *Eichhornia azurea* (Swartz) Kunth. (Barreto and Evans 1996). The same authors also compiled the worldwide records of the mycobiota collected on, or isolated from, *E. crassipes*. A reanalysis of this amended list (Table 1) shows that of the 60 potential pathogens reported, 54 are from countries or regions where water hyacinth is an undisputed alien invasive species, 36 of which are exclusively Old World. Of the New World records, 18 are from the USA, 3 are from the Caribbean or Central America, while only 2 have a South American (ex Brazil) origin.

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Table 1. Mycobiota recorded on *Eichhornia crassipes*, worldwide (amended from Barreto and Evans 1996)

Fungi	Distribution
Ascomycotina and Deuteromycotina	
Acremonium crotocigenum (Schol-Schwarz) W. Gams	Australia (IMI 288071[a])
Acremonium implicatum (Gilman & Abbott) W. Gams	Australia (IMI 271067)
Acremonium sclerotigenum (F. & R. Moreau ex Valenta) W. Gams	Sudan (IMI 284343)
Acremonium strictum W. Gams	Australia (IMI 288318, 288319)
Acremonium zonatum (Sawada) W. Gams	Australia, India, Pakistan, Panama, USA, Sudan
Alternaria alternata (Fr.) Keissler	Egypt
Alternaria eichhorniae Nag Raj & Ponnappa	Egypt, India, Thailand, USA, Kenya, Ghana, South Africa, Zimbabwe
Alternaria tenuissima (Nees ex Fr.) Wiltshire	Hong Kong
Bipolaris urochloae (Putterill) Shoemaker	Egypt (IMI 324728)
Bipolaris sp.	USA, Brazil
Blakeslea trispora Thaxter	Thailand
Cephalotrichum sp.	USA
Cercospora piaropi Tharp	India, Sri Lanka, USA
Cercospora rodmanii Conway	USA–/India (IMI 329783), Nigeria (IMI 329211)
Chaetomella sp.	Malaysia
Cladosporium oxysporum Berk. & Curt.	Hong Kong–/Nigeria (IMI 333543)
Cochliobolus bicolor Paul & Parbery	India (IMI 138935)
Cochliobolus lunatus (= *Curvularia lunata*) Nelson & Haasis	Egypt (IMI 318639), India (IMI 162522, 242961), Sri Lanka (IMI 264391), Sudan (IMI 263783)
Coleophoma sp.	Sudan (IMI 284336)
Curvularia affinis Boedijn	USA
Curvularia clavata B.L. Jain	India (IMI 148984)
Curvularia penniseti (M. Mitra) Boedijn	USA
Cylindrocladium scoparium var. *brasiliense* Batista	India
Didymella exigua (Niessl) Saccardo	Trinidad, USA
Drechslera spicifera (Bainier) V. Arx	Sudan
Exserohilum prolatum K.J. Leonard & E.G. Suggs	USA
Fusarium acuminatus Ellis & Everhart	Australia (IMI 266133)
Fusarium equiseti (Corda) Saccardo	India–/Sudan (IMI 284344)
Fusarium graminearum Schwabe	Australia (IMI 266133)
Fusarium moniliforme Sheldon	Sudan (IMI 284342)
Fusarium oxysporum Schlechtendal	Australia (IMI 288317)
Fusarium solani (Martin) Saccardo	Australia (IMI 270062)
Fusarium sulphureum Schlechtendal	India (IMI 297053)

Continued on next page

Table 1. (Cont'd) Mycobiota recorded on *Eichhornia crassipes*, worldwide (amended from Barreto and Evans 1996)

Fungi	Distribution
Fusidium sp.	South Africa (IMI 318345)
Gliocladium roseum Bainier	Australia (IMI 278745)
Glomerella cingulata (Stonem) Spauld & Schrenk	Sri Lanka (IMI 264392)
Helminthosporium sp.	Malaysia
Leptosphaeria eichhorniae Gonzales Fragoso & Ciferri	Dominican Rep., Panama
Leptosphaerulina sp.	USA
Memnoniella subsimplex (Cooke) Deighton	USA
Monosporium eichhorniae Sawada	Taiwan
Mycosphaerella tassiana (De Notaris) Johanson	USA
Myrothecium roridum Tode ex Fr.	India, Philippines Thailand–/Burma (IMI 79771), Malaysia (IMI 277583)
Pestalotiopsis adusta (Ellis & Everhard) Steyaert	Taiwan–/Hong Kong (IMI 119544)
Pestalotiopsis palmarum (Cooke) Steyaert	India (IMI 148983)
Phoma sorghina (Saccardo) Boerema, *et al.*	Sudan–/Australia (IMI 288313, 288311, 288312, 288315, 333325)
Phoma sp.	USA
Phyllosticta sp.	Nigeria (IMI 327627, 327628)
Spegazzinia tessarthra (Berk. & Curt.) Saccardo	Sudan 284335
Stemphylium vesicarium (Wallroth) E. Simmons	USA
Basidiomycotina	
Doassansia eichhorniae Ciferri	Dominican Rep.
Marasmiellus inoderma (Berk.) Singer	India
Mycoleptodiscus terrestris (J.W. Gerdermann) Ostazeki	USA
Rhizoctonia oryzae-sativae (Sawada) Mordue	Australia (IMI 289087)
Rhizoctonia solani Kuhn	India, Panama, Thailand and USA
Rhizoctonia sp.	India, USA
Thanatephorus cucumeris (Frank) Donk	China, Taiwan–/India (IMI 3075)
Tulasnella grisea (Raciborski) Saccardo & Sydow	Indonesia (Java)
Uredo eichhorniae Gonzales Fragoso & Ciferri	Argentina, Brazil, Dominican Rep.
Chromista	
Pythium sp.	USA

[a]International Mycological Institute isolate reference number

Most of the records in the exotic range, and especially in the Palaeotropics, comprise a heterogeneous assemblage of generalist, opportunistic pathogens, with a minority group of apparently more specialised species not yet recorded from the native range. For example, *Cercospora piaropi* was reported from Asia, Africa and North America only, before the aforementioned survey in southern Brazil (Barreto and Evans 1996). Thus, Table 1 reflects the distribution of water hyacinth research workers rather than the true coevolved mycobiota. As Barreto and Evans (1996) concluded, the doubts and speculation surrounding the area of origin or diversity of *E. crassipes* need to be resolved and addressed in order to open the way for more targeted and, potentially, more meaningful surveys for exploitable natural enemies.

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The Surveys

Strategy employed

The Amazon basin, and specifically Amazonian Brazil, is most frequently cited as the probable centre of origin of *E. crassipes* (Harley 1990; Holm et al. 1991). However, ad hoc pathology surveys along the lower Amazon and its tributaries in the early 1990s, in the vicinities of Belém (Pará State) and Manaus (Amazonas State) yielded few fungi of interest (H.C. Evans and R.W. Barreto, pers. obs.). This led to speculation that perhaps the true origin lay further south in the great basins of the Paraná or São Francisco rivers (Barreto and Evans 1996), particularly since the earliest record of the plant was from the Rio São Francisco (Seubert 1847). Nevertheless, an exploratory survey along this river in 1996 failed to find any new or exploitable pathogens (R.W. Barreto and H.C. Evans, unpublished data). The only major area in South America for which there were no natural enemy records, and hence in which no surveys appeared to have been conducted, is the northwestern region; specifically, the upper Amazon basin, which comprises a confluence of many river systems and interlinked or isolated lakes or 'cochas'. It was hypothesised that in such ecosystems, natural enemies of water hyacinth may have coevolved in isolation and, as the plant spread naturally down the Amazon to reach the Atlantic and the other river systems of South America, these natural enemies were filtered out, especially those with poor survival or dispersal strategies. Thus, the biota associated with *E. crassipes* in the lower Amazon basin and elsewhere may be depauperate compared with that in the Upper Amazon, some 5500–7000 km upriver. The theory was put to the test, initially by opportunistic surveys, followed-up later by a more organised collecting trip, in the upper Amazon basin of both Peru (in Oct. 1988 and May 1999) and Ecuador (in May and Sept. 1999, and May 2000).

Collecting and isolation

Collecting was done using motorised canoes, travelling down the Napo River in Ecuador from the port of Coca, and up the Amazon River from Iquitos in Peru and along the major feeder rivers of the Nanay and Marañon. In addition, a short survey was undertaken along the Ucayali River around the port of Pucallpa. Diseased leaves were collected and dried in a plant press for processing in the UK. In addition, plants were lifted and petioles, stems and roots examined for disease symptoms. Such fleshy material was stored in waxed packets for later isolation in the UK.

Isolations were made either: directly from spores present on the diseased tissues, using a stereomicroscope; or tissues were aseptically-dissected, surface sterilised (30% hydrogen peroxide for 5 minutes) and rinsed several times in sterile distilled water. All samples were plated directly onto tap-water agar (TWA) or potato–carrot agar (PCA) containing antibiotics (penicillin, streptomycin sulfate), and incubated at 25ºC, with a 12-hour black light regime to stimulate sporulation.

Results

Field assessment

The striking, and initially depressing, observation of water hyacinth populations in the rivers and lakes of the upper Amazon basin is that there is little visible evidence to signify the presence of fungal pathogens, especially compared to *E. crassipes* in its exotic range where patches of senescing or dying plants are not uncommon (caused by both abiotic and biotic factors). However, closer examination reveals that there is a range of fungal pathogens occurring on water hyacinth (see Table 2), and that these fungi fall into three groups. Genera, such as *Didymella* and *Mycosphaerella*, produce their discrete, black ascostromata singly but abundantly in the still green leaf tissues and, thus, apart from some yellowing (chlorosis), symptoms are cryptic. These species represent highly coevolved or biotrophic fungi, living within the host without seriously disrupting its physiology. The second group includes fungi which belong to the genera *Colletotrichum*, *Leptosphaeria*, *Myrothecium*, *Phaeoseptoria* and *Stagonospora*, and which cause necrotic leaf spots: some restricted and discrete (e.g. *Colletotrichum*); others spectacular, such as a prominent target spot (*Leptosphaeria*). However, it is only when the plants are lifted, and the petioles examined, that the high incidence of disease becomes evident. Many petioles were attacked by species of *Taosa* (Dictyopharidae; Homoptera) and *Thrypticus* (Dolichopodidae; Diptera), with their characteristic feeding and egg-laying patterns, and a significant proportion of these showed a positive association with fungal necrosis, as evidenced by lesion development around and subsequent spread from the insect punctures. It is considered that these wounds permit the ingress of both specialist and opportunistic fungal pathogens into the petiole, resulting in colonisation and invasion of

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the stele, with decline or eventual death of the plant caused, in part, by the actions of this third group of fungi. There is a less clear association with the tunnels of *Neochetina* larvae, although microorganisms readily invade such damaged tissues. Interestingly, there was no association of fungi with the feeding scars of *Neochetina* adults on the leaves. The fungi isolated from these tissues, excluding well-documented and ubiquitous saprophytic species, are listed in Table 2.

Table 2. Mycobiota associated with *Eichhornia crassipes* in the Upper Amazon basin

Identification	Country	Associated tissue	Isolate reference no.[c]
Ascomycotina and Deuteromycotina			
Acremoniella sp.	Peru	Petiole	–[d]
Acremonium sp. (New species)	Peru	Petiole	384422
Acremonium sp. (New species)	Peru	Petiole	384429
Acremonium sp.[a]	Peru	Petiole	384427
Asteroma sp.	Peru	Petiole	379974
Cephalosporiopsis sp.	Peru	Petiole	–
Cephalosporium sp.	Ecuador	Leaf	–
Chaetophoma sp.	Ecuador	Leaf	–
Cochliobolus lunatus R.R. Nelson & F.A. Haasis	Peru	Petiole	379965
Cochliobolus pallescens (Tsuda & Ueyama) Sivan	Peru	Petiole	379971
Coniothyrium sp.	Ecuador	Petiole	–
Curvularia sp.	Ecuador	Petiole	
Fusarium sp. (New species)	Peru	Petiole	384418
Cylindrocladium sp.[a]	Peru	Petiole	384414
Fusarium poae (Peck) Wollenw.	Peru	Petiole	384424
Fusarium sacchari (E.J. Butler & Hafiz Kahn) W. Gams.	Peru	Petiole	384423
Fusarium sp. (New species)	Ecuador	Petiole	384434
Fusarium sp.	Peru	Petiole	–
Fusarium sp.	Peru	Petiole	–
Fusarium sp.[a]	Ecuador	Petiole	384433
Gliocladium roseum Bainier	Ecuador	Petiole	384435
Gliocladium sp.	Peru	Petiole	
Glomerella cingulata (Stoneman) Spauld. & H. Schrenk.	Brazil[b]	Leaf	384437
Glomerella cingulata (Stoneman)	Ecuador	Leaf	384432
Glomerella cingulata (Stoneman)	Peru	Leaf	384416
Glomerella sp.	Peru	Leaf	–
Hyphomycete sp. 1[a]	Ecuador	Petiole	384431
Hyphomycete sp. 2[a]	Ecuador	Petiole	384430
Hyphomycete sp. 3	Ecuador	Petiole	–
Hyphomycete sp. 4	Ecuador	Petiole	–
Hyphomycete sp. 5 with dictyochlamydospores (New species).	Peru	Petiole	379967

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Table 2. (Cont'd) Mycobiota associated with *Eichhornia crassipes* in the Upper Amazon basin

Identification	Country	Associated tissue	Isolate reference no.[c]
Idriella sp.[a]	Peru	Petiole	384417
Leptosphaeria sp.	Brazil[b]	Leaf	–
Leptosphaeria sp.[a]	Peru	Leaf	384425
Leptosphaerulina sp.	Peru	Leaf	379972
Mycosphaerella sp. (New species)	Peru	Leaf	384426
Myrothecium verrucaria (Alb. & Schwein.) Ditmar	Peru	Leaf	379973
Myrothecium sp.	Brazil[b]	Leaf	–
Phaeoseptoria sp.	Peru	Leaf	379966
Phoma chrysanthemicola Hollós	Peru	Petiole	384421
Phoma leveillei Boerema. & Bollen	Ecuador	Petiole	–
Phoma section *Peyronellaea* (Goid. ex Togliani) Boerema	Peru	Petiole	384420
Phoma sp.[a]	Brazil[b]	Petiole	384436
Phoma sp.[a]	Peru	Petiole	384428
Phoma spp.	Ecuador	Petiole	–
Phoma spp.	Peru	Petiole	–
Pseudocercosporella sp.	Peru	Leaf	384415
Sarocladium sp.	Peru	Petiole	–
Stagonospora sp.	Peru	Leaf	–
Stauronema sp.[a]	Peru	Petiole	384419
Basidiomycotina			
Basidiomycete sp. 1	Peru	Petiole	–
Basidiomycete sp. 2	Peru	Petiole	–
Basidiomycete sp. 3	Peru	Petiole	–
Rhizoctonia sp.	Ecuador	Petiole	–
Rhizoctonia sp.	Peru	Petiole	–
Thanetophorus sp.	Peru	Petiole	–

[a] Preliminary identification awaiting confirmation from CABI Bioscience, International Mycological Institute (Egham) or Centraalbureau voor Schimmelcultures (Baarn, Netherlands).
[b] Recent survey along the Xingu River (Pará).
[c] International Mycological Institute Herbarium
[d] – = not yet accessed in collections.

Laboratory assessment

An analysis of the fungi collected on, and isolated from, diseased water hyacinth samples in the upper Amazon basin shows some notable differences from those fungi reported from other countries or regions (see Discussion). Notable among the Amazonian records are undescribed species of *Acremonium* (2 spp.), *Fusarium* (2 spp.), *Mycosphaerella* (1 sp.) and probably undescribed taxa, belonging to the genera *Phaeoseptoria*, *Stagonospora* and *Pseudocercosporella*, since there are no previous records of these genera from *E. crassipes*. In addition, there are still some tentative identifications which may represent novel species and/or genera, and for which more taxonomic inputs are awaited. In this context, of particular interest is Hyphomycete sp. 5, which cannot be assigned to any known genus or indeed a taxonomic group. In culture, this fungus produces masses of

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hydrophobic, greenish-grey resting bodies ('sclerotia') within which are produced more thick-walled resting structures or dictyochlamydospores. It can be hypothesised that the 'sclerotia' are adapted for floating and for dispersal of the resting spores, perhaps attaching to the leaves and petioles of water hyacinth plants, but the rest of the fungal life-cycle, and specifically its invasion of the host, remains highly speculative.

Greenhouse assessment

Several of the *Acremonium* species and other verticillioid Hyphomycetes have been screened on water hyacinth plants (ex Africa) in a quarantine greenhouse facility in the UK. Only one species (*Cephalosporiopsis*) has demonstrated high pathogenicity; causing a spreading necrosis and death of inoculated, unwounded petioles. Clearly, more in-depth screening, particularly with and without wounding (to simulate insect attack), is necessary before the potential of these Amazonian fungi as biocontrol agents of *E. crassipes* can be properly evaluated.

Discussion

These essentially preliminary surveys demonstrate that there is a rich mycobiota associated with *E. crassipes* in the upper Amazon basin. Moreover, few of these species share a common link with the mycobiota recorded in other regions or countries where the plant is an alien invasive species. For example, of the ubiquitous pathogens which have been targeted and assessed as biocontrol agents of water hyacinth, only *Myrothecium roridum* has been found in both situations. This suggests that other common taxa and potential biocontrol agents such as *Alternaria eichhorniae*, *Acremonium zonatum* and *Cercospora rodmanii* (= *C. piaropi*), which have been recorded during routine surveys in the USA (Freeman et al. 1974), South Africa (Morris et al. 1999) and India (Evans 1987), are altogether absent or rare on *E. crassipes* in the upper Amazon.

Indeed, the origins and, in particular, the original host(s) of *A. eichhorniae* can only be speculated upon. Since its description on *E. crassipes* in India (Nag Raj and Ponappa 1970), it has been recorded from various countries in Africa, as well as from Egypt and the USA (Table 1). However, pathogenicity tests in the latter two countries showed contrasting results, with virulent strains being reported in Egypt (Shabana et al. 1997) but only weakly pathogenic isolates in the USA (Freeman et al. 1974). This fungus is also regarded as a weak pathogen in South Africa (Morris et al. 1999), although virulent strains have recently been found in both East and West Africa (Bateman 2001). Nag Raj and Ponappa (1970) reported that *A. eichhorniae* has a narrow host range, at least in the tests that were conducted, and attacked only a related member of the Pontederiaceae (*Monochoria vaginalis* Pers.). If *E. crassipes* is South American in origin, and if, as the present survey suggests, *A. eichhorniae* is not present in South America (or at least the upper Amazon), then what is its natural host range? A confirmed record of this species on *Bupleurum falcatum* L. (Umbelliferae) from Germany (Evans 1987) only fuels the speculation.

Despite the spectacular success of *Neochetina* weevils as classical biocontrol agents in a number of countries or regions, such control has not always proven to be sustainable or universal, and hence the search for, and assessment of, other arthropod natural enemies still continues apace (Cordo 1999; Hill and Cilliers 1999). The essentially provisional results reported here indicate that new and potentially exploitable fungal pathogens can be found in the upper Amazon basin. The case for this being the centre of origin or diversity of *E. crassipes*, therefore, has been strengthened but there are still some anomalies. For instance, two biotrophic fungi, the rust *Uredo eichhorniae* and the smut *Doassansia eichhorniae*, which were described by the great Italian mycologist R. Ciferri on water hyacinth in the Dominican Republic in the 1920s (Evans 1987), were not found during the Amazonian surveys. A rust, however, was common on *E. azurea* in the same habitats. If these represent coevolved taxa, then this would suggest that the Caribbean is the true centre of origin. Nevertheless, to support this conclusion, the host range of the rust requires clarification, and the identification of the smut needs to be verified. Unfortunately, a recent survey in the Dominican Republic failed to locate either of these natural enemies (R.W. Barreto, pers. comm.).

It is relevant here to ask whether or not classical fungal biocontrol agents could make a useful addition to the armoury to be deployed against *E. crassipes* in its exotic range, and, if so, is it an acceptable strategy? A judgment cannot yet been made on this question since classically introduced fungi have never been used for management of water hyacinth in most of the countries affected by the weed, where the introduction of exotic pathogens as biocontrol agents is still viewed with considerable scepticism (Evans 2000). However,

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based on recent results in South Africa and Australia (Evans 2000), this can be a potentially highly successful strategy and one which can be approached from three possible directions.

Firstly, the traditional classical approach can be adopted, involving the release of a virulent, coevolved fungal agent producing abundant inoculum with highly efficient dispersal and survival mechanisms, such as a rust or smut. However, from the mycobiota documented so far (Tables 1 and 2), there is no indication that a suitable candidate has been found. In fact, the majority of fungi recorded in the upper Amazon are either poor sporulators (e.g. *Didymella* and *Mycosphaerella*), producing relatively few, delicate ascospores; or possess slime-spores (conidia) which are adapted for short-distance, rain-splash dispersal only (e.g. *Colletotrichum*, *Acremonium*, *Fusarium*, *Phaeoseptoria* and *Stagonospora*). This restricted dispersal ability may account for the fact that they appear not to have spread with the plant during its migration from the headwaters of the Amazon. The exploitation of such fungi as 'classical' mycoherbicides could be considered, in which the strategy would be to spot-spray rather than blanket-spray, allowing for natural spread (rain or water-splash) within contiguous populations, and perhaps a single application, rather than repeated doses, relying on the specialised survival propagules to ensure carryover and thus provide long-term or sustainable control.

However, perhaps the most potent use of these fungi would be in conjunction with insects, as recommended by Charudattan et al. (1978), and there is evidence from the current surveys that there is a close association between certain fungal species listed in Table 2 and insect natural enemies such as *Taosa* and *Thrypticus* species. Indeed, an analysis of the early data relating to prickly pear control in Australia, reveals that success was achieved through a combination of *Cactoblastis cactorum* and the introduction of exotic microorganisms (Mann 1970).

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A Water Hyacinth Resource Manual

G. Hill[*] and R. Day[†]

PROBLEMS associated with water hyacinth infestations are well documented throughout those parts of the developing world where the weed has become a menace. Annual recurrent costs associated with water hyacinth globally have been estimated to more than US$100m (Joffe and Cooke 1997). Solutions to the problem of water hyacinth infestations are many and varied, and depend upon the particular situation in which the weed has appeared, the level of infestation, and the kinds of communities and facilities that are being affected, but are usually divided into three categories: biological control, chemical control and physical control. In addition to these, a wide range of processes and applications has been developed for the utilisation of water hyacinth.

The extensive published and unpublished literature on water hyacinth control and utilisation is characterised by a dearth of information in two key areas: 1. control decision-making and the integration of control options, and 2. the integrating of control and utilisation. To overcome these obstacles to the effective control and utilisation of the weed, we propose to develop a comprehensive, authoritative and practical water hyacinth resource manual. The manual will be targeted principally at decision-makers and project implementers in developing countries, but would have information which would be of value and interest to anyone involved in water hyacinth control and utilisation. The contents of the resource manual will include:

- details of all currently available control options;
- a guide to weed utilisation;
- guidelines for integration of different control options;
- guidelines for integration of control measures with utilisation;
- management decision aids for different infestation scenarios;
- how to design an integrated control and utilisation project; and
- a comprehensive directory of resources and information sources.

The project is a collaborative undertaking involving several organisations (CABI Bioscience, the International Union for the Conservation of Nature (IUCN), Anamed, Clean Lakes Inc., the United Nations Environment Programme) and forms part of the work program of the IUCN Africa Regional Office and the Global Invasive Species Group (GISP). It will link directly with and provide information for the IUCN initiative 'Wetlands and Harmful Invasive Species in Africa—Awareness and Information'. A team of four technical editors, assisted by a professional editor, will produce the manual. The team will include specialists in physical, chemical and biological control, wetland management and utilisation of water hyacinth. The editors will use an iterative (Delphi) process of consultation with a large group of specialists working on water hyacinth from around the world, on the content of drafts of the manual. It plans to consult widely amongst the members of the IOBC Global Working Group on Water Hyacinth. This will ensure that the contents and recommendations are as authoritative and complete as possible.

The plan is to have a first draft of the manual prepared by mid 2001, with a final publication date 9–12 months after that. Further information can be obtained from Garry Hill at <g.hill@cabi.org>.

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Water Hyacinth Information Partnership for Africa and the Middle East

L.A. Navarro*

Abstract

A 'water hyacinth information partnership' is proposed as an information–communication mechanism to facilitate timely decisions in cases of water hyacinth infestations across Africa and the Middle East. The idea arose from a consultation of stakeholders across the region, which was supported by the International Development Research Centre in 1996–1997. The proposal responds to the finding that countries across Africa and the Middle East usually start to control water hyacinth too late, after infestations have reached crises levels, despite the availability of expertise within the region. The partnership is to serve the countries as a decision-support information–communication mechanism, making the region able to detect and respond early and cost-effectively to infestations of water hyacinth in its water bodies. Its mission is to facilitate communication and exchange of information on water hyacinth among affected people, decision-makers, experts and donors, thereby contributing to control of the weed. It will serve its constituency by: facilitating their access to scientific information on water hyacinth, both biophysical and socioeconomic; raising awareness among decision-makers and leaders about the characteristics of the weed and of the implications for infested water bodies and the people who depend on them; helping to identify and mobilise expertise and resources available for the control of water hyacinth within the region and globally; calling early attention to impending water hyacinth infestations in water bodies of the region; and championing early and effective control efforts of the weed. The funding for and specific plans to install the partnership are still under discussion.

THE Water Hyacinth Information Partnership (WHIP) has been conceptualised as an information–communication mechanism to alert communities and especially decision-makers concerned with water bodies of Africa and the Middle East (AME), including Egypt, Lebanon, Syria, Jordan, Palestine and Israel, that are facing impending infestations of water hyacinth. It would also foster and facilitate quick reaction to the threat by providing countries with timely information.

The vision is that of a region that is able to halt, and it is hoped, revert the spread of water hyacinth across its water bodies, and thereby prevent water hyacinth from reaching costly crisis levels in any water body in the region.

WHIP's mission is, through the use of modern and more traditional information–communication technologies, to target and tap key sources of information and expertise on water hyacinth and to mobilise decision-makers and to stimulate efforts to control the weed. In the longer term, the expectation is that WHIP would foster and support the integrated management of water bodies and their basins to diminish soil erosion and other sources of water pollution that favour the growth of aquatic weeds.

WHIP's Origins and Rationale

The idea and concepts of WHIP emerged from a 1996–97 consultation of selected researchers, decision-

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makers, donors and community leaders concerned with water hyacinth across AME. This consultation began in late 1996 with a survey of key informants implemented by a team of 5 expert consultants across 29 countries of the region. These countries included those with the most experience of water hyacinth, such as Benin, Egypt, Kenya, Nigeria, South Africa, Sudan, Tanzania, Uganda and Zimbabwe. The consultation ended with a consultative workshop of water hyacinth experts and stakeholders ('Improving reaction to water hyacinth in affected countries across Africa and the Middle East; consultative workshop on the capability of communities, authorities and organisations to react and handle problems of water hyacinth in the region), held in Nairobi, Kenya, in September 1997 (Navarro and Phiri 2000).

The results of the survey and consultation indicated that water hyacinth was present in all 29 countries surveyed and had reached crisis levels in 21 of them.

Water hyacinth entered AME in the late 1800s in Egypt. Its spread indicates that it also later entered through other countries. The spread of the weed has accelerated and become critical since the 1980s.

Water hyacinth infestations have been worst in the intricately connected water bodies of eastern and southern Africa. The most recent hot spot, in terms of crisis water hyacinth infestation, has been Lake Victoria in East Africa.

The consultation also revealed that mechanical and labour-intensive manual methods of water hyacinth control have been the most commonly used in AME, despite their acknowledged higher costs. Chemical control was used successfully in earlier efforts to control water hyacinth e.g. in Egypt, South Africa and Zimbabwe. More recently, however, different countries have grown wary of chemical control because of concerns for potential environmental damage, and have shifted most of their interest to biological control, e.g. Lake Victoria. Countries such as Egypt have banned the use of chemicals to control water hyacinth.

Finally, the consultation made clear that, whatever type of control was used, organised and effective control of water hyacinth began only after infestations had reached crisis levels in all known cases. This happened even in cases where control has been deemed successful, such as Benin, South Africa, Sudan, Zimbabwe and, most recently, Lake Victoria. The consultation also noted that the region now has sufficient experience and expertise to manage water hyacinth infestations.

Concern about Delayed Reaction to Water Hyacinth Infestations

Delayed reaction to infestations of water hyacinth, given available capabilities in the region, was the main concern expressed by the stakeholders surveyed. Such concern arises because of the speed with which water hyacinth infestations can spread and the negative economic, social and environmental consequences of wide water hyacinth infestations.

The cumulative cost of water hyacinth infestation for countries in AME is estimated to run to billions of dollars. In the recent crisis in Lake Victoria, some estimates indicated that water hyacinth covered at least 40,000 ha at its peak, affecting the livelihoods of many fishing and other riparian communities in Kenya, Tanzania and Uganda. For example, at the end of 1997 media agencies reported a 70% decline in economic activities at the Kenyan port of Kisumu as a result of water hyacinth choking the port and fish-landing grounds. Port Bell in Kampala was also closed for periods as a result of water hyacinth mats. The water hyacinth infestation in Lake Victoria has receded recently, due to the release of two *Neochetina* weevil species.

Stakeholders consulted are aware that a quicker response would help to minimise the social, economic and environmental damage and costs of water hyacinth infestations, and that a longer term strategy is also needed. The longer term effort should foster and support a focus on the integrated management of the basins around affected water bodies to control nutrients polluting the water and stimulating water hyacinth growth. The intention is that WHIP would eventually include such concerns as part of its brief.

Reasons for Delays in Response to Water Hyacinth Infestations

The stakeholders identified institutional/organisational, technical and financial reasons for the delays in the responses to water hyacinth infestations.

Institutional/organisational reasons for delayed response were cited as the most common and widespread. These included lack of focused policies and institutional attention. Few countries have policies such as that in force in South Africa, which identify and treat water hyacinth as a menace requiring public mobilisation to control it. Usually there are too many, weak, uncoordinated and bureaucratic 'water hyacinth units', with no clear mandate or leadership. Certainly, there is a lack of early warning and information–communication mechanisms to inform decision-makers and quickly link them to sources of expertise and support when needs arise.

Technical reasons identified for delayed response included a lack of well defined integrated control strategies. Studies of control efforts, even the successful ones, reveal reliance on improvisation, with little analysis and use of existing experience. There is also an absence of information on the spread and economic, social and environmental costs of water hyacinth with which to inform and alert the public, decision-makers and donors.

Generally, however, the experts that were consulted agreed that the region already has enough experience, knowledge and expertise to control any water hyacinth infestation quickly, if these resources were mobilised on time. There is also some experience in the use of water hyacinth but the approaches involved are not yet considered to be good control options.

Financial reasons for delayed response were often cited, but not well defined. Although lack of funds was usually cited as a matter-of-fact constraint, delays have occurred even in cases where funds existed or interested donors have been ready to help. In most cases, there were other major reasons for the delay.

The Proposal

While delays in reaction to infestations with water hyacinth were the main concern, the consultation also identified an absence or tardy flow of existing information relating to water hyacinth among key players as a major contributor to the problem.

In discussions during the survey and the closing consultative workshop, stakeholders identified the development and establishment of an information–communication mechanism to foster and support timely decisions and efforts to control water hyacinth using regional capabilities, as the best immediate option to help improve the existing situation. The improvement of the information–communication flow among water hyacinth stakeholders, with a focus on the decision-makers, was identified as the point of least resistance and best option to start building on regional strengths to solve the 'problem of water hyacinth'.

The initial proposal called for developing the concepts and blueprint for a 'water hyacinth information clearinghouse'. Participants at the Nairobi workshop in 1997 requested the International Development Research Centre (IDRC) to further this proposal in consultation with other donors and partners.

Water Hyacinth Information Partnership

IDRC, through its People Land and Water program, continued consulting with other donors and partners. These consultations indicated that the concept of a clearinghouse was considered too restricted or appeared to focus only on the contributions of scientific experts on water hyacinth. Since the intention was to serve a wider constituency, a more inclusive concept was needed. Thus, the concept of an information partnership and the name of Water Hyacinth Information Partnership (WHIP) were adopted.

Vision and mission

WHIP has been conceptualised and is expected to be structured and installed as a decision–support information–communication mechanism to serve the AME region, with the vision of making the region able to detect and respond rapidly and cost-effectively to infestations of water hyacinth in the region's water bodies. As part of this, WHIP's mission is to facilitate communication and the exchange of information on water hyacinth among affected people, decision-makers, experts and donors, thereby contributing to control of the weed and minimising its effects on the well being and development of affected communities in AME.

Objective functions

As part of its mission, it is expected that WHIP will serve its constituency and especially its main users by:

- facilitating their access to biophysical and socioeconomic information on water hyacinth;
- raising awareness among decision-makers and leaders about the characteristics of the weed and of their implications for infested water bodies and for the people who depend on them;
- helping to identify and mobilise expertise and resources available for the control of water hyacinth within the region, and globally when necessary;
- calling early attention to impending water hyacinth infestations in important water bodies of the region; and
- championing early and effective control efforts of the weed when and where needed.

Structure and organisation

WHIP will be constituted by the water hyacinth stakeholders—the beneficiary groups, and an information exchange and networking service—a service group and its resources.

Water hyacinth stakeholder groups

These groups will include:

- direct beneficiaries, including leaders, community based organisations, women and other groups in communities affected by water hyacinth;
- decision makers—including policy-makers, public officers, managers, specialised research units and others responsible for monitoring or control of water hyacinth;
- expert individuals and organisations, including documentation centres, expert and research centres in universities and other units; and
- supporters, including donors, NGOs, the private sector, the media, etc.

Information exchange and networking service

An information exchange and networking service (IENS) will include the following personnel and facilities:

- a coordinator—team leader;
- secretarial, documentation and information–communication technical staff support (the service team); and
- housing facilities, equipment and materials, including a computer server and connectivity to the Internet and with stakeholders and partners.

It will deliver its services through two types of activities:

- Core activities – in a permanent alert mode, which will include:
  - updating of data on critical information needed or which can be provided by different stakeholder groups;
  - updating databases on relevant data and available literature titles and their access;
  - an awareness service to key stakeholders and general information to all stakeholders;
  - question-and-answer referral services; and
  - an Internet web site and discussion group facilitation.
- Special activities – in a championing and facilitating mode when needs or opportunities arise:
  - organisation of workshops, seminars and short courses;
  - preparation or special packaging of training materials and tool kits—production of interactive CD ROM, special web sites, etc.;
  - development of specially targeted research and intervention proposals, and contributions to fund –raising; and
  - management and implementation of special studies and projects.

Management

It is expected that the management of WHIP will be in the hands of a steering committee that represents the assembly of stakeholders and is facilitated in its functions by the coordinator of IENS. The coordinator IENS will be in charge of the day-to-day operations and delivery of WHIP plans and services.

The WHIP steering committee will represent the 'assembly' of stakeholders. It will be led by a chairperson and include a technical sub-committee and an executive sub-committee, to facilitate committee functions and support day-to-day operations.

The coordinator–team leader of IENS will have the following functions and responsibilities:

- executive secretary of the WHIP steering committee
- lead the IENS unit and implement the WHIP work program in consultation with stakeholders through the steering committee, including:
  - implementation and administration of the WHIP programs and core activities;
  - preparation of annual work plans and budgets for review and approval by the steering committee;
  - maintain contact with the steering committee during plan implementation through the technical and executive committees;
  - maintain contact with and inform stakeholders on a continuous basis;
  - champion and facilitate special activities, according to plans;
  - facilitate steering committee meetings; and
  - facilitate fund-raising.

Estimated budget and issues to be resolved

As result of the consultations and discussions to date, the suggestion is to obtain support to install and operate the WHIP for an initial period of five years. Given the level of activities and the cost of personnel, equipment and other support anticipated for the initial five years, the estimated budget is US$1.5m.

The following issues remain to resolved :

The host institution. Several institutions have evinced interest in housing WHIP. The initial idea was that IDRC would house WHIP temporarily, allowing

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time for discussions among the different stakeholders to agree on a final location. Later ideas have suggested that the decision about where to house WHIP must be taken immediately. Thus accelerated consultations are required to reach agreement on this.

Water hyacinth only or invasive water weeds in general? A second interest emerging among stakeholders has been to extend the coverage of WHIP to other invasive water weeds. This would seem to be a rational extension of the coverage, but more discussion is needed to make sure that such a move would not obstruct the implementation of WHIP effort. The main questions relate to the implications of this idea on budgetary and organisational matters, and on strategies for fund raising and allocation.

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Can Competition Experiments Be Used to Evaluate the Potential Efficacy of New Water Hyacinth Biological Control Agents?

T.D. Center*, T.K. Van*, and M.P. Hill†

Abstract

Two factors are of concern when considering a new biological control agent for introduction. The first is the safety of the organism (i.e. its host specificity) and the second is the potential for the organism to control the target weed (i.e. its efficacy). Methods for evaluating safety before introduction are well known but scant attention has been paid to pre-release evaluation of the efficacy of the candidate organisms. This is understandable inasmuch as the agent's performance depends on the presence or absence of density-dependent population regulating factors that will differ between the donor area and the recipient country. However, this is of less concern when the agent has already been introduced elsewhere, where it can be studied without the influence of density-dependent regulators. Experiments comparing the effectiveness of the new agent with that of another, more widely known agent, can then be used to determine the relative value of the former with the known impacts of the latter. Additive series analysis (inverse linear models) of competition between water hyacinth and water lettuce as mediated by herbivory has been suggested as a means of judging the relative value of new agents. This approach is fraught with difficulties inasmuch as there will always be unknown factors that affect the abundance of new agents (i.e. biotic resistance), but it could enable assessment of the *potential* value of the proposed introduction and, in so doing, perhaps pre-empt the introduction of risky agents that provide little control value.

CLASSICAL biological control of a pestiferous non-native plant involves the deliberate introduction of plant-feeding insects, mites, or phytopathogens (collectively called biological control agents, or herein, bioagents) from foreign sources to provide previously missing density-dependent regulation of the pest species in its adventive range. Typically, the bioagent is derived from within the native range of the pest and introduced into a new area where control is needed. The safety of the introduced organism is of utmost concern inasmuch as economically or ecologically important non-target plant species in the recipient region may be at risk, and this risk escalates as more and more agents are introduced. Thus, it is essential to introduce the least number of species needed to provide the control needed. In order to minimise the number of introductions, it would be useful to determine beforehand which species, from among the cadre of potential bioagents available, would be the most effective. While this is often called for (Harris 1973), it is seldom done.

Techniques for determining the safety of a bioagent, in terms of its fidelity towards the use of the target plant, consist mainly of bioassays of host specificity. These 'host-specificity tests' have a long history of use and are very predictive (Pemberton 2000).

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However, standardised methods for evaluating the potential impact of candidate bioagents are lacking. Harris (1973) and later Goeden (1983) attempted to develop a scoring system based on specific attributes of the candidate agents. Both systems emphasised the amount of damage done to the plant on a per insect basis or the capacity for population growth of the agent. Unfortunately, these tended to be 'one size fits all' and failed to take into account the uniqueness of each weed–insect association. As a result, while they do provide 'rule-of-thumb' guidelines, these scoring systems are otherwise of limited usefulness. Among other things, they fail to consider compensatory abilities and complementary characteristics of the various target plants, which render them vulnerable (or not) to damaging effects of the agents. In other words, in order to be effective, the damage done by the agent must be directed towards the invasive attributes of the plant that enable it to dominate, so a useful scoring system must be tailored to each weed target. This is difficult, at best, especially when, at the outset of a project, so little is usually known about these agents and the target plant.

There are few alternatives for directly assessing the value of a new, previously unused bioagent. Any such appraisal must mimic a true biological control scenario in which the population increase of the agent is not limited by density-dependent regulators, thus enabling their populations to attain greater densities than those normally found in the native environment. Such assessments, which are best done under natural circumstances, may be difficult to accomplish in the native range of the bioagent, because of the presence of density-dependent regulators that pre-empt buildup of the bioagent's population and therefore fail to simulate a true introduction scenario involving hyper-abundant bioagent populations. Furthermore, any such assessment must be sensitive to subtle effects of the bioagents, so as not to disqualify those that might provide important, long-term effectiveness.

We propose direct experimentation to provide data on the relative value of one agent compared to another. This does not resolve the difficulties involved in doing the studies in the native area, but this approach is quite possible when the agent has been previously introduced elsewhere and is being considered for introduction into a new area. The mirid bug *Eccritotarsus catarinensis* provides a useful example. It was first introduced into South Africa and is being considered for introduction into North America. Laboratory-based host-specificity testing showed that it fed and developed on pickerelweed, a valued North American native plant. Follow-up field studies in South Africa revealed that, while it might spill-over to pickerelweed when adjacent to heavily infested water hyacinth mats, it did little damage and did not colonise isolated pickerelweed stands (Hill et al. 2000). Thus, it seems as though this agent might, in fact, be safe to release in North America. However, the host-specificity data clearly indicate that there is some risk to pickerelweed. Considering that pickerelweed is severely damaged by drifting water hyacinth mats as well as by herbicidal control operations directed against water hyacinth, this risk might be worth taking. The decision to release the mirid must therefore weigh the potential damage to pickerelweed against the benefit that it might provide. However, the effectiveness of the mirid is not yet known. We are proposing to compare the effects of the mirid with the effects of the better-known bioagent, the weevil *Neochetina eichhorniae*, on the competitive relationship between water hyacinth and water lettuce. In so doing, we hope to determine whether the mirid would be more or less effective than the weevil and to quantify the difference.

The effects of the mirid are likely very subtle. It is a quite small insect that causes little damage per individual, which is neither overt nor easily quantified. It feeds on leaf surfaces by sucking plant juices, creating brownish patches that vary in extent and intensity (similar to spider mite damage). While this damage may be debilitating to some degree, it does not seem lethal. In situations such as this, competition studies may be able to detect these subtle effects by measuring the reduction of the plant's competitive ability against another aggressive species. Pantone et al. (1989) proposed the use of additive series experiments analysed using inverse linear models to evaluate the efficacy of bioagents before release (although they did not address the aforementioned difficulties in doing these studies in the agent's native range). They further demonstrated the utility of the method by detecting the effects of a nematode on competition between the fiddleneck weed and wheat. It thus occurred to us that this approach might be useful for determining the value of the water hyacinth mirid. We have used this model previously (Van et al. 1998, 1999) to compare the influence of two hydrilla biological control agents and to investigate the effect of soil fertility on competition between the two aquatic plants *Hydrilla verticillata* and *Vallisneria americana*.

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Additive Series Competition Experiments and the Inverse Linear Model

Pantone et al. (1989) provided a thorough explanation of additive series competition experiments and the application of the inverse linear model. Their paper should be consulted for details. Competition experiments involve planting mixtures of two plant species and, after a period of growth, measuring yield components of each species and comparing them between species. Additive series competition experiments differ from replacement series competition experiments in that the total number of plants used for the two species varies as the mixture ratio increases (i.e. 3 of species A vs. 0 of B for 3 total; 3 of A vs. 3 of B for 6 total; 3 of A vs. 6 of B, or 9 total; etc.). In contrast, replacement series experiments use a constant total number of plants while the ratio of the two varies. Pantone et al. (1989) used the mixtures given in Table 1 in their additive series experiments

Table 1. The additive series planting ratios of wheat and fiddleneck used by Pantone et al. (1989)

Wheat	Fiddleneck			
	:0	:20	:80	:160
0:		0:20	0:80	0:160
20:	20:0	20:20	20:80	20:160
80:	80:0	80:20	80:80	80:160
160:	160:0	160:20	160:80	160:160

A control series was planted without nematodes and a duplicate second series (treatment) was planted and the plots were inoculated with 10^6 fiddleneck gall nematodes (*Anguina amsinckiae*). Plants were harvested after 5–6 months and average yield per plant (Y) was measured in terms of shoot dry weight, seed number, and total seed biomass per plant.

Data were analysed using multiple linear regressions of the inverse of the yield component as the dependent variable and the planting density of wheat and fiddleneck as two independent variables as such:

$$1/Y_f = a_{fo} + a_{ff}d_f + a_{fw}d_w$$

$$1/Y_w = a_{wo} + a_{ww}d_w + a_{wf}d_f$$

Here Y_f is the average yield per plant for fiddleneck, Y_w is the average yield per plant for wheat, d_f is the planting density of fiddleneck, and d_w is the planting density for wheat. The coefficients a_{ff} and a_{ww} measure intraspecific competition of fiddleneck and wheat, respectively. The coefficient a_{fw} measures the interspecific effect of wheat on fiddleneck yield, and the coefficient a_{wf} measures the interspecific competitive effect of fiddleneck on wheat yield. The ratio a_{ff}/a_{fw} measures the effects of intraspecific competition of fiddleneck on itself relative to the interspecific competition of wheat on fiddleneck. In other words, it equates the competitive effect of a single fiddleneck plant with the number of wheat plants that would be expected to have an equivalent effect on fiddleneck yield (i.e. it takes x number of wheat plants to produce the same effect as a single fiddleneck plant on fiddleneck yield). Likewise, the ratio a_{ww}/a_{wf} measures the effect of wheat on wheat yield relative to the effect of fiddleneck on wheat yield. The data can be graphically analysed as a 3-dimensional surface response plane for each plant species in which the slope in one direction represents the effect of the species own density upon its yield (intraspecific competition) and the slope in the other direction represents the effect of the competing species (interspecific competition). It must be borne in mind that, because the inverse of the dependent variable is used, a higher value represents a lower yield. Likewise, a steep slope represents a strongly reduced yield in response to increasing plant density. Results of one of the experiments conducted by Pantone et al. (1989) are presented in Table 2. Note that increasing fiddleneck density strongly reduced fiddleneck yield per plant, as evidenced by the steep slope reflected in the coefficient a_{ff}, when nematodes were absent. However, the effect of wheat on fiddleneck yield per plant was slight. The ratio of the two values (a_{ff}/a_{fw}) indicates that the effect on fiddleneck yield of increasing the density of fiddleneck by a single plant was equivalent to increasing the density of wheat by 33 plants. When nematodes were present, however, the effects of the two species were similar, as reflected by the ratio of the two coefficients being near unity.

The complementary analysis similarly indicates that the interspecific effect of fiddleneck on wheat yield was much greater than the intraspecific effect of wheat on itself. Increasing the density of wheat by one plant had the equivalent effect on wheat yield of adding 0.3 fiddleneck plants. When nematodes were present this increased to 0.72 fiddleneck plants.

Recently, similar experiments have been done in Florida (Van, unpublished data) to examine the effects of the weevil *N. eichhorniae* on competition between water hyacinth and water lettuce (*Pistia*

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stratiotes) (Table 3). In this example, without weevils, increasing the density of water hyacinth by one plant produced 18.5 times the effect on water hyacinth yield of increasing the water lettuce density by one plant. In other words, it required nearly 20 water lettuce plants to produce the equivalent effect of a single water hyacinth plant on water hyacinth yield. With weevils in the system, however, water hyacinth remained the superior competitor but its advantage was reduced to less than 2 to 1. Likewise, without weevils an increase in water lettuce density of one plant affected water lettuce yield by an amount equivalent to only 0.15 water hyacinth plants (or 7 water lettuce plants were required to produce the effect of 1 water hyacinth plant) but with weevils present this ratio increased to nearly unity.

Clearly, these analyses provide a useful way of assessing the impact of a bioagent on two-species competition, but can they be used to compare bioagents? The studies by Van et al. (1998) indicate that they can. They compared two hydrilla control agents in terms of their effects on competition between *H. verticillata* and *V. americana*. They showed that, in the absence of bioagents, intraspecific competition by *Hydrilla* on itself was 8.3 times stronger than interspecific competition from *Vallisneria*. In the presence of the leaf-mining fly, *Hydrellia pakistanae*, however, intraspecific and interspecific effects were nearly equal (a_{hh}/a_{hv} = 1.3). The weevil *Bagous hydrillae* produced a much smaller shift in the competitive balance (a_{hh}/a_{hv} = 7.6), which was not much different from the control. As a result, one might conclude that the fly is nearly six times better than the weevil, in terms of its ability to alter the competitive balance between these two plant species.

Given the positive results of these studies, we are now comparing the two species of *Neochetina* (*N. eichhorniae* vs. *N. bruchi*) in terms of their ability to alter the competitive relationship between water lettuce and water hyacinth. The results are not yet in. This experiment involves 96 experimental units (8 planting densities × 4 insect levels × 3 replicates). The 8 planting densities (the minimum necessary) encompass factorial combinations of 0, 3, or 9 water hyacinth and water lettuce plants (minus the 0:0 combination). The insect treatments consist of *N. eichhorniae* alone, *N. bruchi* alone, both species together, or neither species (as a control).

The logistics of setting up such a large experiment have been difficult. Nevertheless, if this experiment produces useful results, we are planning a similar experiment to be conducted in South Africa to

Table 2. Regression coefficients from analyses of the effects of nematodes and plant density on reciprocals of the biomass yields of wheat or fiddleneck (from Pantone et al. 1989)

Plant	Treatment	Regression coefficients					
		a_{ff}	a_{fw}	a_{ff}/a_{fw}	a_{ww}	a_{wf}	a_{ww}/a_{wf}
Fiddleneck	Control	8.24	0.25	33.0			
	Nematode	8.76	8.40	1.04			
Wheat	Control				4.97	16.4	0.30
	Nematode				5.81	8.09	0.72

Table 3. Regression coefficients from multiple regression analyses of the impacts of weevils and plant density on the reciprocal biomass yield of water hyacinth and water lettuce (from Van, unpublished data)

Plant	Treatment	Regression coefficients ($\times 10^{-3}$)					
		a_{ww}	a_{wl}	a_{ww}/a_{wl}	a_{ll}	a_{lw}	a_{ll}/a_{lw}
Water hyacinth	Control	0.943	0.051	18.5			
	Weevil	3.72	2.28	1.63			
Water lettuce	Control				9.41	62.1	0.15
	Weevil				3.24	3.52	0.92

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compare the mirid with *N. eichhorniae*. In so doing, we hope to quantify the effect of the mirid relative to the effect of the weevils using the weevil as a standard. However, this involves another difficulty: how to determine the numbers of each insect species to be used when two very different plant-feeding insects are involved. In the case of the two *Neochetina* species, this is not a problem. Both are about the same size and produce the same type of damage. However, comparing the chewing damage of the larger weevils with the sap-sucking damage of the tiny mirid is another matter. Is it appropriate to merely use the same number of each species, despite the size difference and the disparity in the type and amount of damage? Would it be better to introduce equivalent weights of both species? Obviously, it would be best to use a range of infestation levels of each insect to measure the densities of each needed to produce equivalent effects, but the size of the experiment then becomes prohibitive. These and many other questions must be resolved before proceeding with plans for this experiment.

It is important to keep the limitations of these experiments in mind. First, cages are used and several types of cage effects could lead to erroneous conclusions. Secondly, the experiments described above include only a few of the multitude of environmental parameters that might affect the outcome of competition. The effects of the insects might be compromised, for example, by high or low nutrients, but incorporation of a nutrient treatment in the experiment design would at least double the size to 192 experimental units in the case of the two-weevil experiment described above. Thus, while it is important, if possible, to retain the full additive series so as to produce comparable regression coefficients, it might not be possible to answer all pertinent questions in this manner. We are therefore considering additional experiments with varying nutrient levels but fixed combinations of the two plant species for comparisons between *N. eichhorniae* and *N. bruchi.* This is less desirable, but much more practical.

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How Safe Is the Grasshopper *Cornops aquaticum* for Release on Water Hyacinth in South Africa?

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Abstract

The grasshopper *Cornops aquaticum* is currently being considered as a natural enemy for water hyacinth in South Africa. Both the adults and the nymphs are very damaging to water hyacinth plants. The laboratory host range was determined through nymphal and adult no-choice trials. The test plants were selected on relatedness to water hyacinth, similarity in habitat and on economic importance. Full nymphal development was recorded on *Heteranthera callifolia, Pontederia cordata* (pickerelweed) and *Canna indica* (canna) under quarantine laboratory conditions. Pickerelweed and canna are introduced species and are potentially invasive in South Africa, and are therefore of no conservation concern. Of the other native African Pontederiaceae, *Eichhornia natans* supported development of the grasshopper nymphs, but the lack of emergent leaf material suggests that the plant will not sustain a population, and *Monochoria africana* did not support full development of the nymphs. The adult females were not able to oviposit on the thin petioles of *Heteranthera callifolia* and only one eggpacket was recorded on *Monochoria africana,* suggesting these two species are not at risk. Results from the region of origin show that *C. aquaticum* is an oligophagous insect on the Pontederiaceae family of plants, with a strong preference for water hyacinth. In South Africa we intend to conduct further nymphal and adult choice trials which will better represent the field situation to further quantify the risk to native Pontederiaceae.

WATER hyacinth is considered to be the most important aquatic weed in the world (Center 1994; Wright and Purcell 1995). In South Africa, it was first recorded in the early 1900s. Since then the weed has become invasive throughout southern Africa, mainly as a result of human activities (Jacot Guillarmod 1979). Attempts to control the weed have led to different control options being developed, including herbicidal control, mechanical control and biological control. In South Africa, the biological control program has been in place since 1974, with an interruption of 8 years between 1977 and 1985 (Hill and Cilliers 1999). In the course of the program, five arthropod natural enemies were released against the weed: *Neochetina eichhorniae*, *Neochetina bruchi*, *Orthogalumna terebrantis*, *Eccritotarsus catarinensis* and *Niphograpta albiguttalis*. Even with these species released there is a perception that, in South Africa, the correct 'suite' of insects to biologically control the weed has not been introduced. As a result, additional natural enemies are being sought for control of water hyacinth. In this paper we discuss the suitability of *Cornops aquaticum*, a grasshopper species, for release in southern Africa.

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Information from the Literature

Cornops aquaticum was identified by Perkins (1974) as being one of the most damaging insects associated with water hyacinth in the plant's region of origin. However, it appears that fears regarding this insect's host specifi-

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city have prevented it from being given serious consideration as a biological control agent for the weed. Silveira Guido and Perkins (1975) investigated the biology and host specificity of *C. aquaticum* and found that, under laboratory starvation trials, it was able to feed and develop on three species within the Commelinaceae and also on the following species in the Pontederiaceae (*Eichhornia azurea, Eichhornia crassipes* and *Pontederia cordata*). Limited feeding, but no development, was recorded on rice and sugarcane.

Laboratory Determination of Biology

The grasshopper was collected from Brazil (1995), Trinidad and Venezuela (1996) and Mexico (1997) and imported into quarantine in South Africa. The adult female inserts its eggs into the base of the petiole. According to Silveira Guido and Perkins (1975) the endophytic position of the egg packets provides moisture for development and the arenchyma tissue of the water hyacinth petiole prevents excess water uptake. This might well be significant in the host specificity of the insect, as it appears as if the adult female has very specific ovipositioning requirements. These requirements are unlikely to be present in plant species outside of the Pontederiaceae. The egg cases are produced inside a case of foamy substance, that functions as a 'plug' to encapsulate the eggs. The oviposition site is identifiable by this plug, which the female uses to cover the oviposition hole. Eggs that were not oviposited within the plant tissue did not develop.

An incubation period of 25–30 days was recorded. Newly emerged nymphs begin to feed immediately on the water hyacinth leaves. There are 6–7 instars (usually 6) which range in length from 6–8 mm in the 1st instar to 25–30 mm in the 6th instar. The adults are long lived (55–110 days) and the females produce a high number of offspring: between 60 and 560. The insects are highly mobile and very damaging to water hyacinth, both as adults and throughout the immature stages.

Laboratory Host Specificity

Nymphal no-choice trials

Host range was determined through nymphal no-choice trials on 64 plants in 32 families, selected on relatedness to water hyacinth, similarity in habitat and economic importance (Table 1). Details of the development of *C. aquaticum* adults from no-choice nymphal starvation trials are presented in Table 2. Five newly hatched, first-instar nymphs were placed on each of the test plant species. Feeding damage, nymphal development and mortality were recorded daily.

On the majority of species tested, no feeding was recorded and the nymphs died within the first week. Nymphal feeding was recorded on several species outside the Pontederiaceae family. Some nibbling was recorded on rice and cabbage, but no development was recorded. A few nymphs developed to 2nd instar stage on radish, 3rd instar stage was reached on *Nerine* sp. (Amaryllidaceae) and 4th instar stage on *Commelina africana* and *Murdannia simplex* (both Commelinaceae). Complete nymphal development occurred on *Canna indica*, but the surviving number was low compared with survival on water hyacinth. Feeding and development were also recorded on pickerel weed, but nymphal survival was low compared with nymphal survival on water hyacinth. Of 50 nymphs placed on banana, one developed to adulthood.

Of the native Pontederiaceae, feeding was recorded on *Eichhornia natans* but, compared with water hyacinth, the plant produces very little emergent leaf material on which the nymphs can develop completely. This species also has a slender petiole that is submerged below the water and will not support ovipositioning. Limited feeding and development were recorded on *Monochoria africana*. The insects preferred to feed on the epidermis of the petiole, and although this was damaging to the plant, it seemed to provide the nymphs with insufficient nutrition to develop. Full nymphal development was recorded on *Heteranthera callifolia* and although it was lower than on water hyacinth it is still reason for concern.

Adult no-choice trials

Among the 16 species tested, oviposition was recorded on water hyacinth, *M. africana* and pickerel weed (Table 3). Only a few eggs were recorded on pickerelweed, and only one eggpacket was recorded on *M. africana.* Oviposition probes are holes made by females looking to lay eggs at the base of the petiole. Probes were recorded on water hyacinth, *M. africana* and pickerelweed. It appears as if the internal structure of the *M africana* petioles is not suitable for oviposition. In several replicates of non-target species, egg cases were laid on the sides of the cages and pots, indicating that the females were under oviposition stress and plants presented to them did not offer suitable oviposition sites.

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Table 1. Results of the first instar nymph[a] host-specificity tests of *Cornops aquaticum* on selected plant species

Plant species	No.	Common name	Feeding	Development
Aponogetonaceae				
Aponogeton distachyos L.	10	Cape pondweed	0	0
Alismataceae				
Alisma plantago-aquatica L.	6	Water alisma	0	0
Poaceae				
Zea mays L.	10	Maize	0	0
Arundo donax L.	10	Spanish reed	0	0
Phragmites australis (Cav.) Steud.	10	Reed	0	0
Oryza sativa L.	8	Rice	+	0
Saccharum officianum L.	5	Sugarcane	0	0
Araceae				
Zanthedeschia aethiopica (L.) Spreng.	20	Arum Lily	0	0
Colocasia esculenta L. Schott	15	Taro	0	0
Zamioculcas zamiifolia (Lodd.) Engl.	7		0	0
Stylochiton sp.	7		0	0
Restionaceae				
Elegia racemosa (Poir) Pers.	5	Restio	0	0
Eriocaulaceae				
Eriocaulon dregei Hochst var *sonderanium* (Körn) Oberm.	5		0	0
Commelinaceae				
Commelina africana L.	14		+	0
Murdannia simplex (Vahl) Brenan	3		+	+
Pontederiaceae				
Eichhornia crassipes (Mart.) Solms-Laub.	45	Water hyacinth	+	+
Eichhornia natans (P. Beauv.)	6		+	0
Monochoria africana (Solms- Laub.) N.E.Br	5		+	+
Heteranthera callifolia Kunth	5		+	+
Pontederia cordata L.	10	Pickerelweed	+	+
Juncaceae				
Juncus kraussi Hochst. subsp. *krausii*	5	Rush	0	0
Colchicaceae				
Gloriosa superba L.	7	Flame lily	0	0
Asphodelaceae				
Chlorophytum comosum (Thunb.) Jacq.	6	Hen and chickens	0	0
Alliaceae				
Agapanthus africana (L.) Hoffing	10	Agapanthus	0	0
Allium ampeloprasum (L.)	5	Leek	0	0
Allium cepa L.	5	Onion	0	0

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Table 1. (Cont'd) Results of the first instar nymph[a] host-specificity tests of *Cornops aquaticum* on selected plant species

Plant species	No.	Common name	Feeding	Development
Liliaceae				
Kniphofia linearifolia Bak.	6	Red-hot poker	0	0
Tulbachia sp.	10		0	0
Euricomis sp.	10		0	0
Lillium sp.	10		0	0
Bulbine sp.	6		0	0
Aloe sp.	5		0	0
Behnia reticulata Didrichs	5		0	0
Asparagus officinalis L	5		0	0
Amaryllidaceae				
Crinum bulbispermum (Burm. f.)	10	Orange River lily	0	0
Clivia minata (Lindl.)	10	Bush lily	0	0
Nerine sp.	5		+	+
Hypoxidaceae				
Hypoxis sp.	5		0	0
Iridaceae				
Watsonia sp.	5		0	0
Musaceae				
Musa paradisica L.	10	Banana	+	+
Cannaceae				
Canna indica L.H. Bailey	10	Canna	+	+
Chenopodiaceae				
Beta vulgaris L. var. *cicla*	10	Spinach	0	0
Euphorbiaceae				
Manihot esculenta Crantz	5	Cassava	0	0
Brassicaceae				
Raphanus sativus L.	10	Radish	+	+
Brassica oleracea L.	7	Cabbage	+	0
Brassica rapa L.	5	Turnip	0	0
Leguminaceae				
Pisum sativum L.	10	Pea	0	0
Phaseolus vulgaris L.	10	Bean	0	0
Onagraceae				
Ludwigia stolonifera (Guill. & Perr.) Raven	5		0	0
Trapaceae				
Trapa natans L. var *bispinosa* (Roxb) Makino	5	Water chestnut	0	0
Halorgidaceae				
Laurembergia sp.	5		0	0

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Table 1. (Cont'd) Results of the first instar nymph[a] host-specificity tests of *Cornops aquaticum* on selected plant species

Plant species	No.	Common name	Feeding	Development
Apiaceae				
Daucus carota L. var. *sativus*	10	Carrot	0	0
Hydrocotyle sp.	5		0	0
Solanaceae				
Lycopersicon lycopersicum (L.)	10	Tomato	0	0
Solanum melogena L. var. *sativus*	10	Eggplant	0	0
Capsicum annuum L.	10	Pepper	0	0
Rubiaceae				
Coffea sp.	5	Coffee	0	0
Cucurbitaceae				
Cucurbita pepo L.	5	Marrow	0	0
Cucumis sativus L.	5	Cucumber	0	0
Citrillus lanatus (Thunb.)	5	Watermelon	0	0
Asteraceae				
Lactuca sativa L. var. *capitata*	10	Lettuce	0	0

a. Five first instar nymphs per replicate

Table 2. Mean number of *Cornops aquaticum* adults reared from plant species during no-choice nymphal starvation trials

Plant species	No.	Mean number of adults/replicate[a,b]
Eichhornia crassipes	45	3.47 (0.93)
Heteranthera callifolia	6	2.8 (1.21)
Pontederia cordata	10	1.60 (1.08)
Canna indica	10	1.10 (1.45)
Musa paradisica	10	0.02 (0.14)

a. Five first-instar nymphs were used per replicate.
b. Figures in parentheses represent the standard deviation.

Field observations in the region of origin

Observations of host range were made at several localities in northern Argentina and in Peru.

In Argentina, 28 sites were surveyed. Of all the insect species surveyed, at all the sites *Cornops aquaticum* was considered to be the most damaging to water hyacinth. *Cornops aquaticum* was also found to be widespread and abundant on water hyacinth. Egg cases were recorded on water hyacinth, *Eichhornia azurea* and pickerel weed. The insect was found to be less abundant on pickerel weed, suggesting it is an inferior host. *Cornops aquaticum* was not recorded on *Canna glauca* or the two *Commelina* species even when growing close to water hyacinth supporting high populations of the grasshopper.

In Peru, 30 sites were surveyed. *Cornops aquaticum* was recorded on water hyacinth and *Pontederia rotundifolia.* The grasshopper was abundant on *P. rotundifolia* and caused severe damage to plants. The predaceous weevil, *Ludovix fasciatus,* was also found, and even with its presence *Cornops aquaticum* was still abundant.

Discussion

Cornops aquaticum is a very damaging natural enemy of water hyacinth and is likely to make a valuable contribution to the control of this weed in South Africa. This is evident from the fact that, despite being heavily parasitised by the weevil *Ludovix fasciatus* in its region of origin, it is still abundant and damaging to water hyacinth. This weevil is not present in South Africa, so it is predicted that the impact of the grasshopper on water hyacinth would be greater.

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Table 3. Mean number of *Cornops aquaticum* adults surviving and egg cases laid on test plant species during adult, no-choice trails. Two pairs of adults were used per replicate and each replicate lasted seven days.

Plant species	Common name	n	Mean number of egg cases/ replicate[a]	Mean number of probes/ replicate[a]
Eichhornia crassipes	Water hyacinth	8	5.21 (3.56)	3.67 (3.27)
Monochoria africana		6	0.04 (0.19	2.83 (1.72)
Heteranthera callifolia		6	0.00 (–)	0.00 (–)
Eichhornia natans		3	0.00 (–)	0.00 (–)
Pontederia cordata	Pickerel weed	4	2.02 (0.80)	3.45 (1.67)
Canna indica	Canna	8	0.00 (–)	0.00 (–)
Musa paradisica	Banana	6	0.00 (–)	0.00 (–)
Commelina africana		8	0.00 (–)	0.00 (–)
Murdannia simplex		4	0.00 (–)	0.00 (–)
Zea mays	Maize	3	0.00 (–)	0.00 (–)
Raphanus sativus	Radish	3	0.00 (–)	0.00 (–)
Brassica oleracea	Cabbage	5	0.00 (–)	0.00 (–)
Nerine sp.		4	0.00 (–)	0.00 (–)
Oryza sativa	Rice	6	0.00 (–)	0.00 (–)
Zanthedeschia aethiopica	Arum lily	3	0.00 (–)	0.00 (–)
Colocasia esculenta	Taro	3	0.00 (–)	0.00 (–)

a. Figures in parentheses represent the standard error.

The indigenous *Eichhornia* species in Africa, *Eichhornia natans*, supports development of the grasshopper nymphs, but the lack of emergent leaf material and the submerged petioles suggest that the plant will not sustain a population of *C. aquaticum* in the field. Of the other plants in the Pontederiaceae in Africa, *M. africana* does not support full development of the nymphs, and *H. callifolia,* although heavily attacked, did not support oviposition and is considered to be inferior to water hyacinth as a host.

Cornops aquaticum is considered to be oligophagous on Pontederiaceae and should be released only in countries that do not have native Pontederiaceae or where the spillover feeding on native Pontederiaceae would be tolerable. Silveira Guido and Perkins (1975) found that, under high population levels in the laboratory, nymphs fed on members of the Commelinaceae, rice and sugarcane in the Gramineae, and *E. azurea* and *P. cordata* in the Pontederiaceae. However, development was recorded only on *Commelina* spp. outside of the Pontederiaceae. Under performance, or choice tests, they found that damage occurred to the same *Commelina* species and to rice and sugarcane. While we recorded some nibbling on rice, we have not recorded any feeding on sugarcane. Furthermore, Bennett (1970) found that only water hyacinth was attacked during choice tests with other species.

The host-specificity testing of this insect is incomplete. However, despite relying on the most conservative host-specificity tests (nymphal starvation trials) the insect has shown a high degree of specificity to water hyacinth.

Future Research

The emphasis in future research will be on the testing of the insect under more natural conditions. These tests might give less ambiguous results that would clarify the host specificity of *C. aquaticum.* Open field trials in the region of origin are an option, while we believe that choice trials with adults and nymphs will clarify these results (Marohasy 1998). Tests will be conducted using native Pontederiaceae from the southern African region, water hyacinth, canna and banana. All these plants showed development of the nymphs. Special attention will be given to development and ovipositioning of *Cornops aquaticum* under open field conditions.

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Establishment, Spread and Impact of *Neochetina* spp. on Water Hyacinth in Lake Victoria, Kenya

G.S. Ochiel*, S.W. Njoka*, A.M. Mailu† and W. Gitonga‡

Abstract

The Kenya Agricultural Research Institute imported 12,300 curculionid weevils (*Neochetina* spp.) from diverse sources, for biological control of water hyacinth in Lake Victoria, as part of the World Bank-funded Lake Victoria Environmental Management Project in East Africa. In addition to the rearing and quarantine facility at Muguga, a second rearing facility was established in 1996 at Kibos, near Lake Victoria. The Kibos rearing facility and two community rearing facilities at the lakeshores, have produced approximately 100,000 adult weevils and 42,000 weevil eggs over a three-year period. Since January 1997, some 73,500 *Neochetina* weevils have been released at 29 sites and an additional 10,000 redistributed at several sites. Visual observations and regular sampling monitored the establishment and spread and also evaluated the impact of *Neochetina* weevils on water hyacinth. Within two years, weevils were established at 55% of release sites and were being recovered 50 km from release sites. Post-release sampling data from four release sites in Berkeley, Kisumu and Kendu bays, indicated a reduction in leaf length, laminar area and fresh weight of water hyacinth, and a significant increase in number of weevil feeding scars and adult weevils per square metre. Three years after the initial weevil releases, the combined mean number of weevils per plant for Kisumu, Nyakach, Kendu and Homa bays, was estimated to be six, well above the critical threshold of five weevils per plant. *N. bruchi* was the dominant species accounting for 73.3% of the total weevil population. Thus, under Lake Victoria conditions, the critical threshold was attained within 2–3 years of the initial releases.

LAKE Victoria (area ca 69,000 km^2), shared by the three East African countries, Kenya (6%), Uganda (43%) and Tanzania (51%), is the world's second-largest freshwater lake (Figure 1). In 1989, it was invaded by water hyacinth and its presence in the Kenyan part was confirmed in 1992. The origin of the infestation is presumed to be in the River Kagera Basin in Rwanda. At peak infestation in 1997, the area covered by the weed in East Africa was more than 15,000 ha. The tropical aquatic weed of South American origin, has adverse impacts on the health, energy, water and transport sectors (Harley 1990; Harley et al. 1996). The weed presented an enormous challenge for biological control in East Africa.

As early as 1993, the Kenya Agricultural Research Institute (KARI) imported water hyacinth weevils, *Neochetina bruchi* and *N. eichhorniae*, from the Plant Health Management Division of the International Institute for Tropical Agriculture in Benin. These weevils, considered the most important biological control agents against the water hyacinth, have had notable success outside East Africa (Harley 1990; Julien and Griffiths 1998; Julien et al. 1999). However, host-spe-

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cificity tests were ordered in Kenya and Uganda, before releases in Lake Victoria were allowed.

Neochetina weevils were released in Lake Kyoga, Uganda in 1993 (Ogwang and Molo 1997, 1999) and in Lake Victoria in 1996 (James Ogwang, pers. comm.). The first weevil releases in Kenya were in Lake Naivasha, which had water hyacinth since the mid 1980s (Aggrey Mambiri, pers. comm.). *Neochetina* weevils were released in the Kenyan part of Lake Victoria in 1997 (Ochiel et al. 1999; Mailu et al. 1999), while in Tanzania, Mallya (1999) reported the releases of *Neochetina* weevils in the Pangani and Sigi rivers in 1995, and in Lake Victoria in 1996.

This paper presents recent results from a program of classical biological control against water hyacinth in Lake Victoria, implemented by KARI under the Lake Victoria Environmental Management Project.

Materials and Methods

Mass rearing and releases of *Neochetina* spp.

Since 1996, Kenya Plant Health and Inspectorate Services has allowed KARI to import adult *N. bruchi* and *N. eichhorniae* from Uganda, South Africa and Australia for the biological control of water hyacinth in Lake Victoria. KARI established a second weevil rearing facility in December 1996, at the National Fibre Research Centre (NFRC), Kibos, near Lake Victoria. 'Breeding stock' for the Kibos rearing facility was obtained from the quarantined mass-rearing facility at the National Agricultural Research Centre, Muguga, near Nairobi. The breeding material consisted of mature adult *Neochetina* weevils and host plants inoculated with weevil eggs. Later, adult

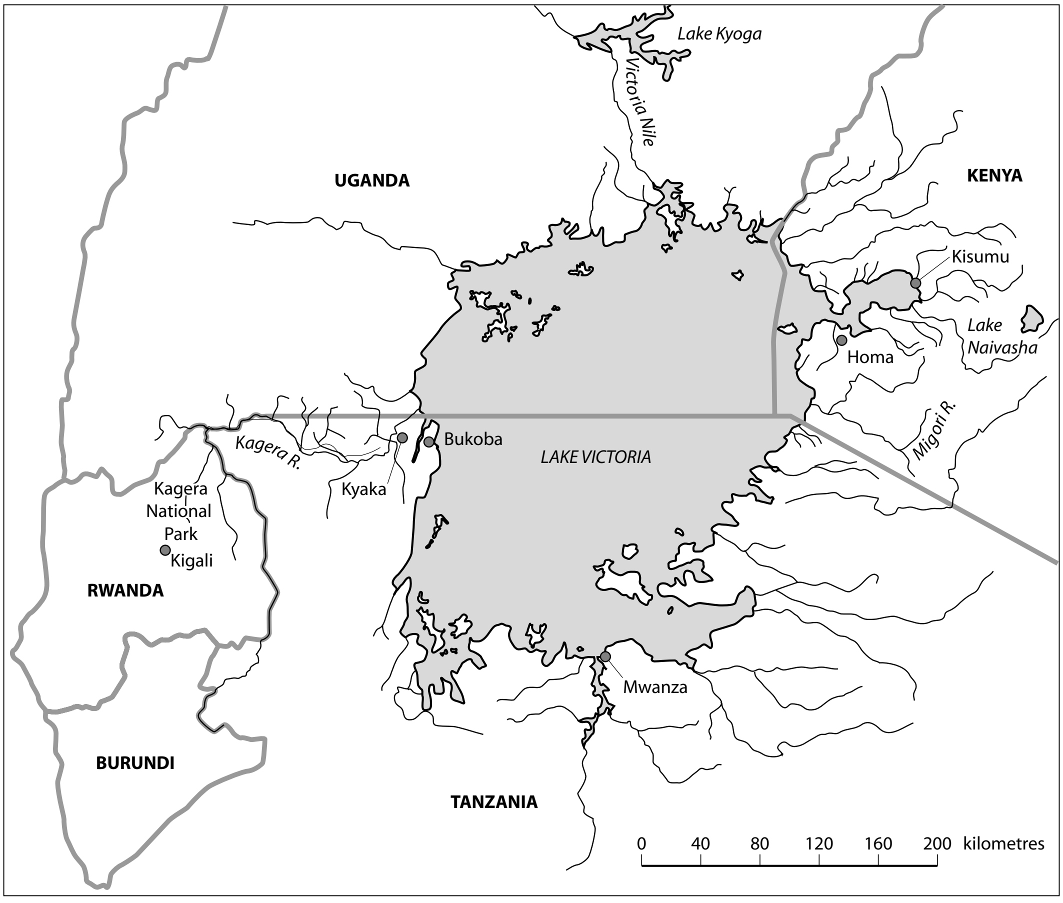

Figure 1. Lake Victoria and surrounds

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Neochetina weevils were imported from Uganda for mass rearing. Julien et al. (1999) describe in detail rearing and harvesting techniques for *Neochetina* weevils from plastic tubs, rearing pools and galvanised corrugated iron sheet tanks, all of which have been in use at the Kibos rearing facility. Additionally, 'Technotank' PVC tanks (120 × 60 cm; 230 L), with sawn-off lids, have been used to rear the weevils at Sango Rota and Nyamware beaches and at Ogenya Primary School (community-based rearing facilities near the lake). Fertiliser NPK 17:17:17 and dried cow-dung were added to the rearing containers once a month to maintain plant vigour.

Weevils were harvested for field releases as described by Julien et al. (1999). *Neochetina* weevils imported from South Africa were released in Lake Victoria in 1997 and further releases were carried out with weevils reared at NFRC Kibos and community rearing facilities. Hyacinth plants infested with weevil life stages and adult weevils were used for releases. Adult weevils were fed on fresh leaves and petioles in plastic jars before transporting them to release sites. Release techniques included planting host plants infested with weevil life stages among hyacinth plants and tipping adult weevils from the plastic containers onto hyacinth plants. Weevils were also released at sites more than 50 m from the shoreline. Canoes were used to release at sites that were inaccessible by motor vehicle or on foot.

Monitoring the establishment and spread of *Neochetina* weevils

We recorded petiole damage by weevil larvae, fresh adult feeding scars and the number of adult weevils on water hyacinth at release sites with resident mats of water hyacinth and at non-release sites. These visible signs are indicators of an establishing or established weevil population at a given site. Weevil recovery at non-release sites indicated weevil spread on water hyacinth.

Evaluation of the impact of *Neochetina* spp. weevils on water hyacinth

Using a modified sampling protocol developed at the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia, we evaluated the impact of *Neochetina* spp. on water hyacinth. The objectives of the sampling were to: (1) evaluate water hyacinth growth parameters; (2) quantify weevil feeding damage; and (3) estimate weevil populations. A half-metre^2 quadrat was thrown randomly on mats of hyacinth plants. The number of plants per quadrat was recorded. For each of 10 or 30 plants from the quadrat or nearby, the following parameters were recorded: fresh weight; leaf laminar area; leaf length; number of feeding scars; number of weevils per plant; and number of adult weevils per square metre (mean number of weevils per plant × number of plants per quadrat). Rapid assessment of weevil populations was done by counting the number of weevils from each of 10 or 20 randomly selected plants at selected sites.

Results

Importation of *Neochetina* weevils

Between 1996 and 1998, KARI imported 12,300 *Neochetina* weevils from Australia, South Africa and Uganda, for mass rearing and releases on water hyacinth in Lake Victoria (Table 1).

Table 1. Importations into Kenya of *Neochetina* weevils for biological control of water hyacinth in Lake Victoria

Species	Year imported	Number	Purpose	Source
Neochetina bruchi	1996	1300	Mass rearing	Uganda
	1997	2000	Mass rearing/releases	Australia
	1998	1000[a]	Releases	South Africa
Neochetina eichhorniae	1997	5000	Mass rearing/releases	South Africa
	1997	2000	Mass rearing/releases	Australia
	1998	1000	Releases	South Africa
Total		12,300		

[a]Batch did not survive

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From December 1996 to December 1999, the Kibos rearing facility and community rearing facilities produced approximately 100,000 adult weevils, of which 25,000 were for 'breeding stock' and for releases in Lake Naivasha and Nairobi Dam.

Between January 1997 and December 1999, approximately 73,200 adult weevils were released at 29 sites in Kisumu, Nyando, Rachuonyo, Bondo, Homa Bay, Migori, Suba and Busia districts (Table 2). An additional 10,000 weevils were redistributed from the Homa Bay Pier and Police Pier release sites to other sites within the Kisumu District.

Monitoring the establishment and spread of *Neochetina* weevils

Monitoring in January 1999 confirmed that the weevils were firmly established at 16 sites in 7 districts along the Lake Victoria shoreline (equivalent to 55% of the sites). Weevil recoveries were also made at distances ranging from 5–50 km from the nearest release sites.

Evaluation of the impact of *Neochetina* spp. weevils on water hyacinth

In general, post-release sampling data collected (November 1997 to May 1998) at four selected release sites in Berkeley, Kisumu and Kendu Bays, indicated a suppression of plant growth parameters (fresh weight, leaf laminar area and leaf length) and substantial increases in number of feeding scars and adult weevils per plant (Table 3). Fresh weight reduction was noted at a single site, Bukoma Beach. Leaf length reduction was noted at two sites, while leaf laminar area reduction was evident at Sio Port and Bukoma. The number of feeding scars and adult weevils per plant increased at all sites.

Estimations of weevil populations

Post-release sampling of water hyacinth at six selected sites in three bays (May–December 1999), gave a combined mean number of 6.0 *Neochetina* weevils per plant, with actual number of weevils per plant ranging from 0 to 32 (Table 4). Table 4 also shows that *N. bruchi* was the dominant of the two weevil species, accounting for 73.3% of the total weevil population.

Discussion

Importation of additional biological control agents, the moth *Niphograpta albiguttalis*, the mite *Orthogalumna terebrantis* and the hemipteran bug *Eccritotarsus catarinensis*, to augment biological control efforts by *Neochetina* weevils, is recommended. Rearing pools, which are easier to manage and have a larger capacity, are preferred over both plastic basins and tanks and galvanised iron sheet tanks. Tub rearing was found to be labour-intensive and time-consuming. Tubs may, however, be used for 'demonstration mass rearing units' in schools and community-based rearing facilities near the lake.

Releases on floating mats assisted in the redistribution and spread to non-release sites. Wind and water currents were responsible for the spread of weevils on floating mats of water hyacinth. Under the environmental conditions of Lake Victoria, weevils established quite rapidly.

At a regional level, monitoring the water hyacinth infestation pattern using aerial reconnaissance photography, ground truthing and satellite imagery has been proposed. At a national level, monitoring and evaluation of the impact of weevils on water hyacinth, redistribution to areas with low weevil populations and scouting for new infestations should continue.

Weevil damage has been held primarily responsible for the reduction of the weed cover by up to 80%, from the peak infestation of 6000 ha in 1998 (Synoptics, Integrated Remote Sensing and GIS Applications, The Netherlands). By late 1999, water hyacinth in the Kenyan part of the lake was no longer capable of flowering and producing ramets (daughter plants). This has been attributed to weevil damage and opportunistic fungi. The El Niño flooding of 1997 may have physically destroyed plants by washing them ashore.

Ecological succession of water hyacinth by emergent plant species, mainly papyrus (*Cyperus papyrus)* and hippograss (*Vossia cuspidata)*, has been noted (Ochiel, personal observations). This phenomenon has also been observed in Lake Kyoga, Uganda, following the successful biological control of water hyacinth by *Neochetina* weevils. However, this is short-lived and the secondary vegetation will disappear after the degraded hyacinth substratum supporting it eventually sinks.

The long-term approach to water hyacinth management and indeed other floating or submerged aquatic weeds, should focus on curbing the discharge of effluents into Lake Victoria from surrounding urban settlements, agricultural and industrial activities.

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Table 2. Releases of *Neochetina* at sites in Lake Victoria, Kenya, January 1997 to September 1999.

Site–Grid Reference	Release dates	Life stage	
		Eggs	Adults
Police Pier 0°5.5'S;34°44.3'E	23.1.97–18.2.98	13 850	5 553
Fisheries Pond 0°5.4'S;34°44.0'E	23.1.97–15.4.97	3 680	1 000
Golf Club 0°5.4'S;34°43'E	23.1.97–18.5.97	600	500
Yacht Club 0°8.5'S; 34° 45.5'E	22.1.97–3.6.98	3 500	6 705
Usoma Beach 0°06'S;34°38'E	21.2.97–14.7.98	10 695	5 967
Karamadhan 0°07'S;34°38'E	27.2.97–15.4.98	6 250	750
Otonglo Beach 0°04S;34°39.5'E	21.7.97–7.6.99	3 100	3 071
Dunga Beach 0°09'S;34°46.5'E	23.5.98–6.8.98	3 680	2 042
Kaloka Beach 0°9.5'S;34°32.5'E	17.5.98–28.5.98		2 075
Sango-Rota Beach 0°16.5'S, 34°47.5'E	7.6.97–25.3.98		2 153
	30.7.99–30.9.99		10 000
Kusa Beach 0°18.5'S,34°51'E	17.11.98		1 066
Nduru Beach 0°15.5'S;34°51.5'E	21.5.98		979
Kendu Bay Pier 0°20'S;34°39'E	7.6.97–10.8.98		2 150
K'Owuor Pier 0°21'S;34°28'E	30.1.98		740
Homa Bay Pier 0°31'S;34°28'E	21.11.97		509
Ombogo Beach 0°28.5'S;34°30'E	29.1.98		430
Tagache Beach 0°58'S,34°6.5'E	28.1.98		100
Sori-Karungu Beach 0°50'S,34°10'E	29.1.98		300
Luanda Nyamasare Beach 0°27'S,34°17'E	21.4.98		508
Aram Beach 0°18'S,34°16'E	12.11.97–11.3.98		1 250
Usenge 0°03'S,34°05'E	12.11.97–16.5.98		1 250
Usigu (Uharia) Beach 0°04'S,34°9.5'E	3.2.98–16.5.98		1 750
Obenge Beach 0°13'S,34°12.5'E	16.5.98		540
Luanda Kotieno 0°18'S,34°16'E	11.3.98		250
Sio Port 0°14'N,34°02'E	12.9.97–13.1.99		1 200
Bukoma Beach 0°12'N,33°58.5'E	29.9.97–2.2.98		1 046
Nyamware Beach 0°16'S, 34°42'E	13.8.98		950
	12.7.99–30.9.99		15 000
Ogenya Beach 0°15.5'S,34°52'E	20.5.99–22.5.99		471
Total		41 975	73 225

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Table 3. Post-release sampling data to evaluate the impact of *Neochetina* weevils on water hyacinth at four sites in Lake Victoria, Kenya

Site	Sampling date	Fresh weight (g) ± SE	Leaf length (cm) ± SE	Laminar area[a] (cm^2) ± SE	Feeding scars ± SE	Weevils/plant ± SE
Sio Port ($40\ m^2$)	19.11.97	1685±958	137.2 ± 14.9	195.4±9.7	2.5 ± 1.9	0.4 ± 1.4
	10.3.98	3550±1755	77.8 ± 23.0	110.2±12.5	100.3 ± 9.6	1.8 ± 2.6
Bukoma Beach ($15\ m^2$)	20.11.97	2270±935	162.9 ± 16.5	178.6±0.7	2.5 ± 2.1	0.2 ± 0.6
	10.3.98	925±528	75.5 ± 19.9	126.8±13.0	107.4 ± 28.2	2.2 ± 1.9
Police Pier ($1500\ m^2$)	28.11.97	251±128	19.9 ± 4.8	49.0±5.0	19.4 ± 6.9	0.4 ± 0.5
	20.5.98[b]	482±271	31.3 ± 15.8	74.6±12.8	138.8 ± 28.3	4.5 ± 3.9
Kendu Bay Pier ($400\ m^2$)	21.11.97	1950±797	78.8 ±19.3	146.8±5.6	2.9 ± 2.3	0.1 ± 0.3
	12.3.98	2510±127	100.3 ±33.1	124.8±13.1	268.3 ± 52.4	6.0 ± 3.0

[a]Second youngest petiole sampled
[b]n = 30. At all other sites n = 10.

Table 4. *Neochetina* weevil populations on water hyacinth estimated from six sites in Lake Victoria, Kenya, May–December 1999.

Site	Sampling date	Mean no. of weevils/plant[a] ± SE	Mean no. of weevils by species[b] ± SE		Range
			Nb	Ne	
Kisumu Bay					
Police Pier	6.5.99	2.5 ± 2.3	1.8 ± 0.9	0.7 ± 0.3	1–4
	14.12.99	6.3 ± 4.5	5.1 ± 3.3	1.2 ± 0.6	0–6
Karamadhan	6.5.99	1.8 ± 2.1	1.1 ± 1.7	0.7 ± 0.9	0–6
	4.12.99	3.7 ± 2.8	2.9 ± 2.3	0.8 ± 0.9	0–7
Nyakach Bay					
Kusa	7.5.99	14.0 ± 6.7	14.0 ± 6.7	0.0 ± 0.0	2–22
	14.12.99	3.2 ± 3.9	3.2 ± 3.9	0.0 ± 0.0	0–11
Sango Rota	7.5.99	5.4 ± 4.4	3.7 ± 2.9	1.7 ± 2.3	1–13
	15.12.99	2.9 ± 1.6	1.5 ± 1.9	1.4 ± 1.6	0–8
Kendu Bay					
Kendu Bay	7.5.99	2.4 ± 2.3	2.0 ± 1.7	0.4 ± 0.7	0–6
Pier	16.12.99	2.0 ± 1.7	1.5 ± 1.6	0.5 ± 0.9	0–4
Homa Bay					
Homa Bay	18.9.99	18.1 ± 15.3	15.4 ± 7.2	2.7 ± 2.3	0–32
Pier	15.12.99	9.2 ± 8.6	6.5 ± 5.9	2.7 ± 3.0	0–32
Grand mean		6.0 ± 5.3	4.4 ± 3.1	1.6 ± 0.9	
Percentage			73.3	26.7	

[a]Mean of 10 plants per site, except for Homa Bay 18.9.99, where n=20
[b]Nb = *Neochetina bruchi*. Ne = *N. eichhorniae*.

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Water Hyacinth Population Dynamics

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Abstract

Neochetina eichhorniae and *N. bruchi* have in some locations been very successful in controlling water hyacinth infestations. Understanding the conditions under which the weevils are not successful is a key area of research. We have used simple analytical tractable models to investigate this problem. We argue that biomass density and percentage coverage are the two most useful parameters to measure in a monitoring program. We modelled water hyacinth as a population of biomass. Under stable conditions, the logistic growth model accurately describes water hyacinth growth. Understanding how abiotoic conditions alter the parameters of the model is essential for accurate prediction of water hyacinth growth. There appear to be five main factors limiting infestations of water hyacinth: salinity, temperature, nutrients, disturbance and natural enemies. The models are modified to include the effect of weevil damage. Simple deterministic models are developed that incorporate developmental delays and population stage structure. For realistic parameter values, the models predict eradication of water hyacinth. We discuss how this prediction is altered in a dynamic environment. The factors that may limit the weevil population under stable conditions, and so prevent eradication, are explored. In order to test these ideas, information on areas where control has and has not been successful needs to be collated.

THE current status of water hyacinth control has been well reviewed in these proceedings and elsewhere (Julien et al. 1996, 1999). Models have been used to investigate the effect of different management strategies (Ewel et al. 1975; Mitsch 1976; Lorber et al. 1984; Musil and Breen 1985b) drawing on the wealth of information from many studies conducted worldwide. However, there has been only one published model investigating the effect of biological control agents (Akbay et al. 1991). Models used to understand when an insect biological control agent will control a weed have produced insights into how control can be achieved (Lonsdale et al. 1995; Rees and Paynter 1997). Furthermore, the Lotka–Volterra model has been successfully used to simulate the growth of another aquatic weed (*Salvinia molesta*) before and during control by *Cyrtobagous salvinae* (Room 1990). This approach can be useful in drawing together existing knowledge, as well as to identify areas where research needs to be concentrated.

The aim of the current research is to develop a predictive model for the control of water hyacinth addressing the following questions:

- what causes variability in water hyacinth infestations?
- how does the introduction of *Neochetina eichhorniae* affect the size of the infestation?
- what can be done to improve control?

In this paper we will outline some preliminary results of modelling work and the hypotheses generated from this work.

Modelling Water Hyacinth Biomass

When building a model, an appropriate state variable, which describes the state of the system at any moment in time, must be selected. With animal populations, the state variable chosen is usually the number of individuals. When modelling diseases, the number infected,

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infectious, immune and susceptible can be used to characterise the host population. With plant populations, the choice of state variable is often less clear. In this section, we explain why we have chosen biomass as the state variable.

The current model will be most useful if the state variable reflects the magnitude of the problem. Water hyacinth infestations have negative impacts on health, food production, navigation, hydroelectric schemes, irrigation schemes and recreation (see e.g. Gopal 1987). These problems are caused by the sheer bulk of vegetation and the fact that the vegetation covers great areas. As the scale of the problem depends on the bulk of the weed, biomass would be an appropriate state variable.

Most studies have been conducted using biomass or individual density. The density of individuals is more easily determined than biomass, but the point at which an offshoot becomes a separate plant is not always clear. The main disadvantage of using individuals is the great variability in the size of an individual. Madsen (1993), using experimental data, proposed a humped relationship between biomass density and individual plant density. We have plotted these results and some from another study in Florida (Center and Spencer 1981) in Figure 1. Similar patterns are shown in several unpublished data sets (M. Purcell, unpublished data; T. D. Center, unpublished data). Plants grown at low density have relatively constant biomass. However, at densities above about 500 g (dry weight) per square metre there is no clear relationship between individual density and biomass. This suggests that biomass provides a better description of the scale of the problem than individual plant density.

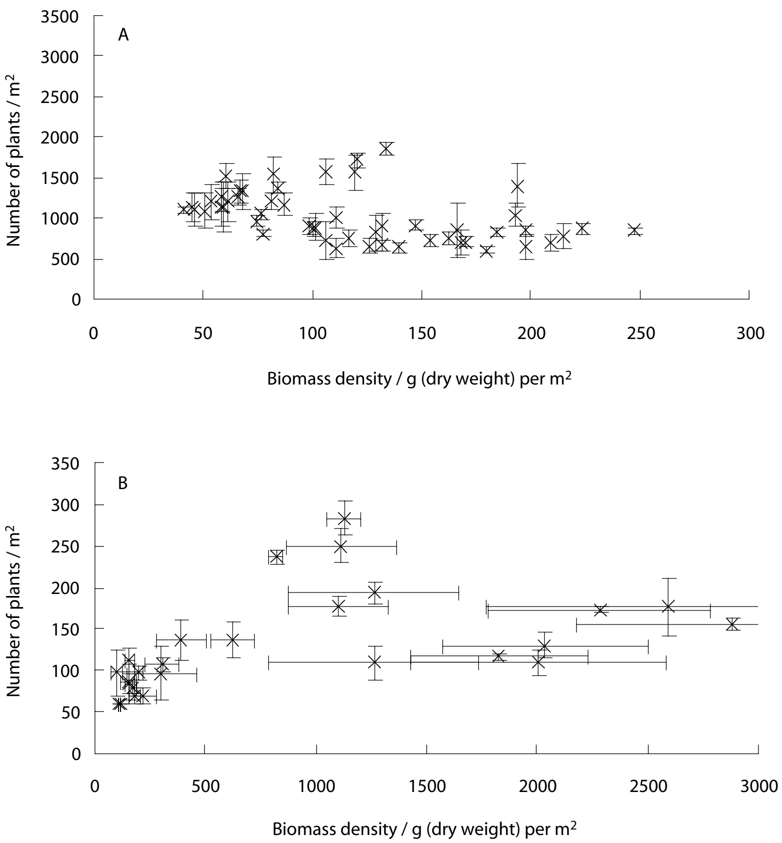

Figure 1. Biomass density plotted against individual density: A (Center and Spencer 1981); B (Madsen 1993)

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Importantly, studies have shown little variation in plant water content (average of 94–95%), although there is some variation between studies and between the different plant parts (Penfound and Earle 1948; Sahai and Sinha 1970; Debusk et al. 1981). Therefore, it is straightforward to convert between dry and fresh weight.

It is possible that other units, e.g. petiole length, can also be converted to biomass, and if these units are easier to measure they might be a more appropriate unit for study. Center and Spencer (1981) found that plant weight in a lake in Florida was closely related to the mean number of leaves per plant and the mean maximum leaf length (including the petiole). It remains to be confirmed whether this relationship holds when weevils are present. Moreover, at different nutrient levels, the ratio of biomass in the roots and shoots is different, and so the proposed relationship may be different. However, finding a reliable surrogate would allow easier monitoring and allow the models to be tested using existing data-sets that do not contain information on biomass.

One of the assumptions of the modelling work is that populations of water hyacinth around the world are not genetically different with respect to growth. Clonal differences have been investigated (Watson and Cook 1987) and currently the genetic variation between populations of water hyacinth worldwide is being assessed as part of the IMPECCA project (Bateman, these proceedings). These studies suggest there is some variation, especially with flowering, but a simple growth model based on biomass should be generally applicable.

Logistic Model of Water Hyacinth

Here we discuss a simple model and how to parameterise this model using data. Understanding how environmental conditions affect the parameters of the model will be useful in predicting the size of water hyacinth infestations. We have modelled the growth of water hyacinth using a logistic model, equation 1 (also see Gutiérrez et al. 2001).

$$\frac{dP}{dt} = r.P.\left(1 - \frac{P}{K}\right) \quad (1)$$

The biomass density of plant material is P (g (dry weight)/m^2) and dP/dt is the rate of change of the population. This model has two parameters: the intrinsic growth rate, r, and the carrying capacity, K. At low densities the population will increase at its intrinsic rate of growth, r. As the density of plants approaches the carrying capacity, K, the rate of increase in the population, dP/dt, tends linearly to zero. Furthermore, if the plant density is above the carrying capacity, then the population will fall to K. With constant parameters, this model has a stable point equilibrium at K and an unstable point equilibrium at zero, providing $r > 0$ (May 1981).

Both r and K are estimated from field and laboratory studies. Changes in biomass with time, r, have been measured in many different situations. We have also estimated the carrying capacity using the highest levels seen in nature and in long-term experiments. In both cases, we have expanded on the review of the water hyacinth growth parameters reported by Gopal (1987). Of these studies, those that have been carried out at several plant densities have been used to estimate both parameters. One of the assumptions of the logistic model is a negative linear relationship between plant density and intrinsic rate of growth. For most situations this gives a reasonable fit (Fig. 2). However, there is some curvature (Fig. 2C) which would imply an under-estimation of K. Within a site and season this model shows a good fit with experimental data. However, between studies and between seasons (Fig. 2C) there is variation in both the maximum intrinsic rate of growth r and the carrying capacity K. This variation reflects the variation in water hyacinth infestations and indirectly how water hyacinth is affected by the environmental conditions.

How the Environment Affects the Parameters of the Logistic Model

The conclusions from the parameterisation of the logistic model appear qualitatively similar to previous reviews. There appear to be five main factors limiting the growth rate and carrying capacity of water hyacinth: salinity, temperature, nutrients, disturbance and natural enemies (in the host range of water hyacinth).

- Salinity—water hyacinth is killed in waters that are more than about 0.2% saline (Haller et al. 1974: Nwankwo and Akinsoji 1988). This is important in estuarine areas e.g. the coastal lagoons of West Africa.
- Low temperature—stops the weed establishing in temperate areas and prevents it from reaching high levels in the sub-tropics e.g. California (Bock 1966). From their experimental study, Knipling et al. (1970) proposed a parabolic relationship between temperature and growth rate, with growth

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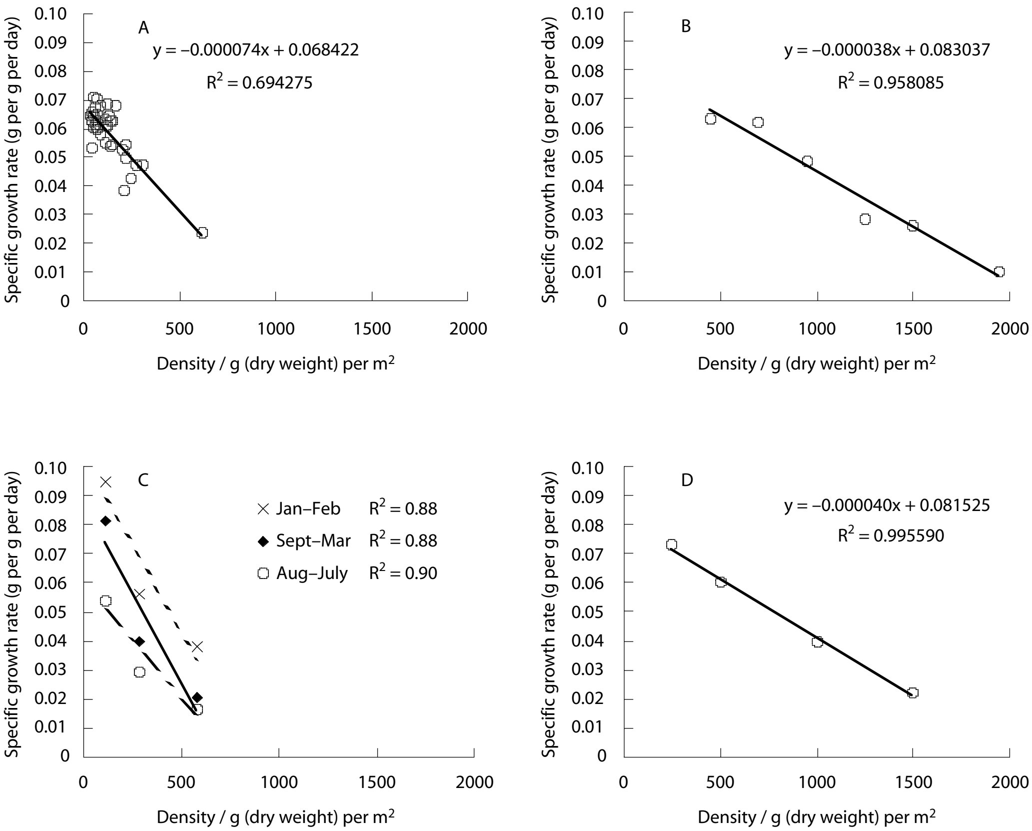

Figure 2. *r* against *K* measured experimentally in: A, Japan (Imaoka 1988); B, Florida, USA (Reddy 1984); C, Argentina (Fitzsimons 1986); and D, Florida, USA (Debusk 1981)

tailing off quickly after the optimum of 30°C. Imaoka and Teranishi (1988) proposed that *r* increases exponentially with ambient temperatures in the range 14 to 29°C. Both models predict that water hyacinth growth stops below 13°C. However, field populations of water hyacinth may be more limited by frost damage, as this increases the loss of biomass.

- Nutrients—the levels of available nitrogen and phosphorus have been often cited as the most important factors in limiting water hyacinth growth (Carignan and Neiff 1994; Heard and Winterton 2000; Musil and Breen 1985a; Reddy et al. 1989, 1990, 1991). The half-saturation co-efficients for water hyacinth grown under constant conditions have been found to be from 0.05 to 1 mg/mL for total nitrogen and from 0.02 to 0.1 mg/mL for phosphates. Water hyacinth growth quickly tails off below the lower limits. The effect of other mineral deficiencies has also been studied (Newman and Haller 1988).
- Disturbance—flooding can break up large mats of water hyacinth and leave plants stranded on land. Similarly, currents flush water hyacinth downstream. However, water hyacinth can still build up on sheltered edges and at blockages. Wave action may itself limit growth by directly damaging plants and by forcing the weed to maintain aerenchymous tissue.
- Natural enemies—in its native range in South America, water hyacinth is controlled by a suite of natural enemies. It can be the dominant floating aquatic weed but not always and not everywhere (H. Evans, pers. comm.).

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Modelling Water Hyacinth and *N. eichhorniae*

We now modify the model to investigate the introduction of a weevil biological control agent, *Neochetina eichhorniae*, to water hyacinth in its exotic range. The weevils do not have discrete generations, although winter or a severe event may synchronise a population. Moreover, plant biomass production is a continual process. Therefore, a continuous time model was used. Caughley and Lawton (1981) presented a range of plant/herbivore models e.g. equation 2.

$$\frac{dP}{dt} = r.P.\left(1 - \frac{P}{K}\right) - c_1.A.\left(1 - e^{-d_1.P}\right) \qquad (2)$$
$$\frac{dA}{dt} = A.\left(-a + c_2.\left(1 - e^{-d_2.P}\right)\right)$$

The equation for the plant population is the logistic growth model with a loss term due to weevil feeding: $c_1.A.(1 - e^{-d1.P})$. The weevil population, A, increases at the maximum rate $-a + c_2$ when there are many plants (i.e. $e^{-d2.P}$ is approximately zero), and declines at the maximum rate of a when there are few plants. Using parameters from the literature (Center and Durden 1986; Jayanth and Visalakshy 1990; Heard and Winterton 2000), this model predicts that water hyacinth will very quickly be eradicated (Fig. 3A).

This model assumes all weevils have the same effect on the plant. However, late larval stages are the most damaging. To mimic this we have added a time delay to the growth of the weevil population. Under these conditions, the weevil no longer drives water hyacinth to extinction, but instead the system undergoes large amplitude cycles. Water hyacinth is driven to extremely low densities during these cycles, which

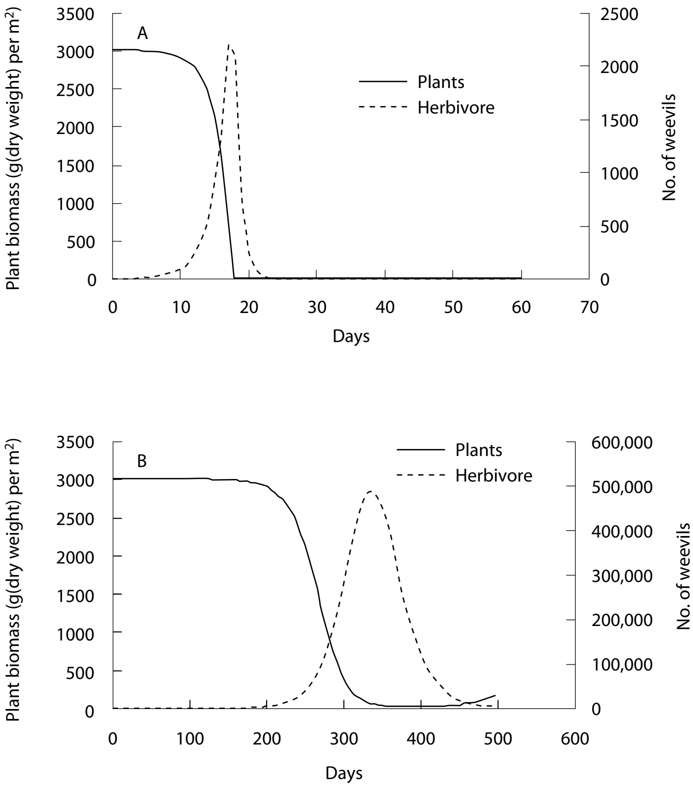

Figure 3. Model outputs for models with A, no time delay, and B, with a time delay

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would effectively result in extinction. This simple model assumes the weevil population can be characterised by the number of larvae. To improve the realism of the model we have added stage structure. The weevil population is approximated by '… a sequence of developmental stages within each of which all individuals can sensibly be regarded as functionally identical (that is all having the same per capita vital rates)' (Gurney et al. 1983). This makes the models more difficult to analyse, but again the weevils appear to eradicate the plant.

These models predict that, given stable conditions, water hyacinth will always be controlled. However, from field sites this is known not to be the case (T. Center, pers. comm.). Therefore, the models appear to overemphasise the effect of the weevils and so in some way fail to capture an important aspect of the water hyacinth/weevil interaction.

What Limits the Weevils?

In this section, we investigate why control is not always as predicted. We first discuss how a fluctuating environment can, within the framework of the existing models, prevent water hyacinth from being eradicated. Then we move onto what happens in stable situations where the models do not give the correct qualitative conclusion.

Under certain dynamic scenarios, the weevils may have little impact on the water hyacinth population. Frost kills leaves, which in turn kills weevil eggs and young larvae. However, late larvae, pre-pupae and pupae may survive around the rootstock. When plants begin to regrow in the spring, the weevils need to finish maturing, mate, oviposit, and develop before the next late larval stages can cause major damage to the plants. This developmental delay in the weevil population may allow the plant to outgrow weevil damage, providing the plant has not been too heavily damaged by the frost. Factors that speed the water hyacinth regrowth, e.g. high nutrients, may exacerbate this. Alternatively, water hyacinth grows at temperatures lower than the weevils and so the weed is freed from herbivore pressure early in the growing season. The effect of cold on the weevil populations is currently under investigation (M. Hill, pers. comm.). Herbicidal or mechanical control may cause similar problems by removing the age structure in the weevil population and, for a short time, freeing the weed from herbivore pressure. Extreme natural conditions may also have an adverse effect on control. Flooding can bring new plants from upstream or remove weevil-infested plants from a population. Drought may dramatically reduce the population of plants and weevils. After drought, water hyacinth seeds will germinate with rising water levels and these new weevil-free plants can re-establish the problem before the weevil population can respond (Guillarmod and Allanson 1978). Furthermore, an infestation may persist despite a high weevil population if new plants continually arrive from upstream.

The lack of control under stable conditions, however, suggests there is something limiting the weevils. Here we explore where density dependence may be acting in the weevil population—at the egg, the larval, the pupal or the adult stage. Oviposition sites are probably not limiting and at very high egg densities the fertility of the eggs does not appear to change. Furthermore, there are few records of egg parasitism or predation, and so it is unlikely to occur at the egg stage. Larval cannibalism has been used as a possible explanation (DeLoach and Cordo 1976), but the few accounts of this suggest it is a rare, accidental phenomenon caused by larger larvae accidentally tunneling through smaller larvae (T. Center and M. Julien, pers. comm.). Larval competition for food may directly increase larval mortality; indirectly increase mortality by prolonging larval duration; or reduce the size of larvae at pupation and thereby increase pupal mortality or decrease adult fecundity (Gurney and Nisbet (1985) presented some models illustrating these). Larval damage can result in the flooding and shedding of a petiole, which would kill any larvae remaining in it (Center 1987). This sort of asymmetrical competition would occur only at high damaging densities, but should result in a few of a given age group developing. In order to elucidate this, we have undertaken an experiment to measure the effect of egg density on larval development at two different water nutrient levels.

Pupae, or pre-pupae, may be the limiting stage because, even accounting for the shorter stage duration, pupal cocoons in the field are often less common than larvae (M. Julien, pers. comm.). Pupal mortality may be higher in silted water or where the plant roots used by the pre-pupae are buried in the sediment. Muddy edges to a water-body appear to be correlated with unsuccessful control (Visalakshy and Jayanth 1996; O. Ajounu, pers. comm.). Experimentally, larvae have been shown to develop and cause damage to rooted plants (Forno 1981). Pupae have also been found on rooted plants in the field (M. Hill, pers. comm.). However, Visalakshy and Jayanth (1996) found that larvae on plants with silted roots were a

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third as likely to survive to adults as larvae on free floating plants, although once pupae had formed a cocoon there was no difference in survival. They proposed that, in silted conditions, there was either a shortage of pupation sites or the pre-pupae have a much lower success in forming cocoons on silted roots.

Finally, the limitation may occur at the adult stage through either emigration or mortality. Adults have been observed to develop flight muscles at the expense of egg production (Buckingham and Passoa 1985). It is possible that, at relatively high densities or when food quality is low, the female weevils switch to a dispersive mode (Center and Durden 1986). Losses to natural enemies may be less important, as few parasitoids attack the weevils outside their native range (T. Center, pers. comm.) and, although birds have been seen to eat adults, adult weevils are generally not available to predators, hiding in the base of the petioles. However, the relatively quick success of biological control agents in western Mexico (T.D. Center, pers. comm.), is thought to be due to eliminating a microsporidian infection which reduces the efficacy of the agents.

The most likely candidates for limiting the weevils in stable conditions appear to be some form of larval competition linked to plant nutritional status; prepupal mortality in silted areas; adult migration again linked to low plant quality or parasitic burden i.e. microsporidians.

Other Modelling Approaches

The models described are designed to be general, and as such have simplifying assumptions; for example, that water hyacinth can be modelled as a population of biomass. However, to answer specific questions the models may need more detail. Plant physiological models, based on the metabolic pool concept (Gutiérrez 1996), are being developed as part of the IMPECCA mycoherbicide project. These models investigate how different application strategies affect water hyacinth population dynamics under different environmental conditions. These questions necessitate a more detailed modelling approach, in particular one that includes leaf dynamics. However, both approaches address the causes of variability in water hyacinth infestations. If the models concur, the conclusions should be independent of the modelling technique used. The latest version of the model is available free at <http://www.agrsci.dk/plb/nho/hyacinth.htm>.

Discussion and Conclusions

In this section we draw the conclusions from the work on modelling water hyacinth, discuss how the addition of the weevils to the models affects the outcomes and why the models may not reflect the real situation.

Monitoring of water hyacinth should be carried out using biomass and surface area covered, as these give the best measure of the problem. Leaf length and number of leaves can be used as a surrogate, but the exact relationship may be very site specific. A simple logistic model gives a good description of water hyacinth growth. The parameterisation of the logistic model has highlighted several conclusions from other studies. Water hyacinth cannot survive at salinities above about 0.2%. Water hyacinth can grow in water temperatures of between 13 and 40°C and grows optimally at 30°C. High temperatures increase water hyacinth mortality, but mortality does not increase at low temperatures without frost. Frost kills leaves and after several days or a hard frost the meristem can be damaged and the plant killed. Under constant conditions, water hyacinth shows a hyperbolic relationship between water nutrient concentration and growth rate, with half-saturation co-efficients of between 0.05 and 1 mg/mL for total nitrogen and between 0.02 and 0.1 mg/mL for phosphates. However, complications mean that the plant nutrient content is a more accurate guide with a linear relationship between the percentage nitrogen in the leaves and the growth rate (Aoyama and Nishizaki 1993). Water hyacinth growth rate is also reduced by wave action, and in such environments it may persist only in sheltered regions or as part of a mat. Natural enemies also limit water hyacinth growth. To test the model predictions, information needs to be collated on where water hyacinth has and has not caused problems and how infestations develop. This would require historical data-sets possibly including remote sensing.

When the models are adapted to include weevils, the prediction is for water hyacinth to be effectively eradicated in all stable conditions. This qualitative prediction does not appear to be affected by refinements to make the model more biologically realistic e.g. introducing time delays corresponding to developmental delays or the introduction of stage structure. However, these predictions are altered in a dynamic situation e.g. frost and flooding. In order to test and refine the model, information again needs to be collated on where control has and importantly where it has not been successful. One important aspect not included in the models is spatial heterogeniety of attack. The adult

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weevils are able to swim and are mobile, but in general they are sedentary and some plants may temporally escape attack. It would be expected, therefore, that in larger water bodies the reduction would be relatively less than on a similar smaller water body. The modelling work has thrown up a number of potentially important questions, the answers to which could be very important in directing future control measures.

Under what conditions does water hyacinth remain at low levels? What limits the size of the weevil populations? Under what conditions are they limited below a level that causes significant reductions in the water hyacinth population? Do shallow or muddy banks provide refuge for water hyacinth plants by preventing *N. eichhorniae* from pupating? Does adult weevil migration prevent damaged water hyacinth from being eradicated? How does the interaction between water nutrient level, plant nutrient level and weevil damage affect the level of water hyacinth and weevils seen? How do the larvae compete when at high densities? How are the weevils dispersed, and can this account for failure in control? Why doesn't *N. eichhorniae* work everywhere? These questions will be addressed by refining the models, experimentation and more detailed investigation of field data.

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Current Strategies for the Management of Water Hyacinth on the Manyame River System in Zimbabwe

G.P. Chikwenhere*

Abstract

The Manyame River System consists of the Manyame River and its tributaries, the Mukuvisi and Nyatsime rivers, which discharge water into man-made Chivero and Manyame lakes situated at 29 km and 33 km, respectively, from Harare. Water hyacinth is the predominant floating aquatic weed in the system. About 15 years ago, the water was covered with various aquatic weeds namely: water hyacinth (35%), *Pistia stratiotes* (36.6%) and *Myriophyllum aquaticum* (1.7%). Ten years later, the estimated weed coverage was water hyacinth (3%), *P. stratiotes* (0.3%), *M. aquaticum* (4%). Also, *Azolla filiculoides* had appeared in Lake Chivero, forming a 1% coverage. In 2000, the weed coverage on the system was 2.4, 0.8, 6,8 and 3.5%, respectively, and 9.5% of the water surface of Lake Chivero had been invaded by *Hydrocotyle ranunculoides*. The control of water hyacinth was accomplished through chemical, biological and mechanical means, while the management of *P. stratiotes* was accomplished mainly through classical biological control. The appearance of *M. aquaticum* and *H. ranunculoides* may have been facilitated by the absence of natural enemies, and reduced competition for space and nutrients by the previously dominant water hyacinth and *P. stratiotes*. In 2000, the Zimbabwe Aquatic Weed Management Committee was formed to manage the aquatic weed problem in a holistic manner.

ZIMBABWE has been involved in the biological control of pests, including floating aquatic weeds, since the 1950s (Chikwenhere 1994, 2001). The country has been working through international collaboration and cooperation as a means to achieving sustainable classical biological control technologies.

Following the First IOBC Global Working Group Meeting for the Biological and Integrated Control of Water Hyacinth, held in Harare, Zimbabwe, in 1998, Zimbabwe adopted a new coordinated approach in the management of the water hyacinth problems, with particular attention to the Manyame River System thus including Chivero and Manyame lakes.

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Formation of Zimbabwe Aquatic Weed Management Committee

The Zimbabwe Aquatic Weed Management Committee was formed in July 2000 and it comprises various stakeholders including government, university and private sector representatives (Table 1). The committee's mandate is to identify water impoundments for immediate chemical and biological control strategies for aquatic weeds, including chemical control of newly emerging water hyacinth seedlings, and to train national parks personnel in the proper use of spray equipment. The committee is also charged with preparing an implementation plan for waterweed management in the short and medium terms. This would:

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1. Identify areas for
   – immediate herbicide application in economically important areas
   – areas requiring herbicide application if resources permit
   – areas reserved for biological control.
2. Immediately spray germinating seedlings along the lake shore areas.
3. Train national parks staff in identification and mass rearing of biological control agents for restocking in areas designated for biological control activities.
4. Train national park staff in calibrating spray equipment, spray mixing and handling of herbicides.

The Zimbabwe Government provided the committee with an annual working budget of ZWD6m (US$125,000) for the year 2000 for aquatic weed control along the Manyame River System. This system has a surface area of approximately 60 km^2 and the estimated weed infestation level was below 5%.

Observations on the Pattern of Weed Infestation in Lake Chivero (September 2000)

1. The major part of the weed biomass in the lake was not water hyacinth but the spaghetti weed, *Hydrocotyle ranunculoides*.
2. Water hyacinth mats were visible as isolated patches, brownish and severely weevil damaged, surrounded by vigorously growing spaghetti weed.
3. On the Upper Manyame River System, spaghetti weed and parrot's feather, *Myriophyllum aquaticum,* appeared to be the dominant species, outcompeting both water hyacinth and water lettuce, *Pistia stratiotes,* for space, light and possibly nutrients.
4. The most significant pocket of water hyacinth was observed at Tiger Bay, but even that was not exclusively water hyacinth, as spaghetti weed constituted a larger proportion of the weed biomass.
5. Other significant pockets of water hyacinth were just below the Lake Chivero Spillway but these were less then 10 cm tall and even in these areas, spaghetti weeds constituted a significant proportion of the biomass.
6. Along the northern shore of Lake Chivero, spaghetti weed formed a continuous fringe extending about 3–4 m from the shoreline into the water. After the spaghetti weed fringe, the water hyacinth formed another belt of about 1 m. On average, the entire weed belt around the lake was about 4 m, approximated 6.5% of the surface area. The current weed cover remains far less than the 35% previously recorded on the lake in the 1980s before the release of the *Neochetina* weevils (Table 2).

Table 1. Composition of Zimbabwe Aquatic Management Committee

Institution/organisation	Representative	Area of interest
Harare City Council	Mr T. Mafuko	Urban water supply and effluent disposal systems
Ministry of Agriculture, Plant Protection Research Institute	Dr G. P. Chikwenhere	Biological control using insects
Agruricura: Agricultural Chemical Company	Mr A. Brent	Chemical control
University of Zimbabwe, Department of Biological Sciences	Prof. B. Marshal	Use of lake waters and water hyacinth control
Ministry of Environment and Tourism, Department of National Parks and Wildlife	Mrs S. Mutsekwa	Fish ecology and committee chairperson
Commercial Farmers Union	Unadale Farm	Tobacco and mixed cropping systems
Lazy River Fisheries	Mr G. Manuwere	Fishing
Zvevanhu Fisheries	Mr B. Chidawanyika	Fishing

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Table 2. Comparisons on previous and present weed cover on the Manyame River System in Zimbabwe

Locality/area	Weed species		Estimated surface area covered (%)	Year observed
	Common name	Scientific name		
Upper Manyame	Water hyacinth	*Eichhornia crassipes*	60.0	1986
	Water lettuce	*Pistia stratiotes*	35.0	
	Parrot's feather	*Myriophyllum aquaticum*	0.1	
	Red water fern	*Azolla filiculoides*	–	
Lake Chivero	Water hyacinth	*Eichhornia crassipes*	35.0	
	Water lettuce	*Pistia stratiotes*	40.0	
	Spaghetti weed	*Hydrocotyle ranunculoides*	–	
	Red water fern	*Azolla filiculoides*	–	
Mukuvisi River	Water hyacinth	*Eichhornia crassipes*	10.0	
	Water lettuce	*Pistia stratiotes*	35.0	
	Parrot's feather	*Myriophyllum aquaticum*	5.0	
	Red water fern	*Azolla filiculoides*	–	
Upper Manyame	Water hyacinth	*Eichhornia crassipes*	4.0	1996
	Water lettuce	*Pistia stratiotes*	0.5	
	Parrot's feather	*Myriophyllum aquaticum*	4.5	
	Red water fern	*Azolla filiculoides*	0.1	
Lake Chivero	Water hyacinth	*Eichhornia crassipes*	5.0	
	Water lettuce	*Pistia stratiotes*	0.5	
	Spaghetti weed	*Hydrocotyle ranunculoides*	3.5	
	Red water fern	*Azolla filiculoides*	1.0	
Mukuvisi river	Water hyacinth	*Eichhornia crassipes*	0.8	
	Water lettuce	*Pistia stratiotes*	0.1	
	Parrot's feather	*Myriophyllum aquaticum*	4.5	
	Red water fern	*Azolla filiculoides*	2.7	
Upper Manyame	Water hyacinth	*Eichhornia crassipes*	3.5	2000
	Water lettuce	*Pistia stratiotes*	1.5	
	Parrot's feather	*Myriophyllum aquaticum*	4.5	
	Red water fern	*Azolla filiculoides*	5.5	
Lake Chivero	Water hyacinth	*Eichhornia crassipes*	3.5	
	Water lettuce	*Pistia stratiotes*	1.0	
	Spaghetti weed	*Hydrocotyle ranunculoides*	9.5	
	Red water fern	*Azolla filiculoides*	0.5	

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Table 2. (Cont'd) Comparisons on previous and present weed cover on the Manyame River System in Zimbabwe

Locality/area	Weed species		Estimated surface area covered (%)	Year observed
	Common name	Scientific name		
Mukuvisi River	Water hyacinth	*Eichhornia crassipes*	0.2	
	Water lettuce	*Pistia stratiotes*	0.1	
	Parrot's feather	*Myriophyllum aquaticum*	6.5	
	Red water fern	*Azolla filiculoides*	2.4	

Discussion

There is still an overall reduction in water hyacinth biomass on Lake Chivero, as has been observed by Chikwenhere and Phiri (1999). The rapid increase of spaghetti weed and other floating macrophytes, particularly in Lake Chivero, may have been facilitated by the absence of natural control enemies, as well as the competitive ability of the weed in the presence of water hyacinth plants heavily stressed by *Neochetina* weevils and water lettuce stressed by *Neohydronomus affinis* weevils. Furthermore, nutrients previously utilised by large mats of water hyacinth and water lettuce became available and may have contributed to the rapid proliferation of the other weeds. At the same time, accelerated succession of spaghetti weed seemed to be favoured by dead biomass of water hyacinth plants, which provided a suitable substrate for the new invader.

The committee has recommended chemical control targeted only on spaghetti weed, but it remained unclear whether water hyacinth will show an upturn once the spaghetti weed levels have gone down.

Herbicidal and mechanical control have traditionally been the methods of choice, but the rising cost of herbicides, and environmental concerns, prompted an investigation of the possibility of using biological control. This aspect of research was initiated during the 1980s (Chikwenhere 1994), and during the 1990s significant improvement in water hyacinth and water lettuce control was achieved, especially in the Manyame River System.

Observations during the past decade have shown that, while effective control of water hyacinth has been achieved, spagetti weed, *A. filiculoides* and *M. aquaticum* have increased, and replaced water hyacinth and water lettuce in many places. Studies of the competitive interactions of the weeds may assist development of holistic weed management strategies.

In Zimbabwe, lakes and reservoirs provide water for domestic use and for irrigation of commercial agriculture and small-scale farming communities. They have aesthetic value and are an important source of foreign exchange earning through tourism. The Aquatic Weed Control Management Committee was formed in 2000 to oversee management of aquatic weeds. The committee will draw up an implementation plan to accomplish aquatic weed control in a holistic and prioritised approach. It will also be responsible for monitoring, evaluation and impact assessment of the control measures.

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Biomass and Productivity of Water Hyacinth and Their Application in Control Programs

E.L. Gutiérrez, E.F. Ruiz, E.G. Uribe and J.M. Martínez*

Abstract

Water hyacinth is controllable if management programs take account of plant dynamics and factors that influence plant behaviour. The project for reclamation of water bodies in Mexico considered water hyacinth standing crop, coverage and growth. The method proposed served to characterise the initial population and monitor the control process. The growth model used was reliable in predicting the effective reduction in the weed in response to control pressure. Change in growth over an annual cycle was characterised by a sigmoid curve. The maximum relative percentage growth rate was 9.34%, with a duplication time of 7.4 days from April to June. During winter, growth decreased by up to 90%. In a dam, 144 t/ha/year of dry matter was produced, characteristic of water plants with a high nutrient content. The water hyacinth population can be reduced by 90% through water level management and mechanical destruction. For example, approximately 3600 t/day was removed over 181 days to reduce the infestation to manageable levels. Physical, chemical and biological methods are used to maintain these levels, but input of urban and industrial contaminants must be controlled for long term rehabilitation.

OUTBREAKS of aquatic plants is the result of changes in the physical, chemical and biological conditions brought about by the uncontrolled flow of nutrients from urban, agricultural and industrial centres and in silt eroded from watersheds (Gutiérrez et al. 1994).

Water hyacinth is successful owing to its life cycle and survival strategies that have given it a competitive edge over other species. Its adaptability to little competed ecological conditions make eradication of this plant virtually impossible and control extremely difficult (Gutiérrez et al. 1996). In Mexico, more than 40,000 ha were infested and specific management programs were needed. The Aquatic Weed Control Program (AWCP) was created in 1993 to combat the excessive presence of the weed in the nation's watercourses.

The aims of the AWCP included to:

- reduce the weed to a manageable level and maintain this level through a maintenance program developed for the body of water;
- use methods most suitable to ecosystem and water uses;
- formulate an integral watershed program which will include the control and maintenance operations; and
- establish biological control using insects and fungi.

Under a national program to control the water hyacinth, guidelines to deal with the related environmental, social, technical and economic factors, and specific strategies to reduce coverage were developed. The environmental factors included the identification of the characteristics of the affected areas and the consequences of the proposed treatments. The social aspects embraced the stimulation of user awareness of the importance of water quality, the creation of organisations to coordinate user-sponsored control activities, and the awakening of the community identity.

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Basic to all are the technical and economic aspects which make the activities feasible and operational (Gutiérrez et al. 1996).

Most of the water hyacinth control methods have been used in Mexico; harvesting by hand and machine, mechanical crushing, and treatment with herbicides and biological agents. Experience indicated that water hyacinth is controllable if the process takes account of plant dynamics and factors that influence plant behaviour. The project considered biomass, cover and growth to be important. The objective of this work was to characterise the initial population of the weed to assist with and assess control programs.

Materials and Methods

The best control strategy is that which reduces the biomass of the water hyacinth in a reasonable time and at an acceptable cost, i.e. the use of one or several control methods that effectively reduce the amount of plants faster than its natural reproduction, without negatively affecting the ecosystem. Even though there are many interacting variables and components, the behaviour of the plants is one of the most important factors. In terms of weed control, plant behaviour can be studied through three parameters: biomass, infestation level (surface area covered), and growth rates. These factors vary in time and space and are site-specific.

Biomass

The biomass is defined as the amount of weed mass in a particular area or volume. The effect of a water hyacinth population over the water ecosystem depends on this characteristic. The excessive increase in biomass is an indication of an increment in the energy conversion rate caused by the availability of resources. Water hyacinth is an example of an exotic plant that competes effectively for the space.

Concerning mechanical control, Hutto and Sabol (1986) mention that the effectiveness of a cropping system depends mainly on the standing crop because that determines a machine's movement rate throughout a work site and the number of loads that can be transported. Biomass of plants also influences the efficacy of herbicides. In practice, it seems unlikely that 100% control of water hyacinth using herbicide can be obtained when it grows in heavy infestations because adjacent plants screen one another (Gutiérrez 1993). These considerations show the need to measure the standing crop of water hyacinth in the infested water bodies where a control program is to be established.

Plant biomass was obtained by weighing samples from the field and estimating the weight of the population. One square metre samples were collected, drained for 5–7 minutes, and weighed using a 50 kg (± 1 kg) scale. Sub samples of 1 kg were dried to constant weight and weighed.

The number of samples per sampling, N, was determined according to Madsen (1993):

$$N = \frac{s^2}{\left(0.1 \times \bar{x}\right)^2} \qquad (1)$$

where s is the standard deviation and $\bar{x}$ is the mean.

Cover

Cover was defined as the space covered by the weed as seen from above (Brower and Zar 1977). To estimate cover on small water bodies, estimates were made by mapping the infestation, at different times, while standing on a predetermined, elevated set-point. The area covered was then determined for each date by comparing the mapped infestation with the known area of the water body. The area was used with the estimated weight per unit area to calculate total biomass.

Landsat-TM satellite images were used to estimate cover on large water bodies. In the images a 'false colour' compound is generated through the Satellite Image Automatic Detection System (SIADIS), by highlighting areas and combining bands 1, 2, 3, 4, 5 and 7, using blue, green and red filters, respectively.

Growth

Weed growth was determined from the weight increase of the water hyacinth mass per area unit and per time unit, i.e. its productivity (Westlake 1963).

Quantification of rate of growth is important for control. The rate is affected by factors such as nutrients, climate, space and compaction.

To measure growth four 1 m^2 compartments were installed into the edges of water hyacinth mats. All material was removed from inside the compartments. One kg of selected ramets (healthy, undamaged, with 3–5 leaves, of uniform size and weighing 30 to 45 g each) was placed into each compartment and allowed to grow. After 30, 60 and 90 days, the wet weight of the 2 m^2 was obtained using the same procedure for biomass determination described above.

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For comparison purposes between sites and other data obtained in different water bodies, the daily relative growth rate (RGR%) and the biomass doubling-time (DT) were calculated according to Mitchell (1974, cited in Sastroutomo et al. 1978):

$$RGR\% = \frac{\ln X_t}{\ln X_0}(100) \quad (2)$$

$$DT = \frac{\ln 2}{RGR} \quad (3)$$

where X_0 is initial weight and X_t is weight after t days.

The three parameters (biomass, cover and growth rates) were obtained in seven water bodies whose main characteristics are shown in Table 1. These reservoirs were classified mesotropic if phosphorus concentrations were between 10 and 35 mg/m^3 or eutrophic if phosphorus concentrations were 35 to 100 mg/m^3 (Vollenweider 1983).

Results and Discussion

The highest biomass average was 49.6 (2.79) kg/m^2, and a maximum value of 76 (4.27) kg/m^2, occurred in Cruz Pintada Dam. This was the smallest dam studied and had the highest level of compaction. In general, these values are similar to those obtained in other parts of the world, except for a value of 5.96 kg/m^2 dry weight observed in Jaipur, India (Trivedy 1980).

Maximum cover generally occurred when the surface area was smallest, and consequently, storage volume lowest. The extraction of water from the dams stranded a great part of the water hyacinth on banks where some died of desiccation. Other plants recovered when water levels increased.

The purpose of measuring water hyacinth growth was to know the relative behaviour of the biomass in an environment that is generally favourable for its increase. The form of this increase and its mathematical representation can be used as a starting point to plan a control program.

It will not be possible to reduce plant infestation while the removal rate of the biomass, either by harvesting, crushing or another procedure, is less than its growth recovery rate.

Table 3 shows the weight changes measured at Requena Dam. Data for location (a) in Table 3, the most comprehensive data set, are also presented as Figure 1.

This ratio showed a growth approximated to the logistic equation 4.

$$W_t = \frac{K}{1+e^{a-rt}} \quad (4)$$

where:

W_t is wet weight for each determined time (kg/m^2);
r is growth rate per day;
K is growth limit value of the population or load capacity (kg/m^2);
t is time; and
a is an integration constant defining curve position in relation to its origin.

When supposing a growth of this type, the parameters r and a can be calculated, and the logistic equation transformed into its rectilinear form (equation 5):

$$W_t = \frac{K-W}{W} = a - rt \quad (5)$$

The results of this exercise are shown in Table 3(a). Even though the correlation of the points was very high (0.986), a significance test of the regression was carried out according to Zar (1974). This test rejected, with a probability higher than 99%, the possibility that the points over the straight line are adjusted by chance. The same test was carried out to the data in Table 3(b) and 3(c) resulting also in the rejection of the possibility that the points are adjusted to a straight line by chance, except that for both cases the reliability level was 95%.

It is accepted that the water hyacinth growth is close to logistic growth. Sato and Kondo (1983) established that the biomass increase (fresh weight per surface unit) closely approximates the logistic equation; and Del Viso et al. (1968) demonstrated that the annual growth cycle of this plant in Argentina can be represented by a sigmoid curve.

Reddy and Debusk (1984), in growth evaluations with plants cultivated in a pond with unlimited nutritional conditions, determined the growth characteristics of water hyacinth in the central part of Florida, USA. They obtained a growth curve characterised by three phases: 1. a delay phase followed by exponential growth; 2. a linear growth phase, and 3. a slow exponential growth phase. These characteristics are very similar to the results obtained in this study, where behaviour was measured directly in the field.

We considered that the carrying capacity of the system (K), was reached during the periods when maximum biomass was obtained: 51 kg/m^2 for July to

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February (Table 3a), 51 kg/m^2 for December to March (Table 3b) and 55 kg/m^2 for April to June (Table 3c). These values are not shown in the respective tables because the values shown are averages. Reddy and Debusk (1984) suggested that the water hyacinth growth cycle was complete when the maximum density of plants was reached and therefore an additional significant biomass increment was not observed. They found a maximum biomass close to 2,300 g /m^2 in dry weight, while in this study a range of 2,101–3,916 g /m^2 was estimated.

The *r* and *K* parameters from the logistic equation provide an objective comparison between different water systems. They also provide a foundation for a prospective model of the water hyacinth behaviour on a water body, as influenced by different rates of biomass removal.

Table 1. Characteristics of the seven water bodies under study (modified from Bravo et al. 1992)

Parameter	Chairel Lagoon	Cruz. Pintada Dam	Sanalona Dam	Solís Dam	Requena Dam	Endhó Dam	Valle de Bravo Dam
North latitude	22° 16'	18° 26'	24°48'	20° 04'	19° 57'	20° 04'	19° 21'
West longitude	97° 54'	99° 01'	107° 09'	100° 35'	99° 18'	99° 20'	100° 11'
Altitude (m)	0	1,011	135	1,880	2,110	2,018	1,830
Climate	Hot	Hot	Hot	Temperate	Temperate	Temperate	Temperate
Temperature (°C)	24.3	22.0	24.4	21.5	15.4	17.0	18.1
Precipitation (mm)	1,096	800–1,000	814	734	553	609.4	1236.9
Surface area (km^2)	38.790	0.100	24.000	57.02	5.4	8.43	17.3
Volume ('000 m^3)	28,794	400	473,000	794,000	30,300	107,900	300,000
Depth (m)	1 a 3	4	19.7	14.0	5.0	15	19.4
Trophic level	mesothropic	eutrophic	mesothropic	eutrophic	eutrophic	eutrophic	mesothropic

Table 2. Weight per m^2, surface area covered and total biomass of seven water bodies in Mexico (modified from Bravo et al. 1992)

Reservoir	Standing crop wet (dry) weight		Cover		Total biomass (t)
	Average (kg/m^2)	Maximum (kg/m^2)	Average (ha)	%	
Chairel Lagoon	39.5 (2.22)	50.5 (2.84)	376	10	148,520
Cruz Pintada Dam	49.6 (2.79)	76 (4.27)	7.5	75	3,720
Sanalona Dam	42.6 (2.39)	57 (3.20)	790	33	336,540
Solís Dam	38.8 (2.18)	63 (3.54)	3,378	59	1,310,664
Requena Dam	35.74 (2.0)	51 (2.87)	498	70	175,803
Endhó Dam	33.5 (1.88)	51 (2.87)	818	80	220,000
Valle de Bravo Dam	45.7 (2.57)	67 (3.76)	109	6	50,00

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Table 3. Comparitive studies at Requena Dam at three locations (a), (b) and (c).

	Date	Time (days)	Biomass (kg/m^2)	Logistic equation parameters	Doubling time (days)
(a)	16-07-86	0	0.25	*a* = 4.7073	8.2–8.45
	14-08-86	29	2.70	*r* = 0.0499	
	17-09-86	63	15.4	*K* = 51 kg	
	13-10-86	89	26.0	Corr. = 0.9860	
	18-11-86	125	39.0	Reliability:	
	10-12-86	147	45.0	greater than 99%	
	19-01-87	187	50.0		
	17-02-87	216	50.5		
(b)	10-12-86	0	0.250	*a* = 5.2780	2.03–34.66
	19-01-87	40	0.563	*r* = 0.0162	
	17-02-87	69	0.675	*K* = 51 kg	
	17-03-87	97	1.288	Corr = 0.9838	
				Reliab. = 95%	
(c)	28-04-87	0	1.0	*a* = 3.2746	9.34–7.42
	12-05-87	14	3.7	*r* = 0.0722	
	12-06-87	48	22.0	*K* = 55 kg	
	30-07-87	93	53.5	Corr = 0.9598	
				Reliab. = 95%	

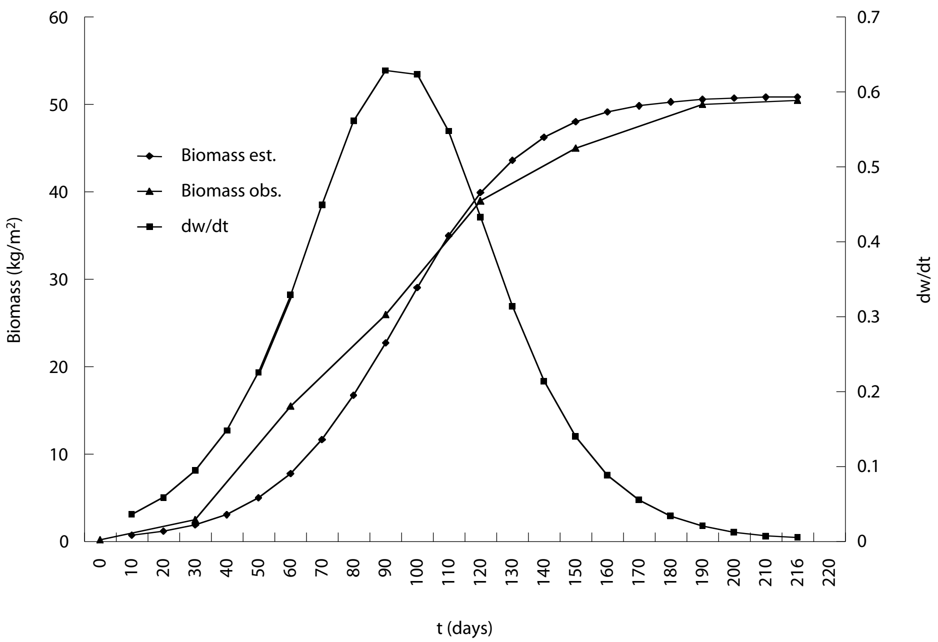

Figure 1. Weight changes for water hyacinth at Requena Dam

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Regarding the growth rate, in Florida an average rate of 52 g/m^2/day was observed during June and July, with a maximum value of 64 g/m^2/day. At the Requena Dam, rates of 59.1 and 60.4 g/m^2/day were estimated for the July to February and April to June periods. The growth rates in both studies were calculated from the slope of the growth curve, adjusted by square minimums. If we consider an average growth rate of 0.551 tonne/ha/day, during the growth season (April to November, 244 days), approximately 134.4 tonne/ha/year can be produced in the dam. Westlake (1963) qualified the water hyacinth as a very productive plant. From data of Louisiana, USA and the Nile, Africa, he estimated that if this species grows under good conditions, with a good density and without space limitations and a continuous predominance of young plants, it can produce as much as 110–150 tonnes of organic matter/ha/year, a value very close to the value estimated in this study.

A wide range of values for the productivity of this plant has been registered in the literature. These values have been calculated in different ways (Gopal 1987). Knipling et al. (1979) estimated that the annual production can be as high as 269 t/ha. Boyd (1976, cited in Gopal 1987) obtained an average productivity of 194 kg/ha/day in an enriched pond. Wooten and Dodd (1976) and Yount and Crossman (1970) determined, respectively, a daily productivity of 290 and 540 kg/ha; the latter value corresponds to a eutrophic lake. Singh et al. (1984) and Wolverton and McDonald (1979, cited in Gopal, 1987), estimated a daily production of biomass of 26 and 72 g/m^2, the latter for wastewater effluent.

This information shows that water hyacinth has a wide productivity range. However, the values that are closer to those obtained in this study are similar to those generated in waters with high content of nutrients, wastewater effluents and eutrophic water bodies.

The determinations made are considered a good approximation to the net primary productivity of this species. Corrections were not made for death, disease and herbivory. Westlake (1963) indicate that unless herbivory is visually obvious, it is probably not important. Herbivory was not observed in this study.

Rates of loss due to natural plant death vary from place to place. Because leaf production is constant and proportional to leaf mortality, each mature shoot maintains a relatively constant number of leaves (Center et al. 1984; Center 1987). Generally, the losses are not higher than 2–10% of the maximum biomass (Harper 1918; Borutskii 1950; Westlake 1965; all cited by Sculthorpe 1967). In tropical and subtropical habitats, mortality occurs throughout the year, usually as much as new material is produced, so that the biomass remains more or less constant (Sculthorpe 1967).

For comparison purposes, it is appropriate to calculate the relative percentage growth rate (RGR%) and the DT of the water hyacinth biomass. The RGR% and the DT were calculated for the first measurement of each experimental lot. They are shown in Table 3.

The daily RGR% was between four to five times greater in summer and spring than in winter, resulting in a shorter DT of the biomass. These results are similar to those obtained by Sastroumoto et al. (1978) who determined in Chiba, Japan, that the RGR% and the DT of the water hyacinth was five times higher and four times faster in summer than in winter. These authors observed that if fertiliser (10 kg N, P, and K) were added, the RGR became eight times higher and the DT five times shorter. We concluded that the differences between spring–summer and winter found in the Requena Dam are the result of differences in water quality rather than in temperature.Table 4 shows RGR%, DT, K and r values estimated in the other water bodies that were assessed. In Mexico, the highest RGR% value obtained was in Requena Dam (9.34%). Higher values were obtained in Florida, 12% (Cornwell et al. 1977) and in the Sudan, 11.8% (Pettet 1964), both in summer and under natural conditions. Growth of water hyacinth is influenced by a number of factors. However, in Mexico its growth varies across a range from 1.07 to 12%.

We did not determine the cause of the variation in growth. The most important factors that influence water hyacinth growth are known to be nutrient availability and temperature. However, those factors do not explain why in places lower than expected rates of growth occurred, for example, Solís Dam or Sanalona Dam.

Control model

The logistic model expressed in equation 4 is the result of the differential equation (equation 6) that, once integrated, represents the growth characteristics found in the Requena Dam:

$$\frac{dW}{dt} = rW - \frac{r}{k}W^2 \qquad (6)$$

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However, to consider the effect of biomass removal, it is necessary to include the corresponding term into equation 6. Thus the expression is (Romero et al. 1989);

$$\frac{dW}{dt} = rW - \frac{r}{k}W^2 - \frac{R}{A} \tag{7}$$

where R is the amount of water hyacinth that can be removed (kg/day) and A is the reservoir area (m^2) covered with water hyacinth.

This model presupposes that the biomass of the plants (W) is distributed evenly in the surface of the water body. The growth rate (r) is proportional to the density when density is low; as density increases, the growth rate diminishes slowly until the maximum biomass (K) is reached. Normally the biomass in K (load capacity), that is, the asymptote in equation 4, stays without apparent changes, which can be caused when impacting a control process or removal of the weed, included in the model with the term – [R/A].

This model consists of four components:

1. a variable growth rate (r) determined by the amount of initial biomass;
2. a measurement of the population size (W);
3. a measure of the limiting factor of growth ($-[r/k]W^2$); and
4. a measurement of the biomass loss ($-[R/A]$).

Romero (1989) deduced from equation 7 that this point can represented as in equation 8.

$$R^* = \frac{ArK}{4} \tag{8}$$

with R^* in kg/day.

This expression is of practical usefulness because it allows us to mathematically predict the total biomass behaviour of water hyacinth in the Requena Dam at its maximum infestation and the effect exercised by the crusher and other actions for its decline.

Thus, if we have:

Requena Dam area	$A = 4{,}928{,}300$ m^2
Growth rate	$r = 0.049$ kg/kg/day
Load capacity	$K = 51.0$ kg/m2
Removal capacity	R

Substituting these data in equation 8 we obtain:

$R^* = ArK/4 = 3{,}080{,}000$ kg/day = 3,080 t/day

If the actual rate of removal was lower than R^* the cover would never be reduced. However, if low initial biomass was present, reduction of cover (or biomass) would be possible. The model greatly depends on the initial density of the water hyacinth, i.e. the biomass per m^2 when population removal begins.

If the removal rate was greater than R^*, reduction in cover would be achieved. Figure 2 shows the biomass behaviour in each of the seven dams under a particular control level. For example, Figure 2e shows the decline in water hyacinth in Requena Dam, if 3,600 tonne/day was removed. A theoretical zero biomass value would be reached at about 200 days.

Table 4. The relative growth rate (RGR), doubling time (DT), carrying capacity (K) and intrinsic rate of increase (r) for water hyacinth in seven water bodies of the Mexican Republic (modified from Bravo et al. 1992).

Water body		Relative growth rate (RGR) (%)	Doubling time (DT) (days)	Load capacity K (kg/m^2)	Intrinsic growth rate r (1/days)
		4.45			
Chairel		1.49	15.58	46.1	0.038
Cruz Pintada		1.07	46.53	60.7	0.152
Sanalona		2.66	64.56	49.0	0.0110
Solís		4.45	26.07	51.1	0.0274
Requena	Summer	8.20	8.45	51	0.049
	Winter	2.03	34.60	51	0.016
	Spring	9.34	7.42	55	0.072
Endhó		7.07	9.9	55	0.065
Valle de Bravo		1.93	13.0	47	0.052

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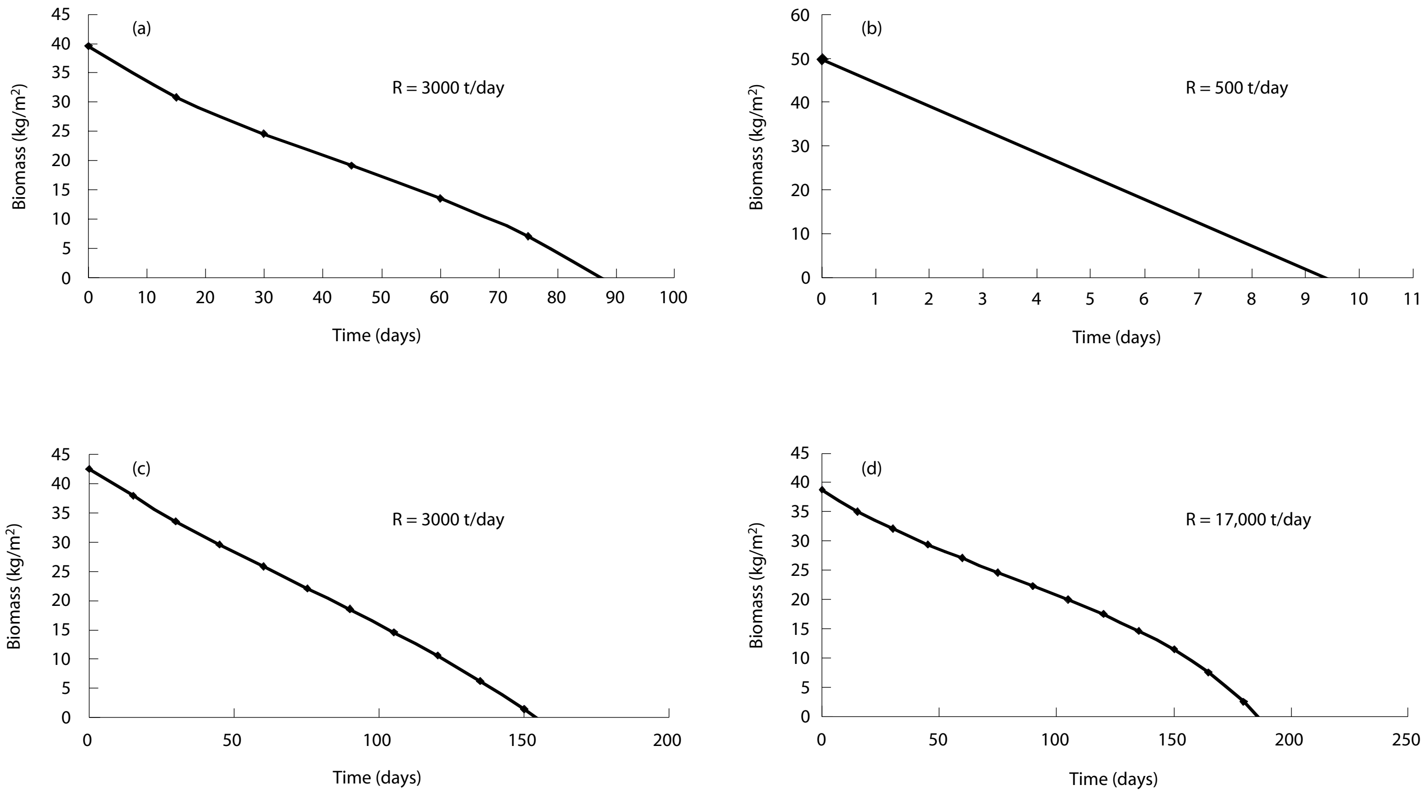

Figure 2. The estimated rate of removal and the duration to achieve a theoretical 100% removal of water hyacinth from each of seven dams; (a) Chairel lagoon; (b) Cruz Pintada dam; (c) Sanalona dam; (d) Solís dam

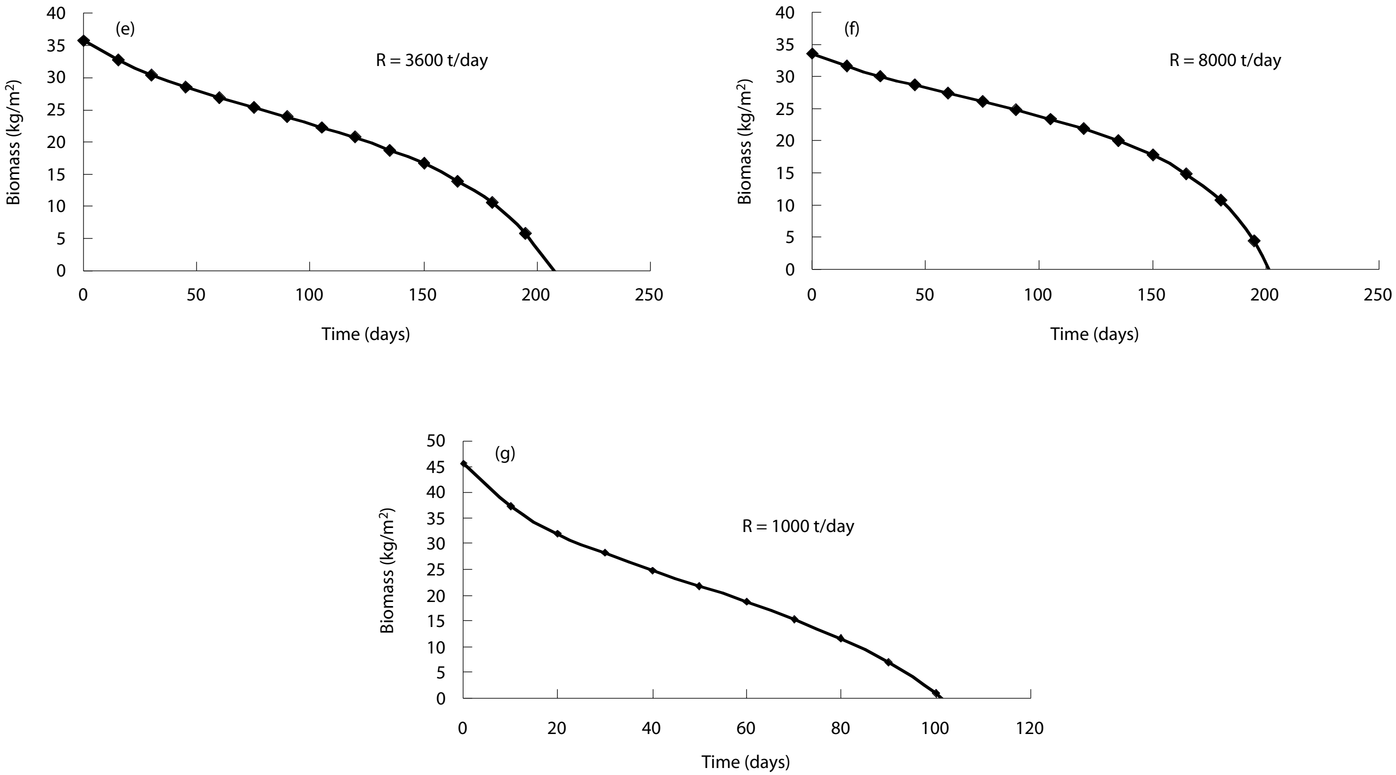

Figure 2. (cont'd) The estimated rate of removal and the duration to achieve a theoretical 100% removal of water hyacinth from each of seven dams; (e) Requena dam; (f) Endh dam; (g) Valle de Bravo dam

This removal logistic model was used to estimate the rate of removal required for a number of water bodies and was successfully applied.

The model assumes a uniform distribution of the water hyacinth over the whole surface of the water and assumes a constant rate of removal. In spite of these limitations the model allowed us to predict the biomass changes and was a useful tool in planning for the control of this weed.

The weed control program included 15 water bodies (Gutiérrez et al.1996). Aquatic weeds were removed by mechanically crushing in Requena Dam, Endho Dam and Valle de Bravo Dam (100% clear) and by mechanically harvesting in Chairel Dam and Cruz Pintada Dam (30% clear). Chemical control was used in Solís Dam, where 100% clean-up was obtained.

It is impossible to remove all water hyacinth due to germination of seeds and regrowth and so management strategies to keep the weed at lower infestation levels are required. Biological control is being used and *Neochetina* adults are produced and released in several water bodies every month. Between April 1994 and August 1998, 85,000 adults were released in 15 water bodies including Requena Dam, Endho Dam and Cruz Pintada Dam. Numerous feedings scars were observed on almost all plants and no substantial reduction in plant size, wet weight or number of plants per square metre was observed 4 years after initial releases of *Neochetina* species. Plant reproduction may be occurring much more rapidly than the weevils can inflict damage (J.M. Martinez, pers. comm. 2000).

Limitations of *Neochetina* in control of water hyacinth were recognised by Perkins (1973), DeLoach and Cordo (1976) and Perkins (1978). The effectiveness of biological control may be improved by the use of additional agents (Charudattan 1986; Forno and Cofrancesco 1993; Martinez et al. 2001). In some locations the *Neochetina* weevils are effective by themselves (Julien 2001). Studies have begun in Mexico to determine indigenous species of pathogens and to evaluate how the most promising of these may be applied as biological herbicides in areas where *Neochetina* is present, in order to enhance the control effect.

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Water Hyacinth Control through Integrated Weed Management Strategies in Tanzania

G. Mallya, P. Mjema and J. Ndunguru*

Abstract

Integrated weed management (IWM) strategies are having a significant impact on water hyacinth control in Tanzania. Water hyacinth has been reduced by over 70% within a period of 3 years. This has been achieved mainly through biological control, manual removal, quarantine regulations, and management of nutrient enrichment. Through manual removal, 60 landing beaches in Lake Victoria were kept free of water hyacinth. Through biological control, two weevils, *Neochetina eichhorniae* and *N. bruchi*, have established with adult populations of up to 30 per plant. There has been a significant reduction in water hyacinth plant population density, from 45 to 7 plants per 0.5 m^2, and large reductions in surface area covered and biomass. Maintenance and construction of wetlands have been used to minimise nutrient loading in lakes, ponds, rivers and satellite lakes. The management of water hyacinth in rivers and ponds that are acting as potential sources of infestation has recently begun.

WATER hyacinth is considered to be the most serious aquatic weed in Tanzania. This free-floating plant of South American origin (Bennet 1967; Jayanth 1988) was observed for the first time in Tanzania in 1955 in the River Sigi and 1959 in the Pangani River. In 1955 it was gazetted as a noxious weed. In recent years, water hyacinth has spread faster, and the most serious infestation is in Lake Victoria (Labrada 1995). In 1995, about 700 ha of the shoreline including bays and gulfs were affected and by 1998 the coverage was estimated at 2000 ha (LVEMP 1999). Water hyacinth has posed serious environmental and socioeconomic problems in the use and management of water resources.

To mitigate the water hyacinth problem in Tanzania, and in Lake Victoria in particular, integrated weed management (IWM) strategies with emphasis on a biological control program were initiated in 1995 under the Lake Victoria Environment Management Project (LVEMP), which is a comprehensive, regional-level environmental program. Under this project, each of the riparian countries of Kenya, Uganda, and Tanzania carries out water hyacinth control in the Lake Victoria within its boundaries. This paper discusses the use of IWM strategies to control water hyacinth in Tanzania, focusing on success achieved so far.

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IWM Strategies

Tanzania has integrated biological control, manual removal of water hyacinth at strategic sites in collaboration with local communities, quarantine regulations and management of nutrient influx into rivers, ponds and lakes to attain sustainable management of water hyacinth.

Biological control

Work towards biological control of water hyacinth in Tanzania was started in May 1995 when 418 water hyacinth weevils (*Neochetina eichhorniae* and *N. bruchi*) were imported from the IITA Biological

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Control Centre for Africa, Benin into Tanzania and mass-reared at Kibaha National Biological Control Centre. By June 1995, the weevils had multiplied to over 2000 insects. Between July 1995 and June 1996, 9000 adult weevils were released into the Sigi and Pangani rivers. *Neochetina* weevils were released into Lake Victoria for the first time during 1997 and were followed by subsequent releases covering all the weed-infested bays, gulfs, ponds and satellite lakes. Eleven (8 community and 3 Institute managed) weevil-rearing units were built around Lake Victoria each with 20 to 50 plastic tanks with 500 L capacity. Adult weevils were held on plants to lay eggs. Adults were then removed and the plants with eggs placed into the field. Assessment of spread and impact of the weevils is done regularly at both release and recovery sites.

Physical control of water hyacinth

Physical control involves manual removal of the weed using simple tools and equipment. This is aimed at keeping landing beaches, water sources, pumps, and recreational areas free from water hyacinth. The local communities and non-government organisations are constantly involved in identifying and clearing infested sites. Hand tools and protective gear worth 14.5 million Tanzanian shillings (ca US$20,000) have been provided to the community by the government to enhance manual removal work.

Quarantine regulations

To prevent the spread of water hyacinth to weed-free areas, legislation is also being used in Tanzania. A draft of 'Water Hyacinth Control Regulations' was prepared in September 1999 based on *National Plant Protection Act* (No. 13 of 1997).

Control of nutrient enrichment

The nutrient conditions and the tropical environment provide fertile conditions conducive to rapid growth and proliferation of water hyacinth. This project identifies the different types of nutrients and other environmental factors that promote water hyacinth proliferation in lakes, ponds, and rivers.

Results

A generally dramatic success in combating water hyacinth infestation has been realised so far in Tanzania, particularly in Lake Victoria. Water hyacinth is no longer a menace in the Lake Victoria Basin. Biological control has worked very well.

- The water hyacinth infestation in the Lake Victoria has been reduced by over 70% over a period of 3 years.
- Data from ground survey in Lake Victoria has revealed only localised water hyacinth infestations and most of the landing beaches are weed-free.
- Plants estimated to contain approximately 30 million eggs of the weevils were placed in the field.
- Preliminary weevil impact data (7 months) from stabilised water hyacinth mats have revealed a significant reduction in plant population from 45 to 7 plants/0.5m^2 (Fig 1).
- Through manual removal, more than 60 landing beaches in Lake Victoria are kept water hyacinth-free.
- The reproductive index of water hyacinth in Lake Victoria has fallen from 6 to an average 0.5 ramets per plant (Fig 2).
- Both *N. eichhorniae* and *N. bruchi* have equally established in release and recovery sites (adult populations of up to 30 per plant) but the efficiency of each species has yet to be determined.
- A survey has revealed the existence of eight water hyacinth infested ponds in the Lake Victoria basin with coverage ranging from less than 1 ha to 35.5 ha and weevils have been released in some of them.
- Nitrogen and phosphorus have been identified as important nutrients in Lake Victoria. They come mainly from industrial, domestic and agricultural effluents.

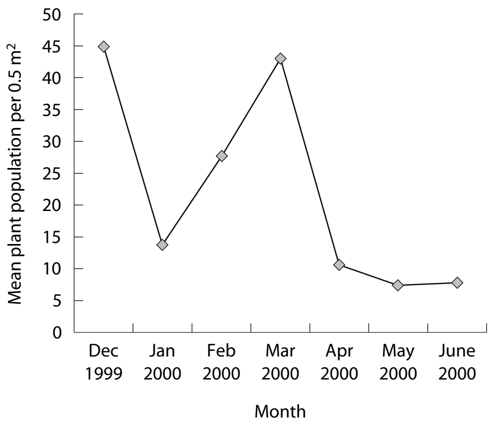

Figure 1. Changes in plant population

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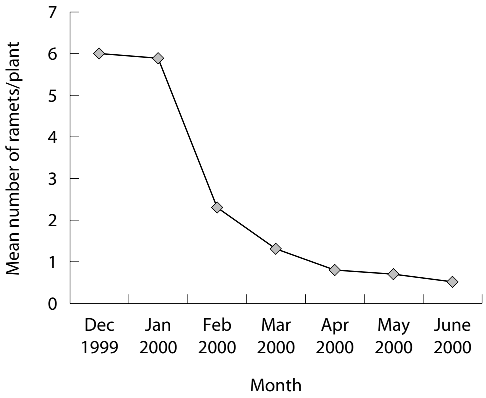

Figure 2. Changes in the number of ramets per plant

- Wetlands have been constructed and maintained to decrease nutrient loading into the lake.
- Ecological succession is evident in water hyacinth management sites whereby pure water hyacinth is invaded mainly by water sedges (*Cyperus* sp.).

Conclusions

The benefits of IWM strategies in dealing with water hyacinth have been demonstrated in Tanzania. Water hyacinth in Lake Victoria has been tremendously reduced. However, there is a continuous inflow of water hyacinth (0.2 to 0.8 ha/day) into Lake Victoria from the Kagera and Mara rivers. Furthermore, resurgence of water hyacinth has been observed in some parts of the water hyacinth managed areas, mainly from seed reserves, and there is a pressing need to manage them. The continuous presence of water hyacinth in the lake and the conditions that supported its rapid spread are still in place. Future work to prepare for any renewed infestation should include:

- research on the relationship between *Neochetina* weevils and water hyacinth;
- examining the possibility of using other water hyacinth control methods;
- carrying out socioeconomic impact assessment of the water hyacinth management strategies in Tanzania; and
- development of a surveillance system that would provide timely information regarding the location, relative size and rate of increase of water hyacinth mats along the shoreline. A network of observers (mainly fishermen) will be developed to report any charges in hyacinth coverage within the area.

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Integrated Control of Water Hyacinth on the Nseleni/Mposa Rivers and Lake Nsezi, Kwa Zulu-Natal, South Africa

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Abstract

Water hyacinth infestations on the Nseleni/Mposa River system were sprayed with a herbicide on an ad hoc basis between 1983 and 1995, with no real results being achieved. During the summer of 1985–86, the first biological control agent, the weevil *Neochetina eichhorniae,* was introduced into the system, and by the end of 1986 beetle activity, estimated by adult feeding scars, was common throughout. During 1995, a formal Integrated Water Hyacinth Control Programme was introduced to form a holistic approach to use the various control options that were available; i.e. chemical, mechanical and biological.

A committee comprising all parties/communities adjacent to the rivers and lake that were affected by the water hyacinth was formed to monitor the new integrated control program. The program consists of four main components, namely: Survey, Plan, Control and Record. The Nseleni River (17.1 km affected), Mposa River (4.9 km affected) and Lake Nsezi (≈ 260 ha) have been divided into eight management units.

By using the integrated control approach, a total of 18.9 km of river has been cleared of water hyacinth between 1995 and the present. The management units that have been cleared of water hyacinth, now require only occasional follow-ups to spray any regrowth with a herbicide or to physically remove it. Recent records indicate that previously recorded 'red data' species of avifauna have returned to the area, namely bitterns (vulnerable and rare), storks (rare) and African finfoot (indeterminate). Oral reports from the local rural communities that rely on fish as a source of food, indicate that their catches have improved—a sure sign that the control of water hyacinth in the system is having a positive ecological impact.

Also of importance is the fact that there is reduced evapotranspiration because of removal of water hyacinth, which in turn makes more water available to the environment, industry and the surrounding communities, both rural and urban. The rural communities have benefited directly, as they are now able to fish and thereby feed their families. As a result of the success of this control program, the entire catchments of the Mposa River (Mbabe and Nyokaneni rivers) have been included in the program.

WATER hyacinth was first recorded in South Africa (Cape Province and Kwa Zulu-Natal) in 1910 (Gopal 1987). It is believed to have been introduced as an ornamental aquatic plant and has since been spread to numerous localities throughout the country by gardeners, aquarium owners and boat enthusiasts (Jacot Guillarmod 1979). The main distribution occurs from low-lying subtropical to high elevations where frost occurs (Cilliers 1991).

Water hyacinth is not the only problematic alien aquatic plant in South Africa, as other aquatic plants such as parrot's feather (*Myriophyllum aquaticum)*, red water fern (*Azolla filiculoides*), water fern (*Salvinia molesta*), water lettuce (*Pistia stratiotes),* the

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reed (*Arundo donax*) and the bullrush (*Thypha capensis*) also occur. Water hyacinth it is believed to be the most problematic. In addition, plants such as the two reeds *Phragmites mauritianus* and *P. australis* have been identified as being plants with future major impact possibilities (C.J. Cilliers, pers. comm.).

Water hyacinth is a declared weed in South Africa and is covered by legislation. This is the *Conservation of Agricultural Resources Act* (Act 43 of 1983) and is administered by the Directorate of Resources Conservation of the National Department of Agriculture. The Act states clearly that this weed must be controlled. The South African Department of Water Affairs and Forestry (DWAF) is mandated to co-ordinate the control of water hyacinth and to execute measures in situations where the weed threatens state water works. In other scenarios it becomes the responsibility of the provincial and local water authorities.

Water hyacinth was first recorded on the Nseleni/Mposa Rivers (28°42'S; 32°02'E) and Lake Nsezi system in 1982 (Ashton 1982) and is believed to have been introduced in approximately 1978 as an ornamental plant. At this stage the water hyacinth infestation had already been recognised as being a problem, covering an area of approximately 1.5 km^2. There were serious concerns that damage would be caused to: (1) the national road bridge over the Nseleni River, and (2) the functioning of the two water treatment facilities on Lake Nsezi.

The Nseleni and Mposa rivers, as well as Lake Nsezi, are used by the surrounding rural communities to supplement their daily food with fish catches. For many, the fish they catch are their main source of dietary protein. Both large-scale sugarcane farms and small-scale subsistence farms also irrigate from the river. Mhlathuze Water Board (the local water authority) pumps water from Lake Nsezi and supplies water for both domestic and industrial use to the greater Richards Bay and Empangeni areas. In addition, extraction points for Richards Bay Minerals (mining) and the rural town of Nseleni are located on the Nseleni River. A sewage plant that serves the rural town of Nseleni is located on the bank of the Mposa River.

The Kwa Zulu-Natal Nature Conservation Service (KZNNCS) at one stage offered boat trips for bird viewing on the Nseleni River. These were abandoned as water hyacinth encroached on the river. Rare species of avifauna, like the African finfoot (*Podica senegalensis*) and other aquatic fauna and flora disappeared from the area, as a result of the increase in the water hyacinth infestation. In addition, the rural communities were not only unable to fish, but also found it impossible to cross the Nseleni River to get to their work places on farms.

Control Efforts

Ad hoc control efforts were practised between the late 1970s and 1994 by various interested and affected parties. By 1982, stretches of the Nseleni and Mposa rivers were covered with water hyacinth (100% coverage) and KZNNCS initiated control of the weed. In 1984, a heavy flood alleviated the problem, as most of the water hyacinth was washed away before an aerial spraying operation could be implemented. Thereafter, little was done to the remaining islands of water hyacinth, because the decreased level of infestation was no longer seen as a threat.

Chemical control was reintroduced in the mid 1980s when the Nseleni River was once again covered by water hyacinth, but there was no management plan and chemical spraying was carried out on an ad hoc basis. It is important to note that eradication/control steps were undertaken only once the water hyacinth became a problem.

In an independent effort, the Plant Protection Research Institute (PPRI) of the Agricultural Research Council imported (via Australia) a weevil, *Neochetina eichhorniae*, releasing 1400 adult insects on the Mposa River in December 1985. By November 1989, most of the water hyacinth had once again washed away as a result of exceptionally heavy floods. However, the biological control agents persisted on the remaining water hyacinth.

To put a monetary value on the economic loss caused by water hyacinth on nearly 22 km of river and 360 ha of lake proved to be extremely difficult, because of the ad hoc control efforts that were implemented. The cost to KZNNCS in just keeping the river open on its 6.3 km of river boundary amounted to R15,000[1] in 1991. When the infestation was at its height by the mid 1990s, it cost R20,000 to clear sections of the river.

Mhlathuze Water Board remains opposed to and concerned about any possible large-scale chemical spraying of water hyacinth and the effect the decaying organic material would have on the odour and taste of the water. In addition, it also feels that water hyacinth partly purifies the water, because of the nutrients it takes up. Large-scale aerial spraying could also have detrimental environmental effects on lake and riparian

[1] R = South African Rand. In March 1991, R3.67 = US$1.

vegetation such as *Papyrus* spp. and *Barringtonia racemosa,* as well as other indigenous flora. This would be undesirable and ecologically unacceptable. In addition, any uncoordinated large-scale chemical spraying at the wrong time would nullify the effect of the biological control agents, as all sessile stages are killed when plants are sprayed when there is not a peak of adult insects.

In an additional independent effort, PPRI (Pretoria) introduced *Niphograpta albiguttalis* (150 moth larvae) and a mite *Orthogalumna terebrantis* (800 adults) in January 1994, in an attempt to supplement the previously introduced weevil *N. eichhorniae.* At the same time as these biological control agents were released, water hyacinth plants were inspected for weevil damage. Results indicated that the weevil *N. eichhorniae* had spread throughout the system, which was a positive sign.

During 1994, an aerial survey was undertaken in an attempt to record the extent of the water hyacinth infestation in the entire system. The results of the survey indicated the infestation varied between 100% and approximately 40% coverage in different sections of the system.

Integrated Water Hyacinth Control

In March 1995, an Integrated Water Hyacinth Control Committee was formed. This committee met regularly and welcomed other representatives from the community to attend these meetings. It also held 'open days' to show the community the results achieved.

The first objective of the committee was to collate all the work that had previously been carried out on the water hyacinth infestation and to formulate a holistic approach to use the various control options that were available; i.e. chemical, biological and mechanical. In addition, a management plan was formulated, consisting of four main components, namely Survey, Plan, Control and Record, as well as an action plan for when floods occurred.

A map of the system (affected areas: Nseleni River – 17.1 km, Mposa River – 4.9 km and the Nsezi Lake – 268 ha) was drawn up and used to designate eight management units (MUs) of controllable size (Fig. 1). Further to this, each MU was assigned a level of control, i.e. total control or containment, as well as the appropriate method of control, i.e. chemical, biological, mechanical or a combination of control methods.

It was emphasised at the outset that the management plan was a working document and that objectives and control methods would change as work progressed. In addition, the committee emphasised and recognised that total eradication was impossible, because of the long lived seed source. Water hyacinth seed can lie dormant for up to 14 years (Penfound and Earle 1948). It was therefore recorded that total maximum acceptable percentage coverage would be 20%.

Each MU was assigned to an individual, organisation or company. For example, MU 1 was assigned to a sugarcane farmer and KZNNCS, MU 2 to KZNNCS, MUs 3 to 5 to MONDI Forestry and KwaMbonambi Conservancy, MUs 6 and 7 to KZNNCS and MU 8 to the local water authority—the Mhlathuze Water Board (to merely inspect and report on the status of biological control agents).

In March 1995 it was stated that the objective for MUs 1 to 4 would be total control using all methods available, and that containment of the infestation using biological control agents in MUs 5 to 8 would take place. Further to this, various sectors from the community were assigned MUs to control. Awareness campaigns were run at the same time, through lectures, radio talks and articles in the local press. Instead of using labour from the local rural community to remove water hyacinth manually, school children and their elders were successfully prompted to replant and stabilise the banks of the river with suitable indigenous vegetation where they had previously chopped down trees to practise subsistence farming. This was done because of the threat from crocodiles in the river, which killed several children every year. This was unrelated to water hyacinth control.

In an attempt to reduce the spread of water hyacinth seed and to make the chemical control cost effective, permanent cable booms (28 mm steel) were placed across the river at the confluence of the Mposa and Nseleni rivers (MU5), at the southern end of MU2 and at the northern end of MU6. Cables were also installed across the river where MUs 6 and 7 met and where MUs 7 and 8 met. The cables were placed in such a manner that they hung beneath the surface of the water, thereby catching the root system of the water hyacinth. Plastic buoys (donated by the Richards Bay Coal Terminal) were used as flotation on the cables. Note that each permanent cable has a 'weak link' in it. Previous experience showed that during floods, not only was there a vast volume of water, but that the cable anchors (trees) were unable to hold the weight of the water hyacinth that built up on the cables.

In addition to the permanent cables across the river, temporary cables placed across MUs 1, 2 and 6 to allow the water hyacinth to back-up against them, which assisted the chemical control method.

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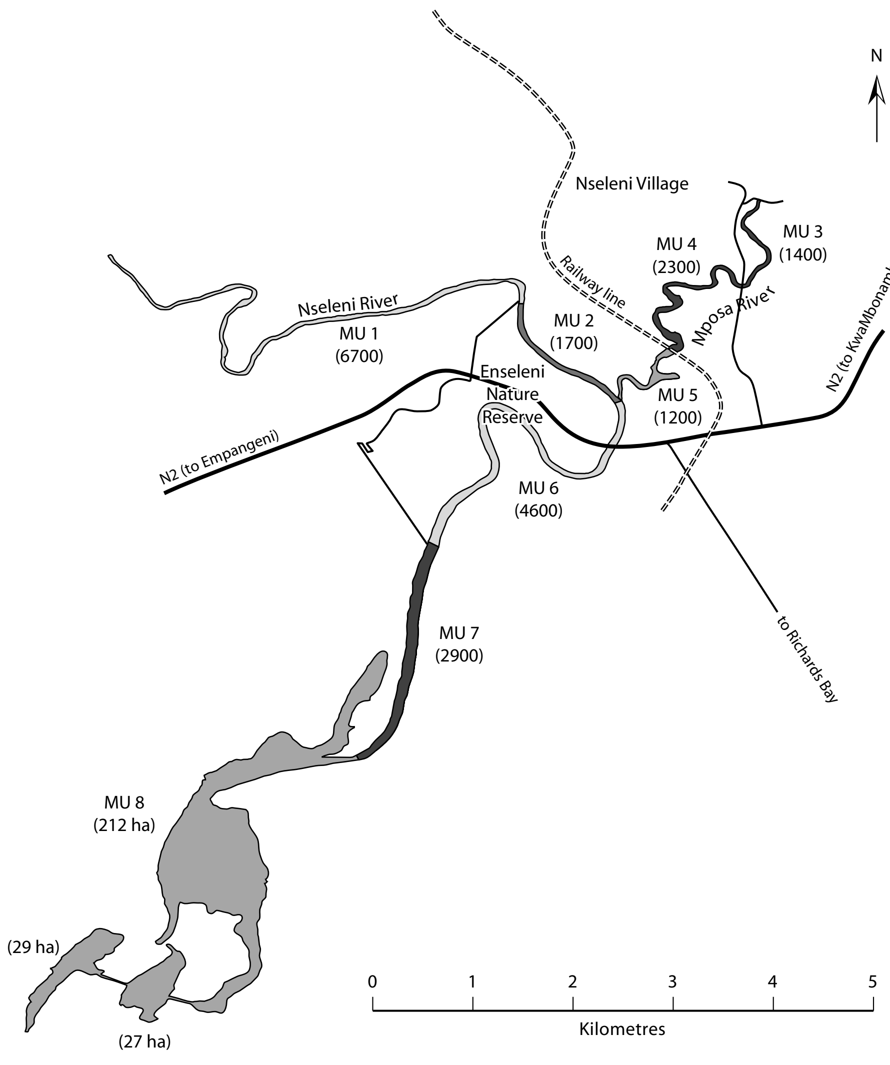

Figure 1. Management units (with length of units in metres) for water hyacinth control on the Nselini/Mposa rivers and Lake Nsezi

Further assistance to the control program occurred when the Nseleni sewerage works on the Mposa River was upgraded, and the effluent quality improved dramatically. Before upgrading, the ammonia (NH_3) was 14.2 ppm and the chemical oxygen demand (COD) 130 ppm. After commissioning, the ammonia dropped to 1.2 ppm and the COD to 53 ppm, a vast improvement. However, it was further recorded that nutrients were entering the system from adjacent sugarcane farms and forestry areas.

During the course of 1995, a total of approximately 2400 litres of glyphosate had been sprayed in MUs 1, 2, 3, 5 and 6 and seven river patrols were carried out to monitor water hyacinth infestations, inspect the effect that spraying and biological control had on water hyacinth and to carry out routine maintenance of the cables

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(total cost R9345.00). As a result of the success levels achieved by the end of 1995, the control committee agreed to adjust the management plan objectives and to elevate MU6 to total control and to retain MUs 7 and 8 as containment MUs (biological control only).

Because the local water authority needs to remove water hyacinth from its inlet screens, it has agreed to remove biological control agents from the water hyacinth and to return them in Lake Nsezi, thereby ensuring that they are maintained in the system.

In March 1996, the first release (50 adults and 100 nymphs) was made of a new biological control agent, the mirid *Eccritotarsus catarinensis*, at the entrance to Lake Nsezi. During June 1996, a further 500 adult *E. catarinensis* were released. It was reported at the June 1996 meeting that no chemical spraying had been done in MUs 1, 2 and 6. Because of the decreased infestation level of water hyacinth, these units had merely been monitored. The status of biological control agents throughout the system was positive, with one or more agents being recorded in the MUs where water hyacinth infestations occurred. In addition, the pathogen *Cercospora piaropi* was found on some plants, and the fungus *Acremonium zonatum* was recorded for the first time.

During October 1996, another weevil species, *Neochetina bruchi*, was obtained from PPRI (Pretoria), as well as additional *E. catarinensis* (10 infested plants), and these were released into the system. In addition, the management plan objectives were again adjusted to reflect the progress being made. The management plan now allowed for total control in MUs 1–7, with only MU8 designated for containment (biological control only). It was also agreed to drop the total allowable coverage percentage from 20% to 10%.

Records indicate that financial expenditure on control of water hyacinth during 1996 fell to R5892.00.

During 1997, glyphosate herbicide continued to be applied to water hyacinth in MU 5 (100% infestation) and MU 7 (infestation increased to 60%), with varying amounts of success. It is important to realise that the islands of water hyacinth are left after the application of chemicals. This is to allow the biological control agents to continue to move within the system.

Entry into the Mposa River (MU 5) from the south became extremely problematic, because not only was there a 100% infestation of water hyacinth, but also indigenous aquatic vegetation had severely encroached on the area. Of note was the invasion of *Echinochloa pyramidalis,* an indigenous perennial plant, which enjoys moist terrestrial or aquatic conditions and uses water hyacinth as a substrate on which to form dense stands. Other possible contributing factors towards the establishment of *E. pyramidalis*, are nutrient enrichment of water and silt-laden watercourses.

During 1997, a distance of approximately 200 m was gained into MU 5, from the southern side. In addition, MU 6 had to receive attention, because the total allowable percentage coverage exceeded 10%. Some 296 litres of glyphosate was used in MUs 5 and 6, with the required result being achieved. The status of biological control agents in MUs 3, 4, 5, 7 and 8 remained positive. A further 300 adult *E. catarinensis* were released on Lake Nsezi during the latter part of 1997.

By September of 1998, a further 238 litres of glyphosate had been applied to MUs 5, 6 and 7. Some 28 hours and 78 labour units, over a period of 25 days, were expended to inspect, carry out cable maintenance and chemically spray the water hyacinth infestations. The results of the water hyacinth infestation inspections indicated a high percentage of biological control agent activity throughout the system. During August 1998 a setback occurred when an area of approximately two hectares of water hyacinth was blown from MU 7 into MU 6, during a period of exceptionally strong southeasterly winds. Fortunately, the cable did not break and a high percentage of water hyacinth remained in MU 7. With the aid of temporary cables the approximately two hectares of water hyacinth that had blown into MU 6 and which had subsequently broken up into smaller pockets, was cordoned off and chemically sprayed.

A major injection to the control program in 1998 was the assistance received from the MONDI forests company, which achieved excellent chemical control results in MU 4 (Mposa River). Between May and October 1998, MONDI spent R2800 per month on chemicals and labour, to open up stretches of the Mposa River from both water hyacinth and invasive indigenous aquatic plants. In addition, KwaMbonambi Conservancy approached various industries in Richards Bay in an effort to get them to become involved in the project. The result of this drive was that R38,000.00 was received (to purchase new spraying equipment and an outboard engine) and MONDI Kraft offered to construct a barge-like boat and a trailer (approximately R50,000) which would be used in spraying. Further to this, KwaMbonambi Conservancy pledged 200 litres of roundup and Richards Bay Minerals pledged R6000 towards the project.

A flood during February 1999 opened up about 1 km of MU 5, and MUs 1, 2, 6 and 7 became 98% free of

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water hyacinth. The infestation in Lake Nsezi had dropped dramatically to approximately 35%. During May 1999, for the first time in many years, members of the control committee were able to proceed from a launch site in MU 2 and travel all the way to the Mhlathuze Water Board extraction point on the south-east bank of Lake Nsezi (MU 8). Biological control agents persisted on the remaining water hyacinth.

As a result of the high success rate achieved with the integrated control on the Nseleni River and a small section of the Mposa River (MU5), it has been decided to expand this project to include the catchment of the Mposa Rivers, namely the Mbabe and Nyokaneni rivers. A management plan is currently being drawn up to focus on 14 management units on these rivers (Fig. 2).

Community Involvement

Community involvement has no doubt been the secret of the success of the integrated control program. Although the control of water hyacinth was initiated by staff from the Enseleni Nature Reserve (KZNNCS), it soon became apparent that additional assistance would be required from the surrounding community, as well as the 'end users' of water, i.e. industry and

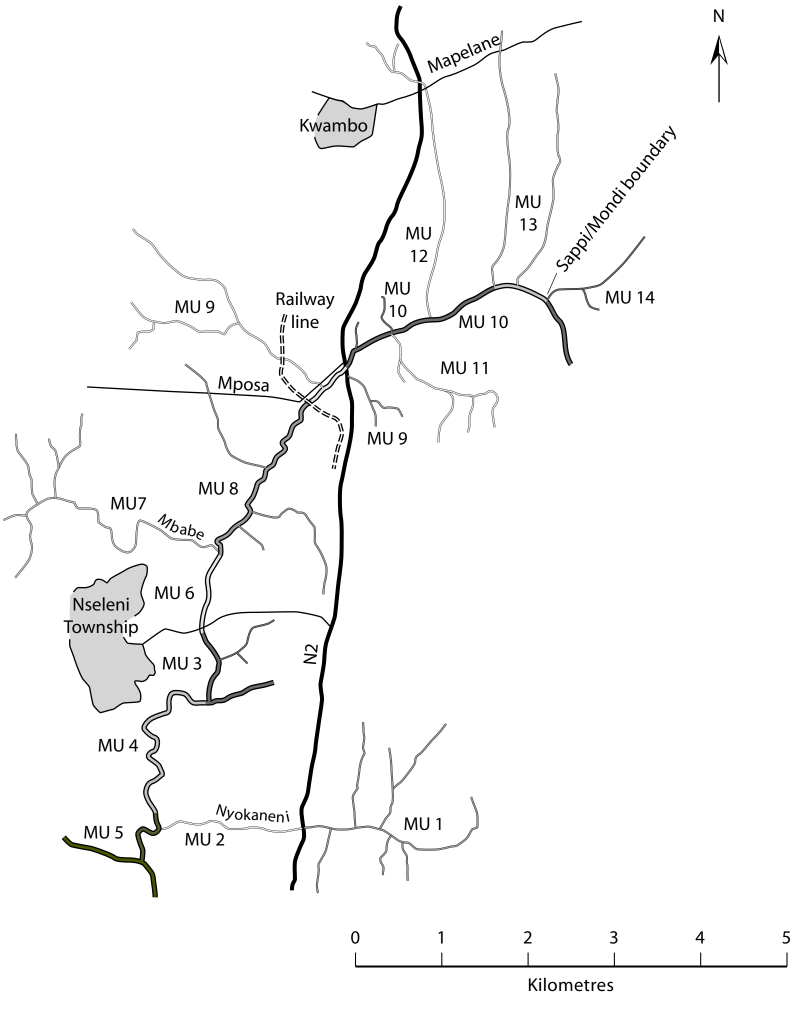

Figure 2. Water hyacinth management units of the Mbabe and Nyokaneni rivers

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urban communities. The surrounding communities became involved in the project because they depend on the water resource directly for their livelihood (fishing and agriculture), or as an extractable resource (for mining, industrial and urban uses).

It is important to note that, although such projects require vast amounts of funding in the initial stages to bring the infestation under control, a level will be reached where only maintenance will be required and therefore a set annual funding requirement must be obtained. However, funding requirements will diminish only if there is enthusiasm, success and a stable authority responsible for the implementation of the project.

Conclusion

By using an integrated control approach, between 1995 and the present, a total of nearly 22 km of river has been cleared of the original infestation of water hyacinth. The sections that have been cleared of water hyacinth now require only occasional follow-up to remove any regrowth. Recent records indicate that previously recorded 'red data' species of avifauna have returned to the waterways. Reports from the rural community, which relies on fish as a source of food, indicate that their catches have improved—a sure sign that the clearance of water hyacinth in the system is producing a positive ecological impact.

The advantages of controlling water hyacinth infestations far outnumber the disadvantages.

Water, as a natural resource, is for many reasons fast becoming a dwindling resource, and therefore demands especial attention.

Because of the success achieved with the integrated control program, the entire Mposa River catchment, i.e. the Mbabe and Nyokaneni rivers, has now been included in the control program.

Uncoordinated efforts to control water hyacinth on the same system by different parties have proven to be a waste of time and money. Once a proper integrated management plan and control is implemented, water hyacinth infestations can be reined in. Nevertheless, prevention is better than cure, and it is of the utmost importance that infestations of water hyacinth be controlled before they become a problem.

The Nseleni/Mposa rivers and Lake Nsezi scenario is an example of what can be achieved on limited budgets but with vast amounts of enthusiasm.

Acknowledgments

For their contributions to the program, I thank PPRI (Pretoria), Enseleni and KwaMbonambi Nature Conservancies, MONDI and Sappi Forests, Mondi Kraft, Mhlathuze Water Board, Richards Bay Coal Terminal, Richards Bay Minerals, the rural community of Nseleni township and the KZNNCS staff at the Enseleni Nature Reserve.

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Preliminary Assessment of the Social, Economic and Environmental Impacts of Water Hyacinth in the Lake Victoria Basin and the Status of Control

A.M. Mailu*

Abstract

The paper presents preliminary data collected in an assessment of the social, economic and environmental impacts of water hyacinth in the Lake Victoria Basin. A summary of the status of control and strategies for the future is given. The report draws on field observations made, studies through interviews of affected communities and organisations, personal communications and published reports by scientists in the region.

Lake Victoria, the world's second largest freshwater body, supports an estimated 25 million people living in the Basin, with an estimated gross economic product of US$3–4 billion annually, mainly from subsistence agriculture and fishing in Kenya, Uganda, Tanzania, and parts of Rwanda and Burundi.

The multiple activities in the Lake Victoria Basin have increasingly come into conflict, thus making the lake environmentally unstable and increasingly inviting environmental threats, including infestation by water hyacinth, which has brought social, economic and environmental problems to the communities living in the Lake Basin since its first appearance in the Lake in the late 1980s and early 1990s.

The maximum water hyacinth cover in Lake Victoria was reached between 1994 and 1995 when 80% of the shoreline in Uganda was covered with about 4000 ha of water hyacinth, there was about 6000 ha coverage in Kenya and about 2000 ha in Tanzania. In Rwanda and Burundi, tributaries feeding into River Kagera currently continue to discharge mats of water hyacinth into the lake at about 3.5 ha per day. The status as at June 2000 was slightly different, with scant water hyacinth in the Uganda side of the lake and much disintegrated and stunted water hyacinth in Kenya and Tanzania sides of the lake and the scene is now dominated by hippo grass.

Impact assessments of water hyacinth have generally been subjective, with few quantitative outputs. However, over the last nine years or so, water hyacinth has had a negative impact on the organisations and communities in the Basin. Surveys have revealed negative social impacts including lack of clean water, increase in vector-borne diseases, migration of communities, social conflict and difficulty in accessing water points. Important economic impacts readily perceived by Basin communities have included reduced fish catches, increase in transportation costs, difficulties in electricity generation and water extraction, fewer tourists, blockage of irrigation canals and environmental impacts such as decline in water quality, water loss through evapotranspiration, siltation, increased potential for flooding and a decline in the diversity of aquatic life.

Although water hyacinth has posed serious economic, social and environmental consequences, there is hope that the control strategies already adopted will continue to reduce deleterious impacts and allow sustained development in the Lake Victoria Basin. There is, however, a great need to undertake research to quantify the levels of damage, and the costs of control, loss of livelihood, disease, and disruption of normal operations caused by water hyacinth.

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LAKE Victoria, with a surface area of 68,800 km^2 and an adjoining catchment of 184,000 km^2, is the world's second largest body of fresh water, second only to Lake Superior. Lake Victoria touches the equator in its northern reaches, and is relatively shallow. Its maximum depth is about 80 m and the average about 40 m. The lake's shoreline is long (about 3500 km) and convoluted, enclosing innumerable small, shallow bays and inlets, many of which include swamps and wetlands which differ a great deal from one another and from the off-shore environment of the lake.

Kenya, Tanzania and Uganda control 6, 49, 45%, respectively, of the lake surface. The gross annual economic product from the lake catchment is in the order of US$3–4 billion, and it supports an estimated population of 25 million at per capita annual incomes in the range US$90–270. The lake catchment thus provides for the livelihood of about one third of the combined populations of the three countries, and about the same proportion of the combined gross domestic product. The lake catchment economy is principally an agricultural one, with a number of crops (including exports of fish) and a high level of subsistence fishing and agriculture. In Kenya and Uganda, the areas of coffee and tea in the catchment are a significant part of those nations' major agricultural exports. The quality of the physical environment is therefore a fundamental factor in maintaining and increasing the living standards of the growing populations in Kenya, Uganda, Tanzania, Rwanda and Burundi (Labrada 1996).

Major Threats to Lake Victoria

The lake is used as a source of food, energy, drinking and irrigation water, transport, and as a repository for human, agricultural and industrial waste. With the populations of the riparian communities growing at rates among the highest in the world, the multiple activities in the Lake Victoria Basin have increasingly come into conflict. This has contributed to rendering the lake environmentally unstable. The lake ecosystem has undergone substantial, to some observers alarming, changes, which have accelerated and are increasingly dominated by the potentially toxic blue–green algae (Twongo and Balirwa 1995). The frequency of water-borne diseases has increased. Water hyacinth, absent until as recently as 1989, has choked important waterways and landings. Overfishing and oxygen depletion in the deeper waters of the lake threaten the artisanal fisheries and biodiversity (over 200 indigenous species are said to be facing possible extinction). Scientists advance two main hypothesis for these extensive changes. First, the introduction of Nile Perch as an exotic species some 30 years ago has altered the food web structure. The second hypothesis is that nutrient inputs from its catchment are causing eutrophication. Thus, although the lake and its fishery have shown evidence of dramatic changes in the past three decades, the problems have arisen mainly as a result of human activities in the lake basin (Bugaari et al. 1998; Freilink 1991; Goodland 1995).

Aquatic Weeds in East Africa

The role of plants as a vital component of the aquatic environment is recognised as that of provision of suitable shelter and food for other plants and animals. Some plants, especially when transported to non-endemic areas, will undergo rapid growth and reproduction to out-compete native plants, becoming troublesome. They may thus become weeds that cause environmental and socioeconomic problems. Three plants, namely water hyacinth, salvinia which is also known as Kariba weed or water fern (*Salvinia molesta* (Salviniaceae)) and water lettuce (*Pistia stratiotes* (Araceae)) cause the most serious problems in subtropical regions. They are also the main freshwater aquatic weeds in the Lake Victoria Basin. Other weeds that are of minimal importance are azolla (*Azolla filliculoides*), parrot's feather (*Myriophyllum aquatica*) and pennywort (*Hydrocotyle ranunculoides*).

Aquatic weeds, including water hyacinth, grow best in tropical and subtropical climates where temperatures in the range 25–30°C favour their growth almost all year round. The Lake Victoria Basin is one such area where sufficient nutrients are available and have thus added to the rapid growth of the weed (Mailu 1998a).

Water Hyacinth in East Africa

Although water hyacinth is known to have been kept in Nairobi and Mombasa as an ornamental plant since early 1957, it appeared in the natural water systems of East Africa in Tanzania (River Sigi) in 1956 and later in the Pangani River. In Uganda and Kenya, reports indicate that the weed appeared in Lake Kyoga (Uganda) and Lake Naivasha (Kenya) and later in Lake Victoria in the late 1980s (Twongo 1993, 1996; Twongo and Balirwa, 1995; Taylor 1993). It was, however, between 1990 and 1992 that the negative impacts of the weed started becoming evident along the shores of the three riparian states. The weed has continued to impact negatively on the lives of the lakeside communities living in the Lake Victoria Basin, especially those closest to the lakeside.

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Magnitude and Distribution

Weed distribution and cover in Uganda

Preliminary monitoring of the stationary fringe of water hyacinth in Lake Kyoga demonstrated that the maximum cover was reached in 1994, when about 570 ha of water hyacinth was distributed along close to 60% of the shore. Maximum cover of stationary mats along the banks of River Nile was also estimated in 1994 to fringe about 80% of shoreline length, with total water hyacinth cover estimated at about 500 ha. In Lake Albert in Uganda, the weed remained confined to the northern and southern extremities of the lake, probably because of the turbulence of the lake and the absence of extensive sheltered, shallow banks along other shores, where water hyacinth could anchor. In the Uganda portion of Lake Victoria, the stationary fringe of the water weed stabilised in 1995 when its stretched along about 80% per cent of the shoreline and covered an estimated 2200 ha. Maximum cover of the mobile components of the weed in this lake came to about 1800 ha in 1998 (Twongo et al. 1995). Hence, the maximum cover estimate for water hyacinth in the Uganda portion of Lake Victoria was 4000 ha. Estimates made in April 1999 and in August 1999 indicated that the input of water hyacinth into Lake Victoria through the River Kagera was 3.5 ha per week. However, it was noted that a significant quantity of this influx of water hyacinth into Lake Victoria by the river was fragmented in the vicinity of the river mouth by wave action. Similarly, considerable quantities of the mobile mats of the water weed were also destroyed during its annual long distance movement around the Lake Victoria, including by rainstorms and prevailing winds. Currently only small remnants of water hyacinth plants are to be found in Ugandan waters of Lake Victoria, except in the region where Kagera River enters the lake.

Weed distribution and cover in Kenya

In the Kenyan part of Lake Victoria, the infestation of water hyacinth oscillates during the year amongst the following bays: Kisumu, Kendu, Nyakach, Homa and Asembo. Some water weeds occur also in Wichlum and Uharia in Siaya; and Rukapa and Mabinyu in the Nzoia River Delta in Busia District. Infestations are insignificant in Migori and Suba districts. In April 1998, estimated cover of water hyacinth was 1000 ha in Kisumu Bay, 3200 ha in Nyakach Bay, 600 ha in the Sondu Miriu Delta and 1200 ha in Osodo Bay. Total cover in the Kenyan waters of Lake Victoria is estimated at 6000 ha. However, a survey conducted in mid August 1999 indicated a decrease in the cover in Kisumu, Kendu and Homa bays. The indications are of increasing disintegration of the weed masses, to a point where, in certain areas, ecological succession replaces the original weed mats. A major contribution to the control of stationary mats of water hyacinth along lake shores and river banks in East Africa has been the result of ecological succession, the progressive displacement of one or more species of plants (and animals) by another. Pure mats of the waterweed were invaded initially by aquatic ferns and/or sedges, often to be followed progressively by hippograss (*Vossia cuspidator*) which invariably eventually dominated and shaded out the water hyacinth. Ecological succession has made a major contribution to the control of fringing water hyacinth in Lake Kyoga and in the Ugandan portion of Lake Victoria. As at April and August 1999, stunted water hyacinth in disintegrated mats and weed succession were clearly evident in most parts in Kenyan side of infested parts of the Lake (Mailu 1998b).

Weed distribution and cover in Tanzania

Surveys conducted in April and mid August 1999 indicated that water hyacinth infestations in the portion of Lake Victoria in Tanzania were located in Mara Bay, Bauman Gulf, Speke Gulf, Mwanza Gulf, Emin Pasha Gulf and Rubafu Bay. Currently, water hyacinth occurs also in the Kagera, Sigi and Pangani rivers, as well as in streams and water ponds around Dar-es-Salaam and close to Lake Victoria. The total cover estimate of water hyacinth in the Tanzanian waters of Lake Victoria was 2000 ha. As in Kenya, increased weed stunting and disintegration of original mats indicated that water hyacinth had experienced severe environmental stress, including that occasioned by the weevils already released into the lake.

Weed distribution and cover in Rwanda and Burundi

Currently, verbal reports indicate that water hyacinth infestations are located in the major rivers that feed into the River Kagera from both Rwanda and Burundi. Surveys in April and August 1999 demonstrated that fairly large mats of the weed were floating and moving into the Kagera River and onward into Lake Victoria at the rate of approximately 3.5 ha per

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day. The status of water hyacinth infestation in the inland waters of Rwanda and Burundi is not clearly documented (Lowe-McConnel et al. 1992).

Impact of Water Hyacinth in the Lake Victoria Basin

The concern over water hyacinth

Water hyacinth infestation has resulted in serious socioeconomic and environmental problems for millions of people in riparian communities. Normally, the weed proliferates to form extensive floating mats that cause disruption in electricity generation, irrigation canals, navigation and fishing activities, and cause an increase in water loss through evapotranspiration. The weed also reportedly provides breeding grounds for schistosome (bilharzia)-carrying snails and malaria-carrying mosquitoes. The cost of water hyacinth infestation for countries in the region is estimated to be of the order of billions of dollars. For example, in Lake Victoria, the infestation currently covers 12,000 ha and is affecting the livelihoods of more than 40 million people in Kenya, Tanzania and Uganda. By the end of 1997, media agencies reported a 70% decline in economic activities at the Kenyan port of Kisumu as a result of the water hyacinth choking the port and fish landing grounds. The rapid proliferation of water hyacinth in the region is a result of the absence of natural enemies, and the widespread availability of nutrients in freshwater bodies. The nutrient-enrichment of freshwater bodies in the region is a result of pollution and other factors arising from the rapid increase of human population and corresponding activities in urban and rural areas. Large urban sewers and other effluent discharges are well known sources of point water pollution, while extensive use of improper agricultural methods, and land uses that often result in soil erosion, are a major source of non-point water pollution. Soil erosion, especially when caused by water, carries soil nutrients into the water bodies down hill.

Water hyacinth impacts on lakeside communities

Social and economic impacts

The impacts of water hyacinth may be categorised into social, economic and environmental. Scientists in the region have attempted to gather secondary data on the impact of the weed on the lakeside communities on the Kenyan, Tanzanian and Ugandan sides of the lake. This information was collected through interviews with officers-in-charge of district hospitals, fisheries, water supplies in municipalities, cargo and human transportation. Organisations and communities affected by water hyacinth infestation were thus identified in the various countries. They are listed in Table 1.

An indication relating to the perceptions of a cross-section of the communities and agencies in East Africa on impacts, as well as on control strategies of water hyacinth, was obtained through a survey, the results of which are recorded in Table 2. Lakeside communities deemed socioeconomic impacts more important than environmental impacts. The real costs and quantified impact levels were, however, not clear to the communities. Most of those interviewed identified decrease in fish catches, increase in certain diseases, increased transportation costs, and difficulties associated with clean water availability as major negative impacts.

Fish production

Information from the Fisheries Department, Kenya indicated that there was a 28% increase in total annual fish catches between 1986–1991 and 1991–1997, from 133,097 tonnes to 169,890 tonnes. There was an increase in all species of fish caught except *Oreochromis, Clarias* and *Mormyrus,* which showed declines of 14, 37 and 59%, respectively, over the same period. These declines may have been associated with the inability of fishermen to access the fishing grounds for those species because of water hyacinth infestation.

Generally therefore, as a result of water hyacinth infestation, accessibility to land and water has been hindered, resulting in reduced fish catches, especially of tilapia and mudfish which are found mainly along the shores. Fisherfolk, however, reported increased fish catches from suitable breeding grounds provided by water hyacinth e.g. tilapia, synodontis, protopterus and labeo. There is, however, need to clarify this conflicting information; in many more areas around the lake. A reduced fish catch would have an adverse effect on the quality of life of the communities around the lake and consequently affect sustainable development in the region.

Marine cargo and human transportation

In Kenya, water hyacinth hampered the movement of smaller vessels, especially canoes, used for both cargo and human transportation. The activities of the Kenya Railways have been closed since 1997 at all the piers in Asembo, Homa Bay, Kendu Bay, Kowor, Mbita and Mfangano, except for Kisumu port, which is operational for only larger vessels, though they also

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Table 1. Organisations and communities affected by water hyacinth

Country	Affected organizations/institutions/communities
Uganda	Fishing (fishermen, fishmongers, fish processors, consumers Riparian communities Lake transport (Uganda Railway Corporation) National Water and Sewerage Corporation National Agricultural Research Organization National Environmental Management Authority Department of Fisheries
Kenya	Fishing community Kenya Railways Local councils Local and provincial administration Kenya Agricultural Research Institute (KARI) Fisheries Department Kenya Marine Fisheries Research Institute (KEMFRI)
Tanzania	Fisheries from fishermen, through traders to scientists Agricultural irrigation Electricity generating Navigation Health Water supply
Rwanda	Agriculture; irrigation Community development Various non-governmental organisations
Burundi	Agriculture; irrigation

experience some difficulties. Such vessels (weighing over 700 tonnes) have their propellers deep, avoiding entanglement with water hyacinth. Boats with capacities less than 700 tonnes cannot operate where there is heavy water hyacinth infestation. The Kenya Railways keeps 10 people permanently employed to remove water hyacinth from the bridge at the Kisumu pier. Data made available by the Port Officer, Kenya Railways, Kisumu, covering the period 1996–1998, showed an increase in incoming cargo volume (from about 43,000 tonnes to 130,000 tonnes), while the reverse was the case for outgoing volume (from about 93,000 tonnes to 37,000 tonnes). There were no records for human transportation and cargo for the smaller vessels, as the beaches maintained no proper records. The frequent closure of the Kisumu port affects the communities in several ways including loss of income and a general decline in sustainable development in the affected regions.

In Uganda, where observations had been made between 1994 and 1997, large vessels were, as in Kenya, able to force their way through the weed mats, but physical removal was also necessary in Port Bell. Vessels required extra time to dock, thus resulting in the use of more fuel.

Some initial estimates were made for these costs, but additional data and observations were required to validate the initial observations. It should be noted that these figures represent 1995 estimates. At that time the water hyacinth infestation was increasing at a rapid rate and it was recognised that unless controlled, it would spread and become more of a problem (Twongo and Balwira 1995). In the absence of a successful control program, the following were the estimated costs for the five years after 1995 in Uganda.

1. Maintaining a clear passage for ships to dock at Port Bell in Uganda: US$3–5 million per annum;
2. Cleaning intake screens at the Owen Falls hydroelectric power plant at Jinja in Uganda: US$1 million per annum;
3. Losses in local fisheries from accumulation of water hyacinth at fishing beaches and landing sites around the lake, making it difficult or impossible for fishing boats to be launched or

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Table 2. Problems associated with water hyacinth in the Lake Victoria Basin

Category	Nature of problems	Number of respondents	% Respondents
Social	Lack of clean water (debris-free)	1	5.3
	Less access to water points (domestic and livestock use)	3	15.8
	Societal conflict	1	5.3
	Increase in incidence of snake bite	1	5.3
	Disappearance of the aesthetic value of water bodies	3	15.8
	Increase in disease outbreaks (schistosomiasis, cholera etc.)	5	26.3
	Reduction of riparian-based trade	2	10.5
	Migration of communities	3	15.8
	Percentage of overall responses	*19*	*34.5*
Economic	Reduced fish catches	8	32.0
	Increase in transportation costs	5	20.0
	Difficulties in electricity generation	4	12.0
	Difficulties in water extraction and purification	5	20.0
	Interference with irrigation (blockage of canals)	1	4.0
	Effects on tourism	2	8.0
	Effects of control on government budget	1	4.0
	Percentage of overall responses	*25*	*45.5*
Environmental	Decline in diversity and abundance of aquatic life	4	36.4
	Decline in water quality	2	18.2
	Increased water loss	2	18.2
	Increased siltation	2	18.2
	Increased potential for flooding	1	9.1
	Percentage of overall response	*11*	*20.0*

recovered: US$0.2 million per annum, but with a very serious local impact.

4. Loss of the beaches, water supply for domestic, stock and agricultural purposes: US$0.35 million per annum.

Water supply

Water supply to both villages and municipalities is affected by water hyacinth. In municipalities, water hyacinth interferes with the water intake points through blockage, which lowers the quantity of water pumped. In Kisumu, the municipality reports that the quantity of water supplied has dropped from 20,000 m^3 to 10,000 m^3 per day. Homa Bay reported a capacity of 1400 m^3 per day (Table 3) against a demand of 4000 m^3 for 50,000 residents. Kisumu municipality has an alternative water source of 1000 m^3 per day from the River Kibos; while Homa Bay municipality has none. This situation thus causes constant water shortage in Homa Bay and at certain times in Kisumu.

Water hyacinth infestations have been reported to lower the water quality in Kenya and Uganda (in terms of colour, pH, turbidity (suspended solids) of water), and hence increase the treatment costs. Increased costs are associated with keeping the water intake points free of water hyacinth. For example, Kisumu Municipality employs 12 casuals per day, 6 drivers and 6 boat operators, while Homa Bay municipality engages 2 divers at a cost of 1000 Kenya shillings (Ksh) per day. In Homa Bay municipality, water hyacinth builds up 3 to 4 times in a week and it takes 3–4 hours to remove it.

Table 3 indicates that water supply capacity in Homa Bay municipality has increased over the study period from 1300 m^3 (1986) to 1400 m^3 (1998), while the price of water has risen greatly from Ksh2 (1986) to Ksh120 (1998) per m^3. There were no data for the supply of water for Kisumu municipality.

The villages bordering the lake have no access to the lake to draw water at times when the beach is heavily infested with water hyacinth. Even if they get access to the water, it is dirty and often smelly because of the rotting mats of the weed. This is true for all the 143 gazetted beaches along the Kenyan side of Lake Victoria which may be infested. The same has been noted in areas around Mwanza and Musoma in Tanzania.

Table 3. Water supply in Homa Bay municipality since 1986

Year	Quantity (m^3)	Price (Ksh/m^3)	No. of consumers (water meters)
1986	1300	2.00	500
1987	1300	2.00	520
1988	1300	2.00	550
1989	1300	18.00	600
1990	1300	18.00	650
1991	1300	18.00	700
1992	1400	30.00	770
1993	1400	30.00	800
1994	1400	60.00	950
1995	1400	60.00	1000
1996	1400	90.00	1200
1997	1400	120.00	1500
1998	1400	120.00	1700

Source: Water Engineer, Homa Bay District
Note: 78Ksh ≈1 US$

Health

The hyacinth mats provide breeding grounds for mosquitos and other vectors of disease. However, data from Kisumu District (Table 4) indicate declines in the incidences of malaria (35%) and typhoid (64%) over the study period. The trend in Homa Bay District could not be determined because of sub-division of the old South Nyanza District into five districts since 1991. There were no comparative data given for Migori District. In both Kisumu and Homa Bay Districts, there were no reported cases of snakebites. Statistics for Homa Bay for the period 1986–1991 and 1992–1998 indicated increased incidence of malaria, whereas there was a decrease in malaria cases in Kisumu over the same period. There were more cases of cholera but numbers of typhoid cases fell over the same periods; and there a slight decrease in amoebiosis. The statistics on health should be interpreted with great care as these apply only to incidences reported to the hospitals or health centres in the district. There may have been many more cases of disease that were not reported to hospitals.

Other socioeconomic impacts

Other socioeconomic impacts reported were loss of earning opportunities when fishermen could not access fishing and fish landing sites, as well as interference with fishing gear and clogging of pumps. Recreational activities were also affected. Frequent motor breakdowns and long distance travel in search of uninfested areas added to costs, likely spoilage or extra expenditures on preservation. In Uganda, interference with electricity generation was reported at the Owen Falls. Extra generation costs, and reduced efficiency were apparent until the water hyacinth was successfully controlled.

Environmental impacts

The impacts on the environment were not apparent and thus not well perceived by most of those interviewed among the communities. However, those that affected the communities directly and posed health risks were water quality (foul smell, debris) degradation, increased siltation and potential for flooding. However, other less obvious impacts included interference with diversity, distribution and abundance of life in aquatic environments. The death and decay of water hyacinth vegetation in large masses may create anaerobic conditions and production of lethal gases.

Infestations of water hyacinth affect biodiversity. Dense mats of the weed covering the water surface lead to deoxygenation of the water, thus affecting all aquatic organisms. It is known that a dense cover of water hyacinth enhances evapotranspiration.

Death of water hyacinth mats may influence changes in the composition, distribution and diversity of aquatic organisms as follows.

- Displacement of hydrophytes and depressed algal biomass (Twongo et al. 1995; Twongo and Balirwa 1995).
- Increase in diversity and abundance of some taxa of macrofauna, especially at the borders of the weed mats (Wanda 1997).
- Increase in the distribution and abundance of schistosome (bilharzia) snail vectors e.g. *Biomphalaria* spp. and *Bulinus* spp.
- Willoughby et al. (1993) reported that, based on studies on the Ugandan shoreline of Lake Victoria, mats significantly depressed the diversity of fish species and fish biomass. It was subsequently demonstrated that fish diversity, particularly small taxa, increased along the edge of water hyacinth mats (Twongo and Balirwa 1995).

It is evident that quantitative data for many of the perceived impacts are not available and that if any are available they are difficult to analyse, because of the many interrelated parameters that may influence the socioeconomic status of the riparian communities.

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Table 4. Statistics on disease infection for the Kisumu and Homa Bay districts since 1986

Type of diseases								
	Malaria		Cholera		Typhoid		Amoebiasis	
Year	Kisumu	Homa Bay	Kisumu	Homa Bay	Kisumu	Homa Bay	Kisumu	Homa Bay
1986	342633	362448	–	40	–	23	–	58716
1987	328021	325370	–	91	–	19	–	63158
1988	259839	276841	–	0	–	–	–	46012
1989	227756	377128	–	0	–	–	–	60914
1990	315570	372683	–	0	759	22	–	54641
1991	321942	469242	–	22	312	0	–	64903
Mean	299320	362952	–	26	536	16	–	58064
1992	252363	72775	5	43	252	71	–	7023
1993	19006	68553	–	19	205	152	–	5562
1994	178574	63229	–	38	191	76	–	6518
1995	148467	56692	–	0	107	88	–	4990
1996	177008	55718	–	0	287	114	–	3341
1997	278526	66861	2766	1087	217	113	–	6597
1998	128334	58694	3376	1392	76	76	–	5253
Mean	193454	63227	2049	368	191	99	–	5612

Source: Medical Officer of Health – Kisumu and Homa Bay District.

It may also be argued that, although water hyacinth poses a serious economic cost to the riparian states, the same can be said to have presented an opportunity for income earning to many labourers and manual workers in the region.

Control Strategies and Status of Control

Although water hyacinth has posed serious economic, social and environmental consequences, there is reason to hope that the control strategies adopted will eventually permit effective management of the weed.

Biological control

Since December 1996, KARI has been introducing *Neochetina* weevils from Australia, South Africa and Uganda as part of a biological control program for water hyacinth. Community-based lakeside rearing facilities have produced over 142,000 mostly adult weevils, which were released into the lake at 30 sites in 8 districts bordering Lake Victoria. Visual observations and pre and post-release sampling protocols have been used to monitor and evaluate the establishment, spread and impact of the *Neochetina* weevils on water hyacinth. Weevils are now firmly established in all affected areas and have spread as far as 50 km from points of release.

Natural enemies on the weed have been observed to have a significant impact and localised complete suppression of resident water hyacinth mats has been recorded at all sites including the Police Pier, Yacht club (Kisumu) and Bukoma Pond (Busia) some 24–36 months after release. Ecological succession by other plant species, including hippograss (*Vossia cuspidator*), papyrus (*Cyperus papyrus*) and morning glory (*Ipomea aquatica*), is now evident in most parts of the lake.

Importation and mass rearing of additional biological control agents, the moth *Niphograpta albiguttalis* (previously called *Sameodes albiguttalis*) and mite *Orthogalumna terebrantis,* was attempted, but these did not establish. Nevertheless, it is recommended that these be released in the Lake to augment control by *Neochetina* weevils.

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Recent sampling of weevil populations indicates densities of between 5.4 and 6.1 weevils per plant. Other observations include:

- disintegration of original water hyacinth mats into smaller mats;
- stress on the remaining water plants to reduce them to seriously stunted weeds;
- a general decline in water hyacinth biomass incapable of flowering and also incapable of producing ramets (daughter plants); and
- rotting water hyacinth biomass floating in smaller islands.

Ecological succession

Ecological succession—the progressive displacement of one or more species of plants by other species—has made a major contribution to the control of stationary mats of water hyacinth along the shores and banks of rivers. In Lake Victoria, pure mats of water hyacinth were invaded initially by aquatic ferns/sedges (*Cyperus papyrus* and *Ipomea aquatica*) often to be followed by hippograss (*Vossia cuspidator*) which invariably eventually dominated and shaded out the remaining stressed and dying/rotting water hyacinth. By April 1999, stunted and disintegrated mats of water hyacinth and invading weed succession were clearly evident.

Although water hyacinth will be a permanent feature in Lake Victoria, currently hippograss and not water hyacinth forms the dominant weed. The hippograss is expected to die once the nutrients from dying water hyacinth are depleted.

Myco-herbicide development

Fungal pathogens have been known to attack water hyacinth and so far 32 isolates of fungi have been identified and are maintained in the laboratory. Initial pathogenicity tests indicate that some of the isolates (such as *Alternaria eichhorniae* and *Curvularia lunata*) may cause over 50% damage to water hyacinth plants under glasshouse conditions. Fungal pathogens have thus helped to also stress the water hyacinth after initial attacks are made by the weevils. Additional fungal isolations are still being carried out to increase the level of attack by obtaining even more virulent isolates. Pathogenicity tests under ambient environmental conditions will be carried out at Kibos, while additional isolations, identifications, host-specificity, glasshouse pathogenicity tests and product formulation work continues at Muguga.

Physical control

Manual removal

The fisherfolk communities around Lake Victoria have identified key sites for manual removal. These include fish-landing beaches, ports and piers, irrigation canals and water supply points and sources. Fish-landing beaches in most of the affected districts are the prime targets for manual removal operations. From over 100 gazetted beaches, some 25–30% had been severely infested by water hyacinth at specific periods during the year. In 1997, hand tools were distributed.

Mechanical control

Mechanical control operations have so far consisted solely of chopping and dumping of the chopped pieces of water hyacinth and other weeds into the lake. Regrowth of the chopped weed is likely to take place, especially if most of the natural enemies are destroyed during chopping. In addition, shallow areas of the lake are likely to fill up with vegetation, especially along the shoreline, leading to drying up and subsequent reduction in the size of the lake. The use of machines to destroy or remove water hyacinth has limitations, including their inability to move around a large lake. The future of mechanical control options should be reassessed.

Conclusion

The survey and consultations on the impacts of water hyacinth in the Lake Victoria Basin indicate that, currently, water hyacinth biomass is declining, but slowly. Despite this trend in Lake Victoria, indications are that other freshwater bodies continue to be infested. The precise areas of coverage by the weed cannot be accurately known because of a lack of appropriate tools and systems for monitoring and of proper coordination of activities throughout the region. The range of social, economic and environmental problems caused by the weed are generally well perceived by communities living in the Lake Victoria Basin. However, quantitative data are not usually available to give an idea of the real implications and impacts on the communities. This presents a challenge to socioeconomists to quantify impacts and thus define the real problems caused by water hyacinth. A comprehensive strategy needs to be crafted to address the socioeconomic and environmental concerns associated with water hyacinth. Further, a coordinating mechanism needs to be put in place to ensure that a common approach is adopted in the East Africa and

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Great Lakes regions to manage water hyacinth and other invasive weeds. For the future, it is recommended that a common approach needs to be implemented to the management of water hyacinth in order to enhance understanding and alleviate some of the impacts associated with infestation by this weed.

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Biological Control of Water Hyacinth by *Neochetina eichhorniae* and *N. bruchi* in Wenzhou, China

Lu Xujian*, Fang Yongjun†, Song Darong† and Xia Wanqing‡

Wenhzou is located in the southeastern Zhejiang Province. Water hyacinth was introduced into Wenzhou in the 1960s. Now the weed has become a bio-disaster. Chemical and manual control of water hyacinth cannot control the weed. In co-operation with the Biological Control Institute, Chinese Academy of Agricultural Sciences, *Neochetina eichhorniae* was introduced and released at four sites (Wutian, Liushi, Yaoxi and Kunyang) in 1996. The area of each site is about 1000 m^2 and 1000 adult weevils were released at each site. The weevils have established and spread their population well at Wutian and Liushi. However, although they became established one year after release, there were no weevils at the other two sites, because of the effect of some unknown factor. The study in Wenzou showed that the maximum total numbers of weevils occurred in mid-June each year. Adult numbers were highest in November, larvae in mid-June and pupae in early July. From 1996 to 1999, the area and height of water hyacinth had been reduced greatly at Wutian and Liushi.

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Session Summaries

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Summary of sessions 1 and 2

Session 1, which was of keynote presentations, was chaired by Martin Hill, and session 2, containing general papers on the biological control of water hyacinth, by Mic Julien. This report was prepared by Ted Center.

Sessions on Tuesday 10 October opened with three excellent keynote presentations, the first by Mr Mic Julien on ‘Biological control of water hyacinth by using insects in the world’, the second by Dr R. Charudattan on ‘Biological control of water hyacinth by using pathogens in the world’ and the third by Dr Ding Jianqing on ‘Water hyacinth in China: its distribution, problems and control status’.

Mic Julien presented a review of water hyacinth biology and its status as a worldwide problem, using examples from Papua New Guinea, Thailand and Zimbabwe. This included a historical perspective on the introduction and spread of water hyacinth around the world beginning in the early 1900s and culminating in the recent widespread invasions in Africa. Mic then followed by defining ‘classical’ biological control and he outlined the steps in a classical biological control project. He then listed new proposed agents (as outlined by Cordo in the previous workshop) and reviewed the biology and impact of many of the agents in current use.

Perhaps most importantly, Mic explored the factors that relate to successful control, factors that accelerate success, and factors that limit control. Factors that he associated with successful control included: presence in tropical and subtropical areas; infestations manifested as monocultures in free-floating mats (which are able to sink when damaged); and mats that are stable (i.e. undisturbed) over long periods. Factors proposed that might accelerate control included wave action, reduced growth (by the actions of biocontrol agents, which allows plants to be flushed out of the systems), and high nutrient status (as it relates to the production of high quality plants thus enhancing insect population growth). Factors that limit control included removal of mats by herbicidal or mechanical means (thus disrupting agent populations), shallow water (damaged plants unable to sink), ephemeral water bodies, toxicity effects in polluted waters, low temperatures at high-altitude, temperate sites, and high nutrients at temperate sites. These observations represent important hypotheses needing further testing, but this delineation represents a first attempt to come to understand the variable nature of successful biocontrol.

Mic concluded by providing recommendations for improving water hyacinth biological control. He suggested that existing agents needed wider use, that new agents had to be identified, that better resources were needed to support projects, that stakeholders needed to be educated about biocontrol, that more collaboration with weed scientists and managers was needed, and that catchment-specific integrated weed management plans needed development.

Dr Charudattan began his presentation by stating that, in his view, pathogens would be most useful as biopesticides as opposed to ‘classical’ biological control agents. He

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emphasised that pathogens should be explored fully and *fairly* so as to assess their potential as biopesticides in integrated weed management systems (as opposed to 'stand alone' agents). He felt that the use of 'local' pathogens avoided the quarantine problems associated with exotic pathogens. He noted that no new pathogens had been identified in the past 20 years, despite numerous surveys. The only viable 'classical' candidate that he identified was the rust fungus *Uredo eichhorniae*. He felt that the bioherbicidal approach could produce quick and acceptable levels of control, a need generally perceived by aquatic weed managers and a prerequisite to widespread adoption.

Charu then enumerated and prioritised known water hyacinth pathogens. He considered *Cercospora piaropi* to be one of the most promising, being widespread with many virulent strains. *Acremonium zonatum* also showed some promised, as did *Alternaria eichhorniae* and *Myrothecium roridum* (although the availability of strains with different levels of virulence of the latter two species is not yet clear). *Rhizoctonia solani*, which is highly virulent, had not been considered previously, because of its lack of host specificity but Charu noted, in the present regulatory environment, its use is now possible. Many other species of less widely developed pathogens were noted.

Charu summarised by suggesting ways to make pathogens more effective by overcoming environmental constraints on their growth and efficacy. Once developed as bioherbicides, they can be: applied with low rates of herbicide or with adjuvants; multiple applications can used to increase inoculum loads; applications can be timed to maximise impact with insect agents; novel formulations may be used to provide humidity on the leaf surface, to protect the inoculum from solar radiation, or to promote hyphal penetration of the leaf; or they can be combined with other pathogens or several strains of the same pathogen to provide consistent performance. The overall objectives in these approaches should be aimed at developing a bioherbicide that can be used with existing agents and improve the overall effectiveness under different control scenarios so as to 'knock back' the weed as opposed to 'knock down'. One recommendation was to apply *Cercospora piaropi* in combination with *Myrothecium roridum* using a surfactant.

In conclusion, Charu felt that it was indeed a challenge to develop an effective and practical bioherbicide, but that the challenge could be met given the bio-friendly posture of modern regulatory agencies. However, newer, innovative approaches were required to meet particular needs.

Ding Jianqing provided a history of water hyacinth in China and noted that it is widely utilised as animal food so not everyone regards it as a problem. Water hyacinth was introduced in Taiwan in 1903 from Southeast Asia and then to the mainland in 1930. It was introduced into almost every province in the 1950s and 1960s for use as animal food. It became more damaging as nutrient pollution increased during the 1990s. Water hyacinth is now distributed in 17 provinces and is regarded as a problem in 10 of them, mostly in the south. China spends 100 million RMB annually to manually control water hyacinth. The problems caused by water hyacinth are generally the same as in other countries (however, one that may be unique to China was that it provided hiding places for criminals – nicely illustrated with a self portrait surrounded by the weed!). Ding presented a very interesting example of the impact of water hyacinth on the biodiversity of Dianchi Lake. The number of plant species known in the lake declined from 16 before the introduction of water hyacinth to 3 afterwards. Although invasive species are often blamed for adversely affecting biodiversity, this is rarely documented.

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Ding emphasised that utilisation does not solve the problem and should not be confused with control. Mic Julien had earlier emphatically stated this as well.

Biological control was initiated in China in 1995 and, after demonstrating the effects of the weevils in small-scale tests, *Neochetina bruchi* and *N. eichhorniae* were released in 1996. Significant control is now being realised in Zhejiang and Fujian provinces. More recently, the mirid *Eccritotarsus catarinensis* has been released and surveys for pathogens have begun. Chinese researchers have also demonstrated that integrated control, using herbicides with the weevils, provides better control than either alone. In the future they plan to introduce the weevils into new areas, to introduce new insects, and to develop bioherbicides.

One of the most profound statements of the meeting was made by Ding in his concluding remarks. He stated that control of water hyacinth is not about technology, but rather about politics.

In the general session that followed the keynote presentations, Dr Martin Hill presented the first paper, an introspective look at biological control of water hyacinth in South Africa focusing on constraining factors, success, and new courses of action. South Africa has introduced more agents (6 total) than any other country, yet water hyacinth is still a problem. He identified several of the same factors enumerated by Julien as possibly being inhibitory, plus some others: diverse climate (ranging form high altitude to coastal Mediterranean and coastal subtropical), eutrophication (at some sites 100% of inflow is treated sewage effluent), herbicide interference (direct toxic effects as well as removal of bioagent habitat), hydrological parameters (small, shallow systems), and limited releases (small, inoculative releases as opposed to mass rearing and release).

Martin then presented a case study from an oligotrophic system at New Year's Dam where biological control agents reduced water hyacinth coverage from 80% in 1990 to less than 10% in 1994. Thus, even though biological control is not universally effective everywhere, it is effective in the proper circumstances. He concluded with the feeling that water body managers expected too much from biological control, that the problem of eutrophication needed to be addressed, and that better integration with other control measures was needed. He also echoed the sentiments of almost every participant that additional biological control agents were needed.

Tom Moorehouse then provided an overview of the biological control activities in the Kagera River Headwaters in Rwanda. The Kagera River feeds into Lake Victoria on the western side and is the source of much of the water hyacinth entering the lake. In collaboration with Ugandan researchers, Clean Lakes, Inc. is setting up weevil rearing systems and training the Rwandans in the use and application of biological control.

Dr Yahia Fayad presented great news about the biological control of water hyacinth in Egypt. Although the weevils were studied in the early 1980s, the Egyptian Government refused to grant permission for their release. However, the previous working group meeting provided the stimulus for them to finally issue approval. As a result, both species were released during August 2000 when 2000 weevils were liberated at Mariout Lake and 4000 at Edko Lake.

The afternoon session concluded with another presentation by Dr Hill on the biological control of water hyacinth in Malawi. Water hyacinth was found at Lake Malawi during the late 1960s, and by 2000 it was scattered throughout the country. Rearing systems for *Neochetina* weevils have been set up at two facilities along the Shire River. About 200,000 weevils have now been reared and released, 47% in the upper Shire

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River, along with the water hyacinth mirid *Eccritotarsus catarinensis* and the moth *Niphograpta albiguttalis*. The mite *Orthogalumna terebrantis* was already present. (In contrast to Mic Julien's conclusion that these mites are ineffective, they seemed to be quite damaging in this area.) The weevils have established and monitoring is continuing. Some reductions in water hyacinth have already been noted but new infestations are appearing elsewhere. Nonetheless, Martin was optimistic.

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Summary of session 3

Session 3, 'Biological Control – Pathogens', was chaired by Garry Hill. This report was prepared by R. Charudattan.

Three papers were presented in this session. The first, entitled 'An International Collaborative Program to Investigate the Development of a Mycoherbicide for Use Against Water Hyacinth in Africa', was presented by Roy Bateman (CABI Bioscience, UK), on behalf of the International Mycoherbicide Programme for *Eichhornia crassipes* Control in Africa (IMPECCA) team. He gave an overview of the IMPECCA program, in which the following groups are participating: CABI Bioscience, UK; the International Centre for Research on Agro-forestry, Kenya; the International Institute for Tropical Agriculture, Benin; the Danish Institute of Agricultural Sciences, the Plant Protection Research Institute, South Africa; and the University of Mansoura, Egypt.

The project will build upon existing studies of mycoherbicides that have been carried out in Egypt and Zimbabwe. Explorations will be undertaken to find pathogens native to the African continent and the pathogens will be characterised by cultural and morphological studies. Weed biotypes will be characterised by a molecular (AFLP, amplified fragment-length polymorphism) technique. Preliminary results indicate that the water hyacinth biotypes examined to date are similar—a promising sign that host genotypic differences will not be a complicating factor in this mycoherbicide program. Formulation studies are under way with emphasis on an oil-based formulation that could be sprayed like a conventional herbicide. An application technology based on the successful locust-control program (LUBILOSA program) will be evaluated for implementation of a mycoherbicide for water hyacinth. Pathogenicity tests are also being carried out with the following fungi found in the participating countries: *Alternaria alternata, A. eichhorniae, Acremonium zonatum, Cercospora piaropi, Rhizoctonia solani,* and *Myrothecium roridum.*

The IMPECCA program will be promoted and widely publicised. The Water Hyacinth Newsletter published by CABI Bioscience will be continued under this program. A technical bulletin, edited by Roy Bateman, will be made available to interested individuals and agencies. A web site (http://www.impecca.net) has been set up and is running. Another key output will be the strengthening of technical capability and linkages within African national programs to undertake biological control of weeds.

Harry Evans (CABI Bioscience, UK) then presented a paper (by Evans and Robert H. Reeder) on the fungi associated with water hyacinth in the upper Amazon basin, and the prospects for their use in biological control. He pointed out that few fungi have been reported on water hyacinth in South America, most of the fungal taxa reported coming from the Palaeotropics rather than the Neotropics. He detailed his observations from surveys he undertook in 1998 and 1999 in the upper Amazon basin of Ecuador and Peru. The objective of the surveys was to document both the distribution of water hyacinth and its associated microbial pathogens. Ecuador and Peru are within the purported center of

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origin or diversity of water hyacinth and no surveys had previously been made in this area.

Three groups of fungi were collected: biotrophs, colonising green tissues without significant external symptoms; necrotrophs, causing prominent leaf lesions; and those associated with tissues damaged by insects (*Taosa* spp., *Thrypticus* spp.), typically on the petioles. Several fungi that belong to known plant pathogenic genera were isolated or recorded on the collected specimens. These remain to be tested. These surveys have yielded several interesting fungi, including some that appear to be new species. In my view, this collection represents an important resource and it would be very worthwhile to test and evaluate these fungi.

Yasser Shabana (Mansoura University, Egypt; currently and temporarily at University of Hohenheim, Stuttgart, Germany) reviewed his work on *Alternaria eichhorniae* conducted during the past 16 years. This work (by Shabana, Elwakil and Charudattan) has covered a large area of the subject, including the initial surveys in the Nile Delta (Egypt), host-range and safety tests of *A. eichhorniae,* investigations on several aspects for improving the efficacy of this mycoherbicidal agent i.e. sporulation, phytotoxin production, bioherbicide formulations, determination of optimum epidemiological conditions for disease incidence and disease severity, and physiological and ultrastructural studies. This work has clearly established this fungus as a leading candidate for mycoherbicide development in the African continent. Shabana presented results from his most recent work on formulation and field-testing of this fungus, concluding that, for best results, spore or mycelial inoculum of this fungus should be formulated in an invert oil emulsion, along with phytotoxic metabolites produced in culture. The phytotoxic fractions promote disease development, while the invert emulsion protects the fungal inoculum from dehydration.

Overall, this was an interesting and informative session highlighting the importance of pathogens as biological control agents of water hyacinth.

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Summary of session 4

Session 4, 'General', was chaired by Ding Jianqing. This report was prepared by Harry Evans.

Two talks were presented in this session, both covering information technology relating to water hyacinth. Firstly, Garry Hill introduced the idea of a multifunctional Water Hyacinth Resource Manual which, as well as being an information source, could also be used both as a training tool and as a guide to decision-makers. The manual would be focused specifically on developing countries in Africa and would be prepared in the form of a comprehensive, practical and authoritative directory, by an editorial team under a professional editor. It was envisaged that there would be a workshop around mid-2002 to finalise the contents of the document.

The session participants considered this to be an excellent initiative and a potentially valuable and much-needed resource, although the ambitious subject area could mean that the manual may run into several volumes. It was further suggested that the document could be in a loose-leaf format and that the initial drafts should be presented on a web site.

A lively discussion ensued over the costs involved and the potential donor sources.

Luis Navarro then presented a proposal to aid decision-making through the establishment of a Water Hyacinth Information Partnership (WHIP). While WHIP would be aimed at presenting information to African and Middle Eastern countries, its principal mission would be to link this information rather than to create it, facilitated by an Information Exchange and Networking Mechanism (IENM).

Thus, the partnership could be employed for the early detection of water hyacinth infestations and thereby stimulate decision-makers to respond more rapidly to their control or eradication. In the past, such decisions have not been taken until weed levels have become critical and this has been the experience in 21 countries since the 1980s. Thus, there are political reasons for WHIP: to raise donor awareness of the problem and to serve as an information source to decision-makers; as well as technical reasons—to provide data on the spread, socioeconomic costs and integrated control strategies.

It was proposed that this concept could be extended to other invasive weeds and that a conference should be organised to present the initiative, particularly to potential donors. The general view of the session participants was that the projected budget (US$1.5 million) was excessive for the envisaged outputs.

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Summary of session 5

This session, 'Biological Control – Insects', was chaired by Dr Lu Qingguang. This report was prepared by Mic Julien.

Ted Center presented thought-provoking ideas and early studies that assess the changes in competitiveness of water hyacinth when attacked by biological control agents. This is work prepared by Center, Van and Hill. He suggested that this technique could be used to select the most damaging agents for release. The idea has considerable merit, especially if it improves our predictive capacity and thus saves time and resources. The experimental design may need to pay attention to nutrient levels. Changes in nutrition may alter agent impacts or the plant's ability to withstand or compensate for damage. The experimental design is already large, and adding nutrients as a treatment will increase its size considerably.

The Oberholzer and Hill paper, presented by Martin Hill, reported the results of studies on *Cornops aquaticum*, a potential control agent that has long been waiting in the background. It appears that this insect is specific to Pontederiaceae. That *C. aquaticum* took a bite of banana during testing is undoubtedly an aberration. Because of the importance of bananas, the South African Plant Protection Research Institute will study this phenomenon further. Even if later studies show that banana is not a suitable host, the original results should be reported and decision-makers may misconstrue this. In this respect we are all obliged to educate the people who sit on committees and make decisions about what is and is not safe to import and release.

Andrew Mailu described the impacts of water hyacinth on life on, in and around Lake Victoria. He indicated the importance of prior experience in decision-making. Kenya moved quickly to embrace biological control of water hyacinth following experience with salvinia. He indicated that the project on water hyacinth was bigger than just water hyacinth and embraced the whole of catchment management, and that the success of biological control of water hyacinth will have far-reaching effects in the area. He discussed the importance of obtaining reliable scientific and socioeconomic data to describe the costs of problems and the benefits of solutions.

John Wilson, PhD student, outlined progress with modelling the water hyacinth and the impact of controls. His study attempts to bring together data and ideas worldwide, and to investigate some areas of plant–insect interactions. The broad aims are to identify areas needing research, identify the factors that limit control and to help make area-specific predictions about control.

Martin Hill gave an outline of activities in Benin and Zambia, and indicated that a biological control project was starting in Burkina Faso. Excellent control has been achieved in several locations in Benin, with the weed infestations less than 5% of their former sizes. The project included community involvement with very beneficial results. The problems in the Kafue River (95 km infested) in Zambia remain. The weevils were released in the 1990s and are established. *Niphograpta* and *Eccritotarsus* were recently

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released. Nutrient levels are being sampled. Insufficient work is being conducted to assess progress. However, the continued presence of the weed suggests that the weevils and the mite are insufficient. This infestation presents itself as an ideal location to undertake a large-scale integrated management trial.

Godfrey Chikwenhere outlined the status of biological control of water hyacinth in Zimbabwe and the continued involvement of politics in the decision-making processes. Regardless, and this has been shown in other situations, he indicated that once the weevils were widely established they were able to contribute to control despite other antagonistic controls that were imposed. He also indicated the importance of considering other aquatic weeds at the same time, so that weeds such as water lettuce did not immediately take up space made available after water hyacinth was controlled.

Finally, Eric Gutiérrez outlined biomass and productivity studies he had conducted in Mexico with Gomez and Franco, preparatory to determining appropriate control methods for each site. Such studies have rarely been carried out before purchasing mechanical removal machines and hence the tropics are littered with expensive and largely useless machinery. He outlined successful mechanical removal operations conducted at a number of impoundments and described the current ongoing efforts of releasing 4000 adult weevils per month into other locations. It would be instructive to know the costs of the mechanical removal procedures.

This session of seven presentations was varied and very stimulating. We enjoyed talks including assessment of potential agents, development of predictive capacity, reports of successful control (biological and mechanical), reports of apparent failure of agents to control the weed, the need for total catchment management and to collect sound data that describe the costs of weeds and benefits resulting from control. I thank the presenters and the audience for the lively discussions.

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Summary of session 6

Session 6, 'Integrated management', was chaired by Roy Bateman. Martin Hill prepared this summary.

There were two talks and one video in this last session of the workshop. In the first paper, Gasper Mallya presented an update of the water hyacinth biological control program in Tanzania. As with elsewhere on Lake Victoria, fantastic results have been achieved with the release of *Neochetina eichhorniae* and *N. bruchi*. Much of the success has been ascribed to having dedicated staff and enlisting participation of the local fishing communities. This has resulted in the release of large numbers of the weevils and has ensured that collection and redistribution of the weevils to other localities has occurred. Currently, as a result of biological control, water hyacinth is not considered a problem on the Tanzanian shores of Lake Victoria.

Several initiatives have been put in place in Tanzania to ensure sustainable control of water hyacinth. Firstly, utilisation of the weed has been prohibited, thus preventing the potential spread of water hyacinth to other freshwater bodies in Tanzania. Secondly, fishermen are required to report basic information on water hyacinth infestations on the lake to the relevant authorities. This includes general observations on the size of the plants, but more importantly the occurrence of any new infestations to aid in the early detection of the spread of the weed to new sites. Thirdly, releases of the weevils in the Kagera River, where it runs through Tanzania, will facilitate the biological control of water hyacinth on Lake Victoria.

The water hyacinth program in Tanzania, as with the programs in Kenya and Uganda, has been extremely successful in reducing the environmental and socioeconomic threat posed by water hyacinth on Lake Victoria.

In the second presentation, Roy Jones showed a video and then presented a paper on the integrated control of water hyacinth on the Nseleni River and Lake Nsezi in northern Kwa Zulu–Natal, South Africa. This program was inexpensive and highly successful and has resulted in the return of a number of endangered waterfowl species to this conservation area. Roy stressed that having realistic expectations of what can be achieved was the first step. The second step was to obtain commitment from the communities along the system. Without this commitment, the program was likely to fail. The third step was to divide the system into manageable units from the top of the system, downstream. However, follow-up in units after initial clearing of the weed, to control regrowth, was vital. This single most important factor in the success of this project appeared to be having a dedicated manager who spent considerable time on the system and who could coordinate the control efforts.

This Nseleni River program was well planned from the start. It relies on biological control but uses herbicidal control and mechanical intervention (the use of cables across the river to prevent the movement of water hyacinth into previously cleared areas) in a coordinated manner. In addition, nutrient control through the upgrading of a wastewater treatment plant in the upper catchment has facilitated the control efforts. Furthermore, the

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public awareness campaign through the production of a video, the involvement of the local community around the system and the fact that the program has been well documented has ensured that this is possibly the best example of integrated management of water hyacinth that we have.

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