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

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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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Biological and Integrated Control of Water Hyacinth, *Eichhornia crassipes*,
edited by M.H. Julien, M.P. Hill, T.D. Center and Ding Jianqing
ACIAR Proceedings 102
(printed version published in 2001)

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.

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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).

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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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ACIAR Proceedings 102
(printed version published in 2001)

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).

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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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