4 WATERHYACINTH

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PEST STATUS OF WEED

Waterhyacinth, *Eichhornia crassipes* (Mart.) Solms.-Laubach (Fig. 1), is considered one of the world's worst weeds (Holm *et al*., 1977), invading lakes, ponds, canals, and rivers. It was introduced into many countries during the late 19th and early 20th centuries, where it spread and degraded aquatic ecosystems. It is still rapidly spreading throughout Africa, where new infestations are creating life-threatening situations as well as environmental and cultural upheaval (Cock *et al*., 2000). Control with herbicides, particularly 2,4-D, is feasible, but is costly and temporary.

Nature of Damage

Economic damage. Waterhyacinth grows rapidly (Penfound and Earle, 1948) forming expansive colonies of tall, interwoven floating plants. It blankets large waterbodies (Fig. 2), creating impenetrable barriers and obstructing navigation (Gowanloch and Bajkov, 1948; Zeiger, 1962). Floating mats block drainage, causing flooding or preventing subsidence of floodwaters. Large rafts accumulate where water channels narrow, sometimes causing bridges to collapse. Waterhyacinth hinders irrigation by impeding water flow, by clogging irrigation pumps, and by interfering with weirs (Penfound and Earle, 1948). Multimillion-dollar flood control and water supply projects can be rendered useless by waterhyacinth infestations (Gowanloch and Bajkov, 1948).

Infestations block access to recreational areas and decrease waterfront property values, oftentimes harming the economies of communities that depend upon fishing and water sports for revenue. Shifting waterhyacinth mats sometimes prevent boats from reaching shore, trapping the occupants and exposing them to environmental hazards (Gowanloch and Bajkov, 1948; Harley, 1990). Waterhyacinth infestations intensify mosquito problems by hindering insecticide application, interfering with predators, increasing habitat for species that attach to plants, and impeding runoff and water circulation (Seabrook, 1962).

Ecological damage. Dense mats reduce light to submerged plants, thus depleting oxygen in aquatic communities (Ultsch, 1973). The resultant lack of phytoplankton (McVea and Boyd, 1975) alters the composition of invertebrate communities (O'Hara, 1967; Hansen *et al*., 1971), ultimately affecting fisheries. Drifting mats scour vegetation, destroying

Figure 1. Waterhyacinth growing in the Marañon River, Peru. (Photo by T. D. Center, USDA, ARS.)

Figure 2. A waterhyacinth infestation in southern Florida. (Photo by T. D. Center, USDA, ARS.)

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native plants and wildlife habitat. Waterhyacinth also competes with other plants, often displacing wildlife forage and habitat (Gowanloch, 1944). Higher sediment loading occurs under waterhyacinth mats due to increased detrital production and siltation. Herbicidal treatment or mechanical harvesting of waterhyacinth often damages nearby desirable vegetation.

Extent of losses. Waterhyacinth caused annual losses (all causes) of $65 to 75 million in Louisiana during the 1940s (Gowanloch and Bajkov, 1948). Fish and wildlife losses alone in the six southeastern states exceeded $4 million per year in 1947 and waterhyacinth control provided a benefit to cost ratio of 15.3:1 (Tabita and Woods, 1962). Holm *et al.* (1969) ascribed losses of $43 million in 1956 to waterhyacinth infestations in Florida, Mississippi, Alabama, and Louisiana. The U.S. Army Corps of Engineers estimated benefits from waterhyacinth control programs at nearly $14 million in 1965 (Gordon and Coulson, 1974). Florida spent more than $43 million during 1980 to 1991 to suppress waterhyacinth and waterlettuce (Schmitz *et al.,* 1993). Currently, annual costs for waterhyacinth management range from $500,000 in California to $3 million in Florida (Mullin *et al.*, 2000). The largest infestations occur in Louisiana, where the Department of Fisheries herbicidally treats about 25,000 acres of waterhyacinth per year, mostly at boat ramps, at an annual cost of $2 million (R. Brassette, pers. comm.).

Geographical Distribution

Waterhyacinth was introduced into the United States around 1884 and has since become pan-tropical. Worldwide, the limits of distribution are at 40° N and S latitude (Gowanloch and Bajkov, 1948; Bock, 1968; Holm *et al.,* 1969; Ueki, 1978; Kolbek and Dostálek, 1996; Gopal, 1987). In the United States, waterhyacinth is most abundant in the Southeast (Fig. 3). It also occurs in California and Hawaii, with scattered records in other states (USDA, NRCS, 1999).

BACKGROUND INFORMATION
ON THE PEST PLANT

Taxonomy

The English common names of the plant are waterhyacinth, water hyacinth, and water-hyacinth.

Waterhyacinth is the standardized spelling adopted by the Weed Science Society of America (WSSA, 1984) to denote that it is not an aquatic relative of true "hyacinth" (*Hyacinthus* spp.), as the two-word spelling suggests.

The taxonomic placement of waterhyacinth, based on Cronquist (1988), Thorne (1992), and Takhtajan (1997), is as follows: division Magnoliophyta; class Liliopsida; subclass Commelinidae (Liliidae [Cronquist, 1988; Thorne, 1992]); superorder Commelinanae (Thorne, 1992); order Pontederiales (Liliales [Cronquist, 1988]; Philydrales [Thorne, 1992]); family Pontederiaceae, genus *Eichhornia*; specific epithet *crassipes* (Martius) Solms-Laubach.

Biology

Waterhyacinth is an erect, free-floating, stoloniferous, perennial herb (Fig. 4). The bouyant leaves vary in size and morphology. The short, bulbous leaf petioles produced in uncrowded conditions provide a stable platform for vertical growth. Plants in crowded conditions form elongate (up to 1.5 m) petioles (Center and Spencer, 1981). Leaves are arranged in whorls of six to 10, and individual plants develop into clones of attached rosettes (Center and Spencer, 1981).

The lavender flowers display a central yellow fleck and are borne in clusters of up to 23 on a single spike (Barrett, 1980). The flowers may have short, medium, or long styles, but only the short- and long-style forms occur in the United States (Barrett, 1977). The 14-day flowering cycle concludes when the flower stalk bends, positioning the spike below the water surface where seeds are released (Kohji *et al.*, 1995). Seed capsules normally contain fewer than 50 seeds each (Barrett, 1980). Each inflorescence can produce more than 3,000 seeds and a single rosette can produce several inflorescences each year (Barrett, 1980). The small, long-lived seeds sink and remain viable in sediments for 15 to 20 years (Matthews, 1967; Gopal, 1987). Seeds germinate on moist sediments or in warm shallow water (Haigh, 1936; Hitchcock *et al.*, 1950) and flowering can occur 10 to 15 weeks thereafter (Barrett, 1980). Lack of germination sites limits seedling recruitment except during drought, on decaying mats after herbicide applications (Matthews, 1967), or at the margins of waterbodies. Populations increase mainly by vegetative means.
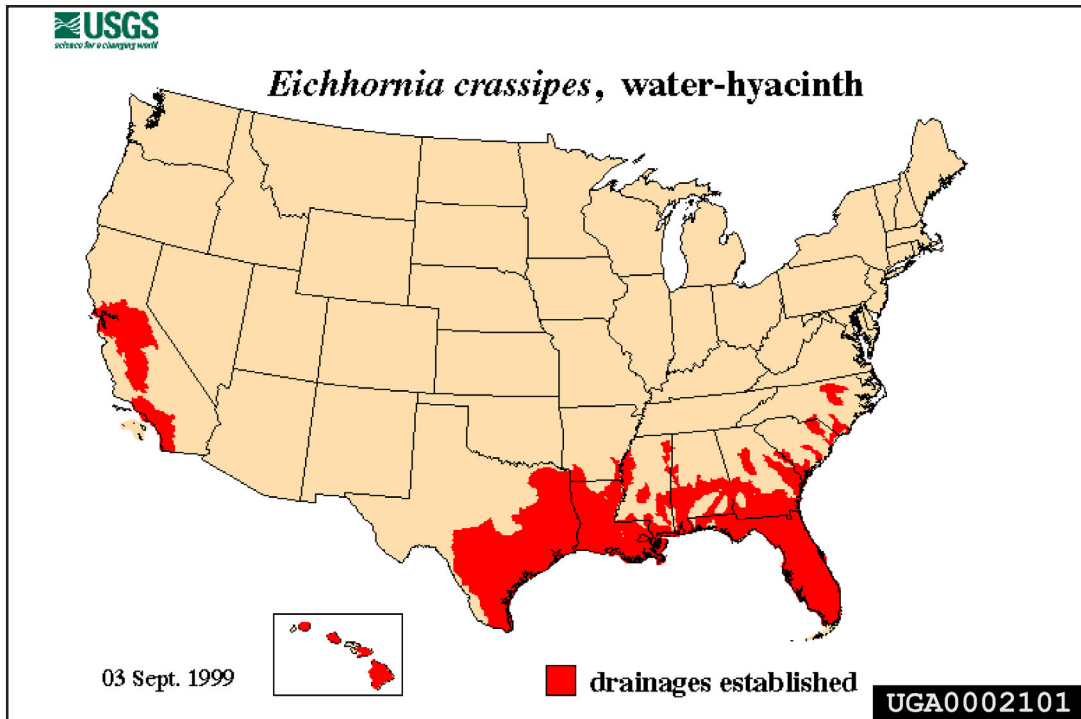
Figure 3. Drainages infested by waterhyacinth in the United States. (Map courtesy of the U.S. Biological Survey, Colette Jacono).
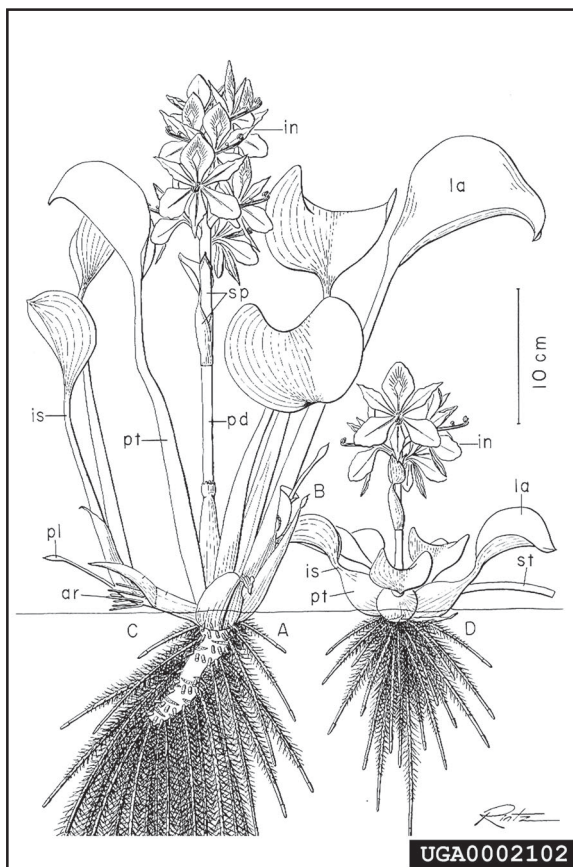

Figure 4. Morphology of waterhyacinth plants (A. the "attenuated-petiole" rosette form produced in crowded conditions; B. an expanding axillary bud; C. a developing ramet; and D. the "bulbous-petiole" rosette form produced in open conditions. Abbreviations: ar – adventitious root; bb – bud bract; in – inflorescence; is – leaf isthmus; la – leaf blade; pl – primary leaf; pd – peduncle of flower spike; pt – leaf petiole; rh – rhizome; sp – spathe; st – stolon.

Weber (1950), Richards (1982), Watson (1984), and Watson and Cook (1982, 1987) describe waterhyacinth growth and population expansion as the result of differentiation of apical or axillary meristems. The single apical meristem on each stem tip can be vegetative, producing leaves with axillary buds, or reproductive, producing flowers. If an inflorescence develops, termination of the apical meristem halts leaf production. In this event, the axillary bud immediately below the inflorescence differentiates into a continuation shoot. This produces a new apical meristem that allows leaf production to proceed. If the axillary bud doesn't form a continuation shoot, then it produces a stolon. Elongation of the stolon internode moves the axillary bud apex away from the parent rosette. It then produces short internodes that grow vertically into a new rosette.

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Waterhyacinth grows best in neutral pH, water high in macronutrients, warm temperatures (28° to 30°C), and high light intensities. It tolerates pH levels from 4.0 to 10.0 (Haller and Sutton, 1973), but not more than 20 to 25% sea water (Muramoto *et al.,* 1991). The plants survive frost if the rhizomes don't freeze, even though emergent portions may succumb (Webber, 1897). Prolonged cold kills the plants (Penfound and Earle, 1948), but reinfestation from seed follows during later warmer periods. Ueki (1978) matched the northern limit of waterhyacinth to the 1°C average January isotherm in Japan. Growth is inhibited at water temperatures above 33°C (Knipling *et al.*, 1970). Plants stranded on moist sediments can survive several months (Parija, 1934).

Analysis of Related Native Plants in the Eastern United States

Waterhyacinth is a member of the pickerelweed family (Pontederiaceae). Families most closely allied with the Pontederiaceae are Commelinaceae, Haemodoraceae (including Conostylidaceae [Takhtajan, 1997]), Philydraceae, and Hanguanaceae (Hahn, 1997; APG, 1998). The subclass Commelinidae includes the Arecales, Poales, Commelinales, and Zingiberales (APG, 1998).

The Pontederiaceae is a small family of herbaceous monocotyledons that includes six genera and 30 to 35 species (Eckenwalder and Barrett, 1986). All are palustrine or aquatic and most are confined to the Americas. All seven members of the genus *Eichhornia* originated in tropical America, except for *Eichhornia natans* (P. Beauv.), which is from tropical Africa. Fourteen species of Pontederiaceae occur in the U.S./Canadian flora (Table 1), six of which are adventive; none are considered threatened or endangered (USDA, NRCS, 1999).

HISTORY OF BIOLOGICAL CONTROL EFFORTS IN THE EASTERN UNITED STATES

Area of Origin of Weed

The diversity of other species of *Eichhornia*, particularly the more primitive *Eichhornia paniculata* (Spreng.) Solms. and *Eichhornia paradoxa* (Mart.) Solms., and the overlapping range of the closely

Table 1. Species of Pontederiaceae in the United States.

Native Species	Introduced Species
Heteranthera dubia (Jacq.) MacM.	*Eichhornia azurea* (Sw.) *Kunth*
Heteranthera limosa (Sw.) Willd.	*Eichhornia crassipes* (Mart.) Solms.
Heteranthera mexicana Wats.	*Eichhornia diversifolia* (Vahl) Urban
Heteranthera multiflora (Griseb.) Horn	*Eichhornia paniculata* (Spreng.l) *Solms*
Heteranthera penduncularis Benth.	*Monochoria hastata* (L.) Solms
Heteranthera reniformis Ruiz López & Pavón	*Monochoria vaginalis* (Burm. f.) K. Presl
Heteranthera rotundifolia (Kunth) Griseb.	
Pontederia cordata L.	

related *Eichhornia azurea* (Sw.) Kunth suggest that *E. crassipes* arose in tropical South America.

Areas Surveyed for Natural Enemies

Although several expeditions have been made to South America to survey for natural enemies of waterhyacinth (Center, 1994), most were limited in scope and failed to encompass the upper Amazon basin where waterhyacinth may have originated. Bennett and Zwölfer (1968) explored the northernmost range of the plant. Other authors have explored the eastern parts of the range but the western portion has seldom been visited. The discovery of new organisms associated with waterhyacinth was thought to be unlikely because of the long history of exploration in South America. Recent findings of new, potentially useful natural enemies suggest otherwise (Cordo, 1999).

Natural Enemies Found

Beginning in the early 1970s, the USDA and CIBC (now CABI-Bioscience) released the weevils *Neochetina eichhorniae* Warner, *Neochetina bruchi* Hustache, and, later, the pyralid moth *Niphograpta (=Sameodes) albiguttalis* (Warren). These three agents, plus the mite *Orthogalumna terebrantis* Wallwork, are now widely used (Table 2).

Many countries that have initiated biological control programs against waterhyacinth have reported successes (Julien and Griffiths, 1998). All four agents are important, although the two *Neochetina* weevils seem most successful. Nonetheless, the control achieved has not always been sufficient. The relatively slow action of the biological control agents is sometimes incompatible with other management practices (Center *et al.*, 1999a). In other cases, the explosive growth of waterhyacinth stimulated by high nutrient levels precludes effective control (Heard and Winteron, 2000). Clearly, needs exist to develop and use compatible management practices and to seek new agents that are capable of rapid population growth.

About 19 of 43 species (Table 2) have been indentified as potential control agents because of the damage they cause or because of their narrow host range (Perkins, 1974). This list suggests that there are additional safe and effective agents among those already known, while others remain to be discovered.

Host Range Tests and Results

The two weevil species (*N. eichhorniae* and *N. bruchi*) have been released on waterhyacinth in 30 and 27 countries, respectively. Both have been subjected to extensive screening. They have been tested against 274 plant species in 77 families worldwide (Julien *et al.,* 1999). Some use of a few non-target species, mainly other Pontederiaceae, was observed that was insignificant when compared to waterhyacinth.

The other agents released on waterhyacinth, the fungus *Cercospora piaropi* Tharp, the mirid *Eccritotarsus catarinensis* (Carvalho), the moths *N. albiguttalis* and *Xubida infusellus* (Walker), and the mite *O. terebrantis,* have been introduced to fewer countries and have therefore been subjected to fewer host specificity trials. However, no host range extensions by these species have been recorded except for the predicted feeding by the weevils on pickerelweed *Pontederia cordata* L. (Center, 1982; Hill *et al.*, 2000; Stanley and Julien, unpub).

Post-release evaluations of natural enemies in countries of introduction can provide additional biosafety data and render further quarantine-based trials unnecessary. For example, field cage studies in Australia showed that the moth *X. infusellus* would harm pickerelweed (Julien, pers. comm.). It is

therefore no longer being considered for release in the United States. On the other hand, the mirid *E. catarinensis* fed and developed on pickerelweed during quarantine trials in South Africa, but subsequent field trials in that country showed that it inflicted little damage to pickerelweed and didn't readily colonize isolated pickerelweed stands (Hill *et al.,* 2000).

Many of the plant-feeding insects associated with waterhyacinth in South America utilize other species of Pontederiaceae (Table 2). Therefore, decisions for their release must rely on a risk-benefit analysis between the importance of native Pontederiaceae and the potential benefits offered by the natural enemy.

Releases Made

Three insects, all originally from Argentina, have been released in the United States. The weevils *N. eichhorniae* and *N. bruchi* were released in Florida in 1972 and 1974, respectively, followed by the pyralid moth *N. albiguttalis* in 1977.

Other Agents That Have Been, or Now Are, Under Consideration

Three native North American species sometimes severely affect waterhyacinth populations, as well. These are the noctuid moth *B. densa*, the oribatid mite *O. terebrantis*, and the spider mite *Tetranychus tumidus* Banks.

The moth *X. infusellus* has been rejected for release in the United States because it is clearly a threat to pickerelweed (DeLoach *et al.*, 1980; Julien and Stanley, 1999). Cordo's (unpublished report) conclusion that the arctiid *Paracles tenuis* Berg was polyphagous led to its rejection as well. Silveira Guido and Perkins (1975) and, later, Hill (unpub.) tested the grasshopper *Cornops aquaticum* (Bruner). Although Silveira Guido and Perkins (1975) considered it to be specific, concerns for pickerelweed precluded further consideration for release in the United States. The mirid *E. catarinensis* is still under consideration as the risk to pickerelweed seems minimal under field conditions (Hill *et al.*, 2000), but information on its efficacy is needed for a proper risk-benefit analysis. Dolichopodid flies in the genus *Thrypticus* and planthoppers in the genera *Megamelus* and *Taosa* are now under consideration.

Table 2. Characterization of Major Arthropods Associated with Waterhyacinth.

Species	Field and Laboratory Host Plants	Attributes, Limitations and Current Status of Research
First Priority – Agents In Use Worldwide		
1. *Neochetina eichhorniae* Warner (Col.: Curculionidae)	*E. crassipes*	In use in North America, Australia, Africa and Asia (Julien and Griffiths, 1998)
2. *Neochetina bruchi* Hustache (Col.: Curculionidae)	*E. crassipes*	Ibid.
3. *Niphograpta albiguttalis* (Warren) (Lep.: Pyralidae)	*E. crassipes*	Ibid.
4. *Orthogalumna terebrantis* Wallwork (Acarina: Galumnidae)	*E. crassipes, E. azurea, Pontederia cordata, Reussia subovata*	Ibid.
Second Priority – Candidates Recently Released Or Under Testing		
5. *Eccritotarsus catarinensis* (Carvalho) (Heter.: Miridae)	Field: *E. crassipes,* Lab.: *E. crassipes, E. natans, P. cordata,* Heteranthera, Monochoria	Heavy attack at Belem, Brazil (Bennett and Zwölfer, 1968);Tested in South Africa, liberated in 1996 and established (Hill et al., 1999, 2000)
6. *Xubida* (=*Acigona*) *infusellus* (Walker) (Lep.: Pyralidae)	Field: *E. crassipes, E. azurea, P. cordata, P. rotundifolia*	Liberated in Australia September 1981; not established. Reimported in 1995 and liberated in 1996 (Julien and Griffiths, 1998)
7. *Cornops aquaticum* (Bruner) (Orth.: Acrididae, Leptysminae)	Field: *E. crassipes, E. azurea, P. cordata*	Testing underway in quarantine in South Africa (Hill, unpubl. reports)
8. *Bellura densa* (Walker) (Lep.: Noctuidae)	Field: *P. cordata, E. crassipes, Colocasia esculenta*	Testing underway in quarantine in South Africa. Release rejected as hazard to *Colocasia esculenta* (Hill, unpubl. reports)
9. *Paracles* (=*Palustra*) *tenuis* (Berg) (Lep.: Arctiidae)	Field: *E.azurea, P. cordata, E. crassipes* Lab.: Various plants in different families	Polyphagous in laboratory testing. It developed readily on *P. rotundifolia, Alternanthera, Canna, Limnobium,* and *Sagittaria.* Rejected from consideration (Cordo, unpub. rpt.)
10. *Thrypticus* spp.- Seven species- (Dip.: Dolichopodidae)	Field: *E. crassipes, E. azurea, P. cordata,* and *Pontederia subovata*	Under study at SABCL. Two species apparently monophagous on water hyacinth. Very promising (Cordo, unp. rep.)
Third Priority - Candidates Poorly Known Or Of Questionable Specificity		
11. *Brachinus* sp. (Col.: Carabidae)	Field: *E. crassipes, E. azurea, P. cordata,* and perhaps others	Feeding on flowers (Silveira Guido, 1965). May be the same as the *Callida* sp. found in Argentina (Cordo, Hill, and Center, unpubl.)
12. *Argyractis subornata* Hampson (Lep.: Pyralidae)	Field: *E. crassipes* and perhaps others. Lab: *E. crassipes* and *Pistia stratiotes* L.	Root feeder; life history and biology studied by Forno (1983)
13. *Macocephala acuminata* Dallas (Heter.: Pentatomidae)	Field: *E. crassipes* and perhaps others	Root feeder; a pest of rice (Silveira Guido, 1965)
14. *Taosa inexacta* Walker (Homoptera: Dictyopharidae)	Field: *E. crassipes, P. rotundifolia* and perhaps others.	Feeding weakens plants and hastens deterioration; moderate degree of specificity (Cruttwell, 1973)
15. *Megamelus electrae* Muir and *Megamelus scutellaris Berg* (Hom.: Delphacidae)	Field: *E. crassipes, E. azurea, P. cordata* and perhaps others	Trinidad to Argentina. No visible damage caused to plants (Cruttwell, 1973). High levels of damage seen in Rio Janeiro, Brazil, in 1967 (Bennett, 1967). *M. scutellaris* under study in Argentina

Table 2. Characterization of Major Arthropods Associated with Waterhyacinth (continued).

Species	Field and Laboratory Host Plants	Attributes, Limitations and Current Status of Research
Third Priority - Candidates Poorly Known Or Of Questionable Specificity		
16. *Eugaurax setigena* Sabrosky (Diptera: Chloropidae)	Field: *E. crassipes, E. paniculata* and perhaps others	Little known on food habits; *Eugaurax floridensis* Malloch reared from *Sagittaria falcata* Pursh. *Eugaurax quadrilineata* reared from eggplant (Sabrosky, 1974)
17. *Chironomus falvipilus* Rempel (Diptera: Chironomidae)	Field: *E. crassipes* and perhaps others	In petioles of waterhyacinth in Surinam and Brazil. Undetermined chironomid from Uruguay (Silveira Guido, 1965)
18. *Hydrellia* sp. (Dip.: Ephydridae)	Field: *E. crassipes, P. lanceolata* and perhaps others	Common in Uruguay (Silveira Guido, 1965)
19. *Flechtmannia eichhorniae* Keifer (Acarina: Eriophyidae)	Field: *E. crassipes* and perhaps others	Described for Brazil (Kiefer, 1979). Mentioned from Uruguay (Silveira Guido, 1965) as being a new species and genus; host specificity is promising

BIOLOGY AND ECOLOGY OF KEY NATURAL ENEMIES

Neochetina eichhorniae and *N. bruchi* (Coleoptera: Curculionidae)

Members of the genus *Neochetina* are semiaquatic weevils that feed only on species of Pontederiaceae. Center (1994) reviewed the biologies of *N. eichhorniae* and *N. bruchi*. Adults of the two species (Fig. 5) are distinguished by the color and pattern of the scales on the elytra (Warner, 1970; DeLoach, 1975; O'Brien, 1976). *Neochetina bruchi* is typically brown with a tan band across the elytra. *Neochetina eichhorniae* is usually mottled gray and brown. Both species have two parallel tubercles on the elytra on either side of the mid-line, which are short and situated near mid-length on *N. bruchi*, but are longer and further forward on *N. eichhorniae*.

The whitish, ovoid eggs (0.75 mm in length) are embedded in plant tissue. Larvae are whitish with a yellow-orange head (Fig. 6). They have no legs or prolegs, only enlarged pedal lobes bearing apical setae. Larvae can be distinguished by the presence (*N. bruchi*) or absence (*N. eichhorniae*) of setal-bearing protuberances on these pedal lobes (Habeck and Lott, unpub. report). Neonate larvae are about 2 mm and fully-grown third instar larvae are 8 to 9 mm in length. Pupae are white and enclosed in a cocoon that is attached to a root below the water surface.

Figure 5. *Neochetina bruchi* (left) and *N. eichhorniae* (right) adults. (Photo courtesy of W. C. Durden, USDA, ARS.)

Figure 6. Late-stage *Neochetina* sp. larvae feed at the base of leaf petioles, often damaging subtending axillary buds. (Photo courtesy of W. C. Durden, USDA, ARS.)

Neochetina eichhorniae deposits eggs singly, whereas *N. bruchi* often deposits several in the same site. *Neochetina bruchi* prefers leaves with inflated petioles, especially those at the periphery of the plant (DeLoach and Cordo, 1976a), whereas eggs of *N. eichhorniae* are found in intermediate-aged leaves (Center, 1987a). Eggs hatch in seven to 10 days at 24°C.

The first instar larva excavates a sub-epidermal burrow and tunnels downwards. There are three instars and late-instar larvae are generally found near the crown where they often damage axillary buds. The entire larval period requires 30 to 45 days with *N. bruchi* developing somewhat faster than *N. eichhorniae* (Center, 1994). The fully developed larva exits the plant and crawls to the upper root zone to pupate. The pupal stage requires about seven days, but teneral adults may remain in cocoons for extended periods.

Emerging adults climb onto emergent plant parts to feed and mate, often aggregating within a furled expanding leaf or beneath membranous ligules. Females lay their first eggs soon after emergence (DeLoach and Cordo, 1976a, b). As many as 300 to 400 eggs are produced cyclically over a life span of up to 300 days (Center, 1994).

Both species of *Neochetina* undergo flight muscle generation and degeneration (Buckingham and Passoa, 1985), possibly reflecting alternating dispersive and reproductive phases. Center and Dray (1992) theorized that plant quality and phenostage influenced the weevil's propensity to switch between phases, with *N. bruchi* being more sensitive to plant quality (see also Heard and Winterton, 2000) and more likely to disperse.

Adult feeding creates characteristic rectangular scars on the leaves, about 2 to 3 mm in width and of variable length, sometimes girdling the leaf petioles at the distal end and causing the blade to dessicate (see DeLoach and Cordo, 1983; Wright and Center, 1984; Center *et al.*, 1999a). Moderate to severe weevil infestations cause plants to be shorter with smaller leaves, fewer offsets and flowers, lower tissue nutrient content, and reduced overall vigor (Fig. 7) than uninfested or lightly infested plants (Center and Van, 1989).
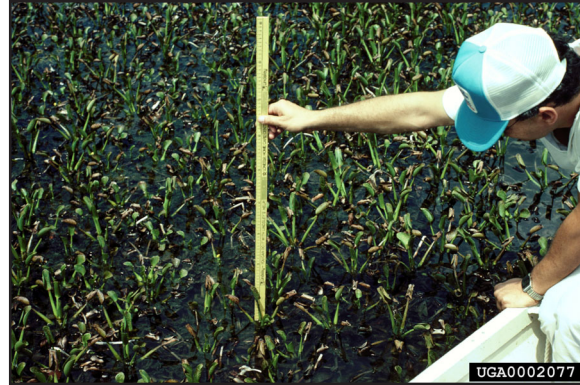

Figure 7. Waterhyacinth plants stressed by weevils tend lose buoyancy and to be of small stature. (Photo courtesy of W. C. Durden, USDA, ARS.)

Eccritotarsus catarinensis (Heteroptera: Miridae)

Eccritotarsus catarinensis (Fig. 8) is a leaf-sucking bug (2 to 3 mm long). Eggs are inserted into the leaf tissue parallel to the surface and the four nymphal instars feed gregariously with the adults on the underside of the leaves, causing severe chlorosis. Development of the eggs and nymphs requires 23 days and adults live 50 days (Hill *et al.,* 1999).

Figure 8. An adult *Eccritotarsus catarinensis*. (Photo courtesy of John Stanley, CSIRO.)

Bennett and Zwölfer (1968) observed a mirid on waterhyacinth in Belém, Brazil, but the insect was never collected or named. A mirid later collected in Rio de Janeiro during 1989 was identified as *E. catarinensis*. It was imported to quarantine in South Africa in 1992 from Canavieras, Brazil (Hill *et al.,* 1999). More recently, it was found on the Kumaceba River in the upper reaches of the Amazon River, near Iquitos, Peru in 1999 (Cordo *et al.,* unpub.).

Host specificity of this mirid was determined in South Africa from tests using 67 species in 36 families. Some feeding and development occurred on three native African Pontederiaceae, (*i.e., Eichhornia natans* [P. Beauv.], *Monochoria africana* [Solms-Laubach], and *Heteranthera callifolia* Kunth.), but the risk to these plants was deemed minimal and the insect was released in 1997 (Hill *et al.,* 1999, 2000). This insect was later imported to Australia, where additional host specificity testing was done. However, the potential for damage to native Australian *Monochoria* species precluded its use (Stanley and Julien, 1999). Some *Monochoria* species are serious weeds of rice paddies and not considered to have conservation value in Asia. As a result, *E. catarinensis* has been released in China (Ding *et al.*, 2001) and imported into Thailand for pre-release evaluation (A. Winotai, pers. comm.).

This mirid is being considered for release in the United States. However, host specificity trials in both South Africa and Australia demonstrated feeding and development on pickerelweed (Hill *et al.,* 1999; Stanley and Julien, 1999). Pickerelweed, being an introduced plant in both of these countries, played no role in the decision to release this insect. But pickerelweed is native to North America, so any threat to it would be unacceptable in the United States. Several studies are therefore being undertaken in South Africa to quantify the impact of *E. catarinensis* on pickerelweed under field conditions.

Eccritotarsus catarinensis is now established in South Africa (Hill and Cilliers, 1999) and its effects are being monitored. Although the impact of this insect on waterhyacinth performance has not yet been quantified, it does reach very high densities in tropical areas of the country where it is capable of causing severe die back of the plants (Fig. 9). It also has been released in Benin, Zambia, and Malawi, and cultures have been sent to Zimbabwe, Thailand, and China.

Figure 9. A waterhyacinth mat in South Africa in decline due to infestation by *E. catarinensis.* (Photo courtesy of C. Cilliers, PPRI.)

Niphograpta albiguttalis (Lepidoptera: Pyralidae)

The small (ca. 0.3 mm), spherical, and creamy-white eggs of *N. albiguttalis* take three to four days to hatch at 25°C. The newly emerged larva (1.5 mm in length) is brown with darker spots and has a dark brown head (Fig. 10). There are five larval instars, the last of which grows to about 2 cm long, with a dark orange head and a cream-colored body covered with conspicuous dark brown spots. Larval development requires about two weeks. The fully-grown larva excavates a cavity in a healthy leaf petiole, in which it forms its cocoon. Pupation occurs in the cocoon and the pupal stage lasts seven to 10 days. The emerging adult moth exits the petiole through a silken tunnel prepared by the larvae before pupation.

Figure 10. *Niphograpta albiguttalis* larva. (Photo courtesy of W. C. Durden, USDA, ARS.)

Adults (Fig. 11) live about seven to 10 days. Mating occurs shortly after emergence from the pupa and the female lays the majority of her eggs the following night. An average female will deposit 450 to 600 eggs. The entire life cycle requires three to four weeks. Center *et al.* (1982a) provide further information on the biology and identification of this species.

Figure 11. An adult male *Niphograpta albiguttalis*. (Photo courtesy of W. C. Durden, USDA, ARS.)

Orthogalumna terebrantis (Acarina: Galumnidae)

The waterhyacinth mite, *O. terebrantis* (Fig. 12), like other mites, has piercing mouthparts with which it sucks plant juices. Its host plants include pickerelweed and waterhyacinth (Gordon and Coulson, 1969).
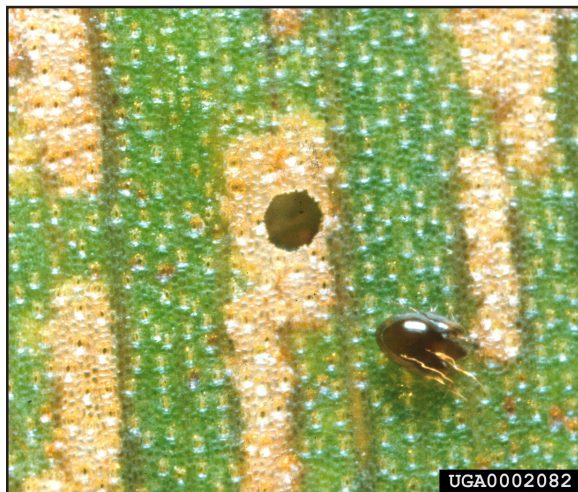

Figure 12. The waterhyacinth mite *Orthogalumna terebrantis*. (Photo courtesy of W. C. Durden, USDA, ARS.)

Cordo and DeLoach (1975, 1976) described the biology and life history of *O. terebrantis*. Adults are shiny black, about 0.5 mm long and narrowed anteriorly. Females lay their eggs in small round holes chewed in the leaves. Eggs hatch in seven to eight days (at 25°C) and produce small (less than 0.24 mm), whitish, slow-moving larvae. Complete development requires about 15 days (at 25°C).

Feeding damage is restricted to the leaf blades. Larval feeding causes small reddish spots on the leaf surface and the nymphs produce galleries that extend about 6 mm towards the apex. The adults emerge through round exit holes at the end of the gallery.

Large mite populations produce up to 2,500 galleries on a single leaf, which desiccate the blade (Gordon and Coulson, 1969). Severe damage is usually localized or confined to a few plants but, when combined with other stresses, it can contribute to declines (Delfosse, 1978).

Xubida infusellus (Lepidoptera: Pyralidae)

Silveira Guido (1965, 1971) considered the pyralid *X. infusellus* (Fig. 13) to be one of the most important phytophagous species on waterhyacinth in South America. Larvae (Fig. 14) severely damage leaf petioles and can destroy shoots by feeding on apical meristems and burrowing into rhizomes. Although damage is similar to that of *N. albiguttalis* or *B. densa*, it was thought that the introduction of *X. infusellus* might complement the effects of *N. albiguttalis* (Bennett and Zwölfer, 1968; DeLoach *et al.*, 1980). *Xubia infusellus* prefers advanced phenostage plants with elongate leaf petioles (see Center *et al.*, 1999a), whereas *N. albiguttalis* prefers younger plants with inflated leaf petioles. Sands and Kassulke (1983) describe the adults in detail.

Silveira Guido (1965, 1971), DeLoach *et al.* (1980), and Sands and Kassulke (1983) provide notes on the life history of *X. infusellus*. The nocturnal females lay egg masses in crevices such as the folds of leaves or the overlapping edges of furled leaves. Females lay indiscriminantly, sometimes on plants not used as larval hosts or, in the laboratory, on cage materials. Numbers of eggs per egg mass vary from a few to several hundred. Eggs hatch in six to seven days at 26° C.

Figure 13. An adult of *Xubida infusella.* (Photo courtesy of John Stanley, CSIRO)
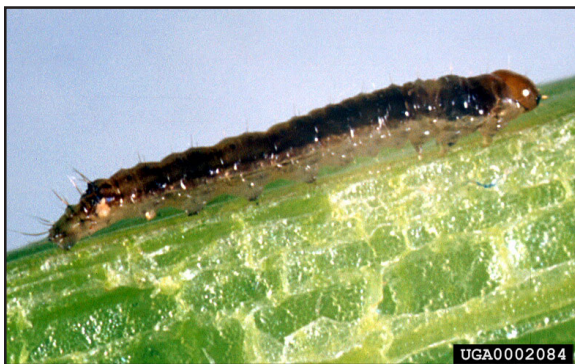

Figure 14. *Xubida infusella* larva. (Photo courtesy of M. P. Hill, PPRI)

First instar larvae briefly feed externally, sometimes girdling a petiole before entering it, but then feed internally. They burrow downward, sometimes transferring to adjacent leaves, until they eventually encounter the rhizome. The number of larval instars varies from seven to ten, and development requires about 48 days (Sands and Kassulke, 1983). Larvae become about 25 mm long when fully grown (DeLoach *et al.,* 1980). Late instar larvae form large burrows, causing extensive damage. Larvae cut emergence holes in the petiole prior to pupation that they close with silk, and then pupate just below the covered opening. The pupal stage lasts about nine days and total developmental requires 64 days at 26°C (Sands and Kassulke, 1983). The adult lives four to eight days (Silveira Guido, 1965, 1971; Sands and Kassulke, 1983).

This insect has established in Australia (Julien and Griffiths, 1998). It also was released in Papua New Guinea (Julien and Stanley, 1999). A decision was made not to release it in the United States due to the threat to pickerelweed.

Thrypticus spp. (Diptera: Dolichopodidae)

Thrypticus species (Fig. 15) are all phytophagous stem miners of monocots in the Cyperaceae, Graminiaceae, and Juncacaeae. Females possess a characteristic sclerotized, blade-like structure used to pierce stems in preparation for oviposition. These tiny flies are generally found in wet grassland or marsh habitats (Bickel, 1986). The genus is nearly cosmopolitan, with 71 known species and a broad radiation in the neotropics (Bickel, 1986). Bennett and Zwölfer (1968) found *Thrypticus* species associated with waterhyacinth in Trinidad, Guyana, Surinam, and Brazil, but Bennett (1972) failed to note its presence in Belize, Jamaica, Barbados, or St. Vincent. Mitchell and Thomas (1972) found members of the genus in Argentina, Uruguay, Brazil, Guyana, and Trinidad. The species found by Bennett and Zwölfer (1968) in northern South America was later identified as *Thrypticus insularis* Van Duzee (Bennett, 1976) and still later synonomized with *Thrypticus minutus* Parent (Dyte, 1993). However, this specific epithet was rarely referred to in later literature and the insect continued to be known as *Thrypticus* sp. Dr. Christian Thompson of the U.S. National Museum concluded that several *Thrypticus* species collected in Argentina probably represented undescribed species.

Figure 15. *Thrypticus* sp. adult reared from waterhyacinth. (Photo courtesy of C. A. Bennett, University of Florida.)

Cruttwell (1973) described the life history of a *Thrypticus* sp. from waterhyacinth in Trinidad. The adults are 1.5 to 2 mm long and light brown in color. Females lay eggs singly in young petioles of *E. crassipes*, inserting eggs into the tissues, usually just above the water line. Eggs are yellow, 0.5 mm long

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and 0.17 mm in diameter, curved, with one end narrower than the other. Petioles are suitable for oviposition only when recently separated from the sheath; thus all galleries in an individual petiole are of similar age. Eggs hatch in a few days and the larvae tunnel horizontally, making a second exit hole at the other end of the gallery. Larvae continue to feed in galleries, which they enlarge and lengthen.   There are three instars and the larval stage lasts 35 to 42 days. Mature larvae are about 4 mm long. They prepare an emergence window in the petiole before pupating in an enlarged chamber below the exit hole. Adults emerge in seven to 12 days and lay up to 50 eggs.

When petioles have large numbers of larval galleries, damage can be extensive (Fig. 16). Mitchell and Thomas (1972) noted that nearly all plants attacked at Santos, Brazil, showed extensive rotting of petioles bases and, in many cases, had completely collapsed.

Figure 16. Damage to a waterhyacinth leaf petiole caused by larvae of *Thrypticus* sp. (Photo courtesy of H. A. Cordo, USDA, ARS.)

Larvae do not leave their galleries; so ovipositing females select the larval host plant. Cruttwell (1973) exposed rice, yam, and sweet potato plants to *Thrypticus* sp. in tanks that also contained waterhyacinth. She noticed that adults regularly rested on waterhyacinth but never on the test plants. Also, galleries never appeared on the test plants even though the waterhyacinth exhibited galleries after eight to 11 days.

Thrypticus were found attacking *E. crassipes*, *E. azurea*, *P. cordata*, and *Pontederia rotundifolia* L. in northern Argentina (H. Cordo, unpub.). Comparisons of genitalia and larval mining patterns of insects from various Pontederiaceae suggested that several

distinct species were represented, some of which seemed restricted to waterhyacinth.

The effects of the mining damage caused by *Thrypticus* species on waterhyacinth performance have not been measured. However, the strict monophagy, ubiquity, and abundance of these species make them promising as biological control agents. The tiny, but often abundant, tunnels produced by the larvae of these species have been judged trivial by some authors, but the damage may enhance the stress produced by other agents. The apparent high degree of specialization of *Thrypticus* species among species of Pontederiaceae suggests that they are host specific and augurs well for their potential use in biological control.

Cornops aquaticum **(Orthoptera: Acrididae)**

Perkins (1974) considered the grasshopper *C. aquaticum* to be among the most damaging of the South American insects associated with waterhyacinth (Fig. 17). Despite heavy egg predation by the weevil *Ludovix fasciatus* (Gyllenhal), *C. aquaticum* is abundant and very damaging. Its broad distribution from Argentina through Mexico indicates that it can tolerate a wide range of climatic conditions. However, concern over its host specificity has precluded consideration for release in the United States.

Figure 17. *Cornops aquaticum* adult. (Photo courtesy of S. Neser, PPRI.)

Females lay groups of 30 to 70 eggs enclosed in egg cases that are inserted into the youngest leaf petiole on a plant (Silveira Guido and Perkins, 1975). Eggs hatch in 25 to 30 days, producing green-and-red-striped nymphs (Fig. 18). There are six or seven nymphal instars and development requires about 50 days. Nymphs are highly mobile and very damaging.

The dark green adults copulate soon after emergence, and produce up to eight egg cases 25 to 30 days later. Adults live up to 110 days, are mobile, strong fliers, and are extremely damaging to the plant (Fig. 19).

Figure 18. *Cornops aquaticum* nymph. (Photo courtesy of S. Neser, PPRI.)

Figure 19. The waterhyacinth grasshopper *Cornops aquaticum* feeds on leaves producing a characteristic "tattered" appearance. (Photo courtesy of H. Oberholzer, PPRI.)

Cornops aquaticum feeds and develops on waterhyacinth, *E. azurea, P. cordata*, and *Commelina* sp. under laboratory conditions (Silveira Guido and Perkins, 1975). We observed *C. aquaticum* on *E. azurea, P. cordata, P. rotundifolia* and *Pontederia subovata (Seub. in Markt.) Lowden,* in addition to waterhyacinth (H. Cordo *et al.,* unpub.) during field surveys in northern Argentina (1997) and the upper Amazon River in Peru (1999). This oligophagous species is clearly not suitable for release in the United States.

Despite these results, *C. aquaticum* is under study in South Africa where its oligophagy, including development on *P. cordata* and *Canna indica* L. (Cannaceae), has been confirmed. Further large-scale, multi-choice trails will quantify the threat of *C. aquaticum* to African Pontederiaceae.

Cercospora spp. (Hyphomycetes)

Cercospora piaropi and *Cercospora rodmanii* Conway cause dark brown leaf spots on waterhyacinth that can lead to necrosis of older leaves and petioles. Characters used to separate these two species are variable, so these fungi may represent a single species (Morris, 1990). *Cercospora piaropi,* described in 1917 from Texas, was apparently introduced into the United States with the plant (Tharp, 1917). Extensive research has been conducted on the use of this species as a natural enemy of waterhyacinth (Freeman and Charudattan, 1984). Charudattan *et al.* (1985) investigated application techniques for *C. rodmanii* and concluded that this pathogen was unlikely to control the plant with a single application.

In 1986, *Cercospora piaropi* was found in South Africa associated with the decline of a waterhyacinth mat at a reservoir in the eastern province of Mpumulanga (Morris, 1990; Morris *et al.,* 1999). It is now established throughout South Africa as the result of transplanting infected plants. *Cercospora rodmanii* was introduced to South Africa from Florida in 1988. Although these pathogens now occur widely in the western Cape province, there has been no resultant decline in weed populations.

Other Species

There are a number of other species about which little is known but which may have potential as control agents. They include the following:

(1) *Bellura densa* (Walker) (Lepidoptera: Noctuidae) is a native North American moth (Fig. 20). The natural host is pickerelweed, but it commonly feeds and develops on waterhyacinth and taro (*Colocasia esculenta* Schott) (Center and Hill, 1999). Parasitoids, predators, and diseases limit its abundance in the United States (Center, 1976; Baer and Quimby, 1982).

Females lay about 300 eggs, in masses of up to 40 eggs each, on host leaves. Egg masses are covered with cream-colored scales. A scelionid parasitoid (*Telenomus arzamae* Riley) kills most of the outer eggs in the masses, but the innermost eggs survive.

Figure 20. *Bellura densa* adult. (Photo courtesy of W. C. Durden, USDA, ARS.)

Eggs hatch in six days and larval development requires five weeks. Larvae pupate in petioles and produce naked, reddish brown pupae. The pupal stage lasts 10 days, with complete development requiring about 50 days.

The damage caused by *B. densa* is similar to that by *N. albiguttalis*, but more severe. Older caterpillars extensively excavate petioles and burrow deep within the rhizomes, fragmenting the stems and killing the shoots. This species is the most damaging of the insects that feed on waterhyacinth (Fig. 21). Vogel and Oliver (1969a, b) and Center (1976) provide further information on the biology of *B. densa* and its effects on waterhyacinth.

Figure 21. Larva of the moth *Bellura densa*. (Photo courtesy of S. Neser, PPRI.)

(2) *Brachinus* larvae and adults (Coleoptera: Carabidae) feed on the flowers of *E. crassipes, E. azurea,* and *P. cordata*. Larvae feed in the ovaries and pupate inside the peduncle. Two other carabids commonly found in collections from waterhyacinth are *Pionicha tristis* Gory and *Alachnothorax bruchi* Libke. The taxonomy, feeding habits, and plant associations of these insects are in need of clarification. They could have value as flower feeders, a part of waterhyacinth otherwise free from attack.

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(3) *Chalepides* species (Coleoptera: Scarabaeidae) are sometimes found tunneling in the crowns of *E. crassipes*, *E. azurea* and *Pistia stratiotes* (Fig. 22). However, larvae, which are believed to feed on the roots of grasses, have never been associated with the Pontederiaceae.

Figure 22. The scarab *Chalepides* sp. (Photo courtesy of S. Neser, PPRI.)

(4) *Hydrellia* sp. (Diptera: Ephydridae) mines the leaf blades of young waterhyacinth before descending into the bulbous petioles. It can be quite damaging, but is usually not abundant.

(5) *Taosa inexacta* Walker (Homoptera: Dictyopharidae) weakens plants and hastens their deterioration under laboratory conditions. Preliminary feeding tests suggest that it is specific to the Pontederiaceae (Cruttwell, 1973). The injury caused by this planthopper (Fig. 23) is similar to that from *Megamelus* species and can be devastating to waterhyacinth populations (De Quattro, 2000). The *Taosa* species found on different species of Pontederiaceae probably include three or more undescribed species, some of which may be waterhyacinth specialists.

(6) *Megamelus electrae* Muir (Heteroptera: Delphacidae) was once considered for waterhyacinth biological control (Cruttwell, 1973), but investigations were never completed. There are no host records for the other four neotropical species. We found several delphacids associated with waterhyacinth and its relatives, in both Argentina and the upper Amazon Basin, including several

Figure 23. Waterhyacinth extensively damaged by the planthopper *Taosa inexacta.* (Photo courtesy of H. A. Cordo, USDA, ARS.)

Megamelus species. One species, *Megamelus scutellaris* Berg (Fig. 24), seems restricted to *E. crassipes.* Host plant associations were observed in the field and host specificity has been tested in Argentina (H. Cordo, unpub.). Specimens of *M. scutellaris* were field-collected only on *E. crassipes.* When the insects were allowed to move freely among several pools containing cultures of different Pontederiaceae, one *Megamelus* sp. developed on several species of Pontederiaceae. In contrast, *M. scutellaris* developed only on waterhyacinth and did not attack pickerelweed varieties from Argentina, the United States, or South Africa. High densities of *M. scutellaris* are uncommon in the field, where parasitoids and predators are abundant. When protected from natural enemies, *M. scutellaris* produces large populations and thus seems a promising biological control candidate.

(7) *Paracles* (=*Palustra*, in part) species, including *P. tenuis* (Lep.: Arctiidae) (Fig. 25) are associated with waterhyacinth and related aquatic plants. Silveira-Guido (1965) first suggested that some of these species might be useful for waterhyacinth control. Mitchell and Thomas (1972) found adults, but not larvae and little evidence of larval damage, associated with waterhyacinth in Uruguay. Perkins (1974) noted their importance as defoliators of waterhyacinth in South America, but that they also fed on other aquatic plants. Its polyphagy was confirmed in the mid-1990s (H. Cordo, unpub.).

Figure 24. The planthopper *Megamelus* sp. (Photo courtesy of C. A. Bennett, University of Florida.)

Figure 25. Larva of the arctiid moth *Paracles tenuis.* (Photo courtesy of H. A. Cordo, USDA, ARS.)

EVALUATION OF PROJECT OUTCOMES

Establishment and Spread of Agents

Neochetina eichhorniae was released in southern Florida in 1972, using eggs from 2,479 adults sent from Argentina during August 1972 to March 1973. Adults removed from founder colonies were then redistributed by numerous agencies. As a result, *N. eichhorniae* was released at 199 sites in Florida, 492 sites in Louisiana, one site in Texas, and four sites in California (Manning, 1979; Cofrancesco, 1984, 1985). This intensive effort seemed necessary because of the belief that this species didn't fly. However,

N. eichhorniae was already present when initial releases were made in Texas, having apparently dispersed from southern Louisiana, and by 1984 it was at several waterhyacinth infestations between Port Arthur and Corpus Christi (Cofrancesco, 1984; Stewart, 1987). Large numbers of weevils, many actively flying, were observed at lights in southern Louisiana during 1980 (Center, 1982), clearly indicating a capacity to disperse.

When *N. bruchi* became available, there was no similar dissemination campaign. As a result, it was released at only 40 sites: 21 in Florida, 10 in Louisiana, five in Texas, and four in California (Manning, 1979; Stewart, 1985, 1987). Despite this disparity in release efforts, both species are now ubiquitous in Florida (Center and Dray, 1992; Center *et al.*, 1999a), but the status of *N. bruchi* elsewhere is unclear.

Niphograpta albiguttalis was initially released only in southern Florida, but populations dispersed more than 500 km within 18 months (Center, 1984). This moth was released at two sites in Louisiana during May 1979 and collected 27 km from the nearest release site a year later (Brou, undated). *Niphograpta albiguttalis* appeared to be absent from Texas in 1985, and so was released at a few sites during May 1986. It was widely dispersed by July 1986 (Stewart, 1987), probably originating from Louisiana, rather than the more recent Texas releases. DeLoach and Center (unpub.) found *N. albiguttalis* in Mexico near Veracruz and near Tapachula, the latter being on the Pacific coast near the border with Guatamala. This insect was never released in Mexico (Julien and Griffiths, 1998). So it is likely that these populations derived from ones in the United States, with the nearest release site being about 1,600 km away. Likewise, although there are no recorded releases of *N. albiguttalis* in Puerto Rico (Julien and Griffiths, 1998), larvae were collected near San Juan in 1995 (specimen records, Malaria Canal, 18 April, 1995, collector T. D. Center; Lago Loiza, 19 April, 1995, collector T. D. Center). Labrada (1996) reported its presence in Cuba, too, so perhaps *N. albiguttalis* "island hopped" from Florida to the West Indies.

Suppression of Target Weed

Numerous field studies document the decline of waterhyacinth in diverse geographical areas of the United States after introductions of biological control agents (i.e., Goyer and Stark, 1981, 1984;

Cofrancesco, 1985; Cofrancesco *et al.*, 1985; Center and Durden, 1986; Center, 1987b). Waterhyacinth now occupies one-third of its former acreage in the Gulf Coast states (Cofrancesco *et al.*, 1985; Center *et al.*, 1990) (Fig. 26). This reduction resulted from both direct plant mortality and reduced regrowth after winter diebacks, perhaps along with reduced flowering and seed production (Center *et al.*, 1999a, b). Feeding by insects destroys meristematic tissue causing the plants to lose their ability to replace senescent tissue. They then lose bouyancy and sink. Often, they merely stop growing as the destruction of axillary buds and reduced carbohydrate reserves prevents clonal expansion. In recent experiments, for example, plots with weevils doubled or tripled in coverage, whereas uninoculated controls expanded nearly six-fold during the growing season (Center *et al.*, 1999b). Hence, control stems from growth suppression, reduction of the seed bank, and destruction of existing plants.

The most recent and most spectacular effects of the waterhyacinth weevils have occurred at Lake Victoria in East Africa (Fig. 27). Waterhyacinth was first recorded on the lake in 1980 and by the mid-1990s some 12,000 ha of the weed were clogging bays and inlets. Uganda made the first introductions of *N. eichhorniae* and *N. bruchi* in 1995, followed by Kenya and Tanzania in 1997 (Anon., 2000). A significant reduction in the extent of the weed on the Ugandan shore was evident by November 1998, with many of the mats having sunk. These results were later repeated on the Kenyan and Tanzanian shores. An estimated 75% of the mats on the Kenyan side had sunk by December 1999 (Anon., 2000). The spectacular results of the biological control program on Lake Victoria using the two weevil species are the same as those achieved on Lake Kyoga (Uganda) (Ogwang and Molo, 1999) and on the lagoons of the Sepik River (Papua New Guinea) (Julien and Orapa, 1999). Similar results have been obtained in Sinaloa, Mexico where the release of *N. eichhorniae* and *N. bruchi* during 1995 to 1996 reduced 3,041 ha of waterhyacinth distributed over seven impoundments by 62% (to 1,180 ha) by 1998 (Aguilar, pers. comm.). These successes reaffirm earlier reports from Australia (Wright, 1979, 1981), Argentina (DeLoach and Cordo, 1983), India (Jayanth, 1987, 1988), and the Sudan (Girling, 1983; Beshir and Bennett, 1985).
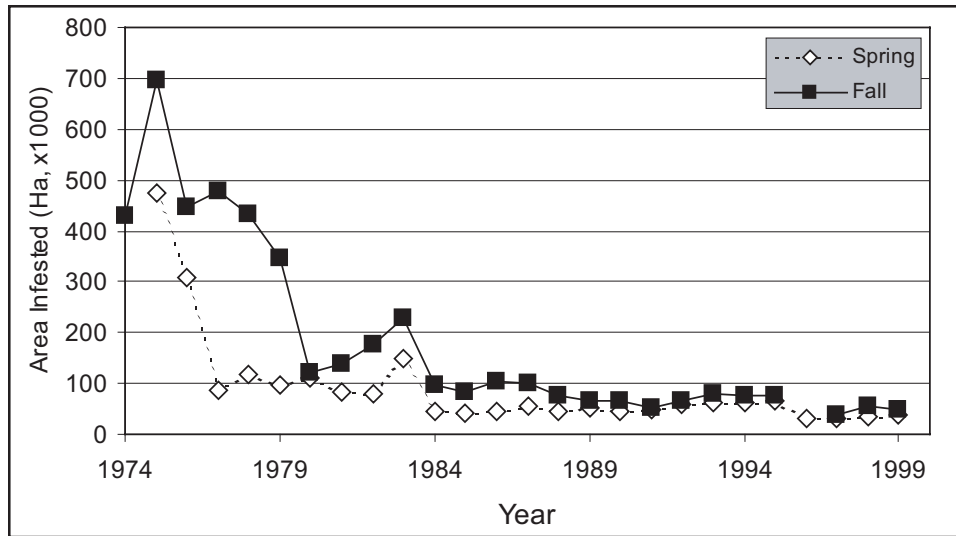
Figure 26. Data from Louisiana showing reduced waterhyacinth acreage and limited annual growth after introduction of *Neochetina eichhorniae* in 1974, *N. bruchi* in 1975, and *Niphograpta albiguttalis* in 1979.

Figure 27A.

Figure 27B.

Figure 27C.

Figure 27D.

Figure 27. *Neochetina* spp. were released at Lake Victoria in Uganda during 1996 and Kenya during 1997. These "before" and "after" photographs of waterhyacinth infestations show the effects of biological control. A. Kisumu Yacht Club, Kenya, 6 June 1999 (Photo courtesy of M. H. Julien); B. Kisumu Yacht Club, Kenya, 16 December 1999 (Photo courtesy of M. H. Julien) ; C. Port Bell, Uganda, 1 June 1997 (Photo courtesy of K.L.S. Harley); D. Port Bell, Uganda, 11 December 1999 (Photo courtesy of M. H. Julien).

Factors that Accelerate Success and Factors that Limit Control

Factors associated with successful control include presence of the infestation in tropical and subtropical areas; infestations manifested as monocultures in free-floating mats that are able to sink when damaged; and mats that are stable (i.e., undisturbed) over long periods of time. Factors that might accelerate control include wave action, reduced growth (due to the action of biological control agents), and high nutrient levels (since high quality plants enhance insect population growth). Factors that limit control include removal of mats by herbicidal or mechanical means (thus disrupting agent populations), shallow water (damaged plants being unable to sink), ephemeral water bodies, toxicity effects in polluted waters, low temperatures at high-altitude or temperate sites, high nutrients at temperate sites, and limited releases (small, inoculative releases as opposed to mass releases or serial releases) (Julien, 2001; Hill and Olckers, 2001).

RECOMMENDATIONS FOR FUTURE WORK

Future Needs for Importation or Evaluation

Surveys done by Center *et al.* (1999a) confirmed that waterhyacinth populations not subjected to repeated control operations become stressed by biological control agents, particularly the two *Neochetina* species. On the other hand, water bodies subjected to continual herbicidal control actions generally have small weevil populations, due to instability of the weevil's food supply. Such sites produce healthier plants due to the reduced level of herbivore damage. The stressed plants typical of many unmanaged sites tend to be of lower nutritional quality than those at managed sites. The breeding condition of the female weevils correlates with host nutritional quality, so routine maintenance probably enhances the *potential* development of weevil populations by keeping host quality high, even though the *actual* populations are small. This suggests numerous possibilities for integrated approaches designed to overcome interference between the two control methods. However, the present maintenance program is considered to be effective, efficient, and affordable. In contrast, an integrated program involving management of populations of biological control agents in concert with herbicide application would probably be more expensive, difficult to implement, and possibly less reliable. Hence, the present system is unlikely to change. Therefore, new agents are needed to improve upon the level of biological control now realized. In particular, more mobile agents, with short life cycles and high reproductive capacities, are needed that can survive non-cyclical disruptions of waterhyacinth communities induced by herbicide applications. Currently, the candidates that best meet these criteria include the doliochopodid fly *Thrypticus* sp., planthoppers in the genera *Taosa* and *Megamelus*, and possibly the mirid *E. catarinensis*.

Plans for Future Work

Further work on the biological control of waterhyacinth is needed in five areas. First, available species should be fully evaluated. Second, additional natural enemies should be sought for use where existing control is less than desired. Third, more active approaches to biological control (e.g., mass or supplemental releases, serial releases) should be examined. Fourth, better methods to integrate biological control with other control options must be evaluated. Finally, the factors that accelerate success or limit control need further delineation.

Despite a fairly long history of biological control of waterhyacinth in the world, and the number of successful programs now reported, much additional research is needed. As new agents are released there will be a need to quantify their impacts. In addition, some available agents have not been fully evaluated. Lack of a quantitative evaluation of *O. terebrantis*, for example, has resulted in it possibly being underrated as a control agent despite its significant effect on waterhyacinth on the Shire River in Malawi (Hill, unpublished data).

A recent survey of the upper Amazon basin near Iquitos, Peru, identified several new candidate agents. The synergy observed between the insect damage and plant pathogens mandates further study. This brief trip was restricted to a small portion of the upper Amazon between Iquitos and Nauta. We do not consider this fruitful area to be fully explored and encourage further exploration. Surveys in other areas, such as the Pantanal region of Brazil and the Orinoco River system in Venezuela, also should be considered.

Other insects that have been mentioned by explorers, for which basic information is not available, should be investigated to determine their field host plant ranges as a first step to assessing their potential for use in biological control efforts. These include the petiole-mining flies *Eugaurax setigena* Sabrosky (Diptera: Chloropidae), *Hydrellia* sp. (Diptera: Ephydridae), and *Chironomus falvipilus* Rempel (Diptera: Chironomidae); the flower-feeding carabid *Calleida* (= Brachinus); and the eriophyd mite *Flechtmannia eichhorniae* Keifer.

The variable results given by biological control efforts against waterhyacinth in different areas have been ascribed to a lack of climate matching between the region of origin and the region of introduction (Hill and Cilliers, 1999). Investigations into the cold tolerances of the agents are required to determine their suitability for use in temperate areas.

The biological control of waterhyacinth is perceived by water authorities to happen too slowly. Therefore, there have been a number of attempts to integrate biological control with other, quicker control options (herbicide application and mechanical control) (Delfosse *et al.,* 1976; Center *et al.,* 1982b, 1999a; Jones and Cilliers, 1999). The integration of two or more control options requires them to be compatible or, at least, not antagonistic. Further studies are needed to identify herbicides and adjuvants that are not toxic to the agents (e.g., Ueckermann and Hill, in press) and to determine more compatible methods of herbicide application.

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