Salvinia molesta (Giant Salvinia) in the United States: A Literature Review and Update

by

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INTRODUCTION

Background:

Salvinia molesta D. S. Mitchell (giant salvinia), a free-floating aquatic fern, is one of the world's most serious weeds second only to *Eichhornia crassipes* (Mart.) Solms (water hyacinth) (Holm et al. 1977; Barrett 1989). Though much smaller than *E. crassipes, S. molesta* has a faster growth rate that, under optimal conditions, enables it to double in size and biomass in less than three days (Farrell 1978, 1979; Harley and Mitchell 1981; Barrett 1989). Proliferation of *S. molesta* is accomplished through vegetative reproduction in which rhizomatous colonies are produced and disseminated through fragmentation (Room 1986a, 1990). Excessive growth of the species forms a thick mat at the water surface that can shade out favorable vegetation providing food and habitat for fish and wildlife. These mats can interfere with water-based transport and recreation, reduce oxygen content and quality of the water, and clog water intakes for irrigation and hydroelectric generation (Thomas and Room 1986a; Room et al. 1989). Public health problems have also been associated with dense growth of the plant, which restricts access to potable water supplies and harbors mosquitos and other vectors of human diseases (Bennett 1975; Room et al. 1989).

Over the past 70 years, *S. molesta* has spread from its native range in South America to over 20 countries including the United States (Oliver 1993; Jacono and Pitman 2001). Its explosive growth has had devastating socioeconomic impacts in parts of Africa, Sri Lanka, New Guinea, the Philippines and Australia. Lake Kariba on the Zambesi River, Africa, experienced

one of the most phenomenal invasions when in 1962 at its peak the weed covered a quarter of what was then the world's largest reservoir (Barrett 1989). Notable invasions in the U.S. have occurred in the Swinney Marsh Complex, Texas, in the Lower Colorado River, Arizona/California, and in Lake Wilson and Enchanted Lake, Hawaii (Jacono and Pitman 2001; TenBruggencate 2003).

Report Objective:

The objective of this report is to review available information on the growth, distribution, and management of *S. molesta*. Information is provided on current taxonomic status, field characteristics, life history, and overseas and U.S. distribution. The ecology of *S. molesta* is also described with emphasis on environmental tolerances, growth requirements, and impacts on the environment. Efforts toward managing its populations using different technologies (i.e., physical, chemical, and biological) are noted with an indication of degree of efficacy, operational status, and/or need for further investigation.

PLANT DESCRIPTION AND ECOLOGY

Taxonomic Status:

Kingdom: Plantae; Subkingdom: Tracheobionta; Division: Pteridophyta; Class: Filocopsida; Order: Hydroteridales; Family: Salviniaceae; Genus: *Salvinia* (cf., Plants National Database 2003).

Salvinia molesta D. S. Mitchell belongs to a monogeneric family (Salviniaceae) of free-floating aquatic ferns coated with velvety hairs on the leaf surfaces (Figure 1). At least twelve species of the genus (*Salvinia*) have been reported worldwide [*S. auriculata* Aubl. (= *S. rotundifolia* Willd.), *S. biloba* Raddi, *S. cucullata* Roxb. ex Bory, *S. hastata* Desv., *S. herzogii* de la Sota, *S. martynii* Spruce, *S. molesta* D. S. Mitch., *S. natans* (L.) All., *S. nymphellula* Desv., *S. oblongifolia* Mart., *S. minima* Baker, *S. sprucei* Kuhn], seven of which (*S. oblongifolia, S. sprucei, S. minima, S. auriculata, S. herzogii, S. biloba, and S. molesta*) originate in the neotropics (Mitchell and Thomas 1972; Sculthorpe 1985; Jacono and Pitman 2001). *S. molesta* and three other closely related species (*S. auriculata*, *S. herzogii,* and *S. bilob.*) comprise the taxonomic assemblage "*S. auriculata* complex." Members of this complex exhibit rows of cylindrical hairs with branches joined at the tips to form an "eggbeater or cage-like" structure. All four species are prohibited as Federal Noxious Weeds but at present, *S. molesta* is the only one of the four that occurs in the U.S. outside cultivation (Jacono 2003).

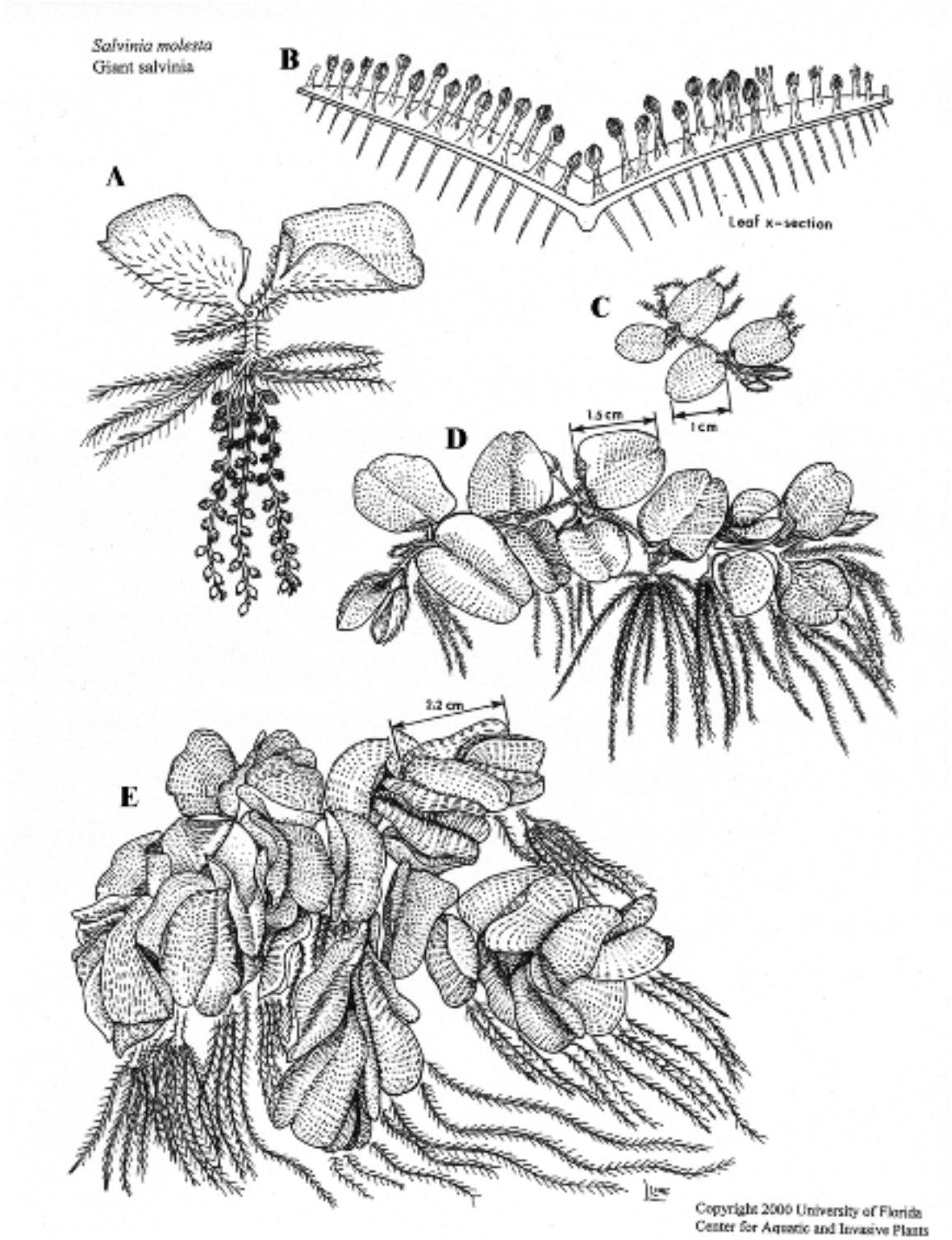

Figure 1. *Salvinia molesta* D. S. Mitchell: A, individual plant; B, leaf cross section; C, primary form; D, secondary form; E, tertiary form.

Initially identified as a form of *S. auriculata, S. molesta* was reclassified in 1972 based on details of the male sporocarps or fruiting bodies (Mitchell 1972). Current taxonomic treatments, thus noting the confusion over species identity, indicate *S. auriculata* auct. non Aubl. (misapplied) as a probable synonym (CPITT 2002). *S. molesta* is also known by a variety of common names (i.e., salvinia, giant salvinia, African pyle or payal, Kariba weed, aquarium watermoss, Australian azolla, water fern, water spangles, and giant azolla) generally recalling plant size, specific infestations, and aquatic nature of the species (Oliver 1993; Hassler and Swale 2002).

***Geographical Distribution*:**

Native and Overseas Distribution. *S. molesta* is considered native to southeastern Brazil, in a subtropical zone (between latitudes 24º05'S and 32º05'S), extending inland to an elevation of ~ 900 m (Forno and Harley 1979; Forno 1983). It was first reported outside its native range in Sri Lanka, in 1939 and has since become problematic in over 20 countries. This species is presently a nuisance in Australia, New Zealand, Fiji, the Philippines, India, and Papau New Guinea. It also plagues aquatic systems in Africa (the Ivory Republic, Ghana, Zambia, Kenya, Namibia, Botswana, South Africa and Madagascar), Southeast Asia (Indonesia, Malaysia, and Singapore), South America (Columbia and Guyana), and two Caribbean countries (Cuba and Trinidad; cf. syntheses by Oliver 1993 and Storrs and Julien 1996). Historically notable infestations have occurred in the Sepik River of Papua New Guinea, and in Africa in the Zambezi River, Lake Naivasha, Kariba Lake, and the Chobe River System. Most recently, *S. molesta* was reported in southern Kalimantan (formerly Borneo), where rivers, swamps, and rice paddies were becoming increasingly overgrown (Jacono and Pitman 2001).

History of Spread in the United States. For nearly two decades, *S. molesta* has been cultivated in the U.S. as an ornamental plant provided by the horticulture industry (Figure 2). It was first reported outside cultivation in this country in 1995 in a private 1.5-ac pond in southeastern South Carolina. Though the infestation was eradicated chemically the same year, numerous outbreaks were reported subsequently for Texas and Louisiana. By 1998, major infestations were found in Toledo Bend Reservoir, oxbow lakes of the Sabine River, and swamplands of the Swinney Marsh Complex. Among these, Toledo Bend posed the greatest threat for interstate dispersal because of its enormous size (186,000 ac) and location on the Texas-Louisiana border. A primary concern was the reservoir's use by many thousands of sportsmen who could inadvertently transport the weed on their boating equipment across Texas, Louisiana, and elsewhere. During the growing season of 2000, 1200 ac of Toledo Bend were chemically treated but these efforts appear to have been only marginally successful.

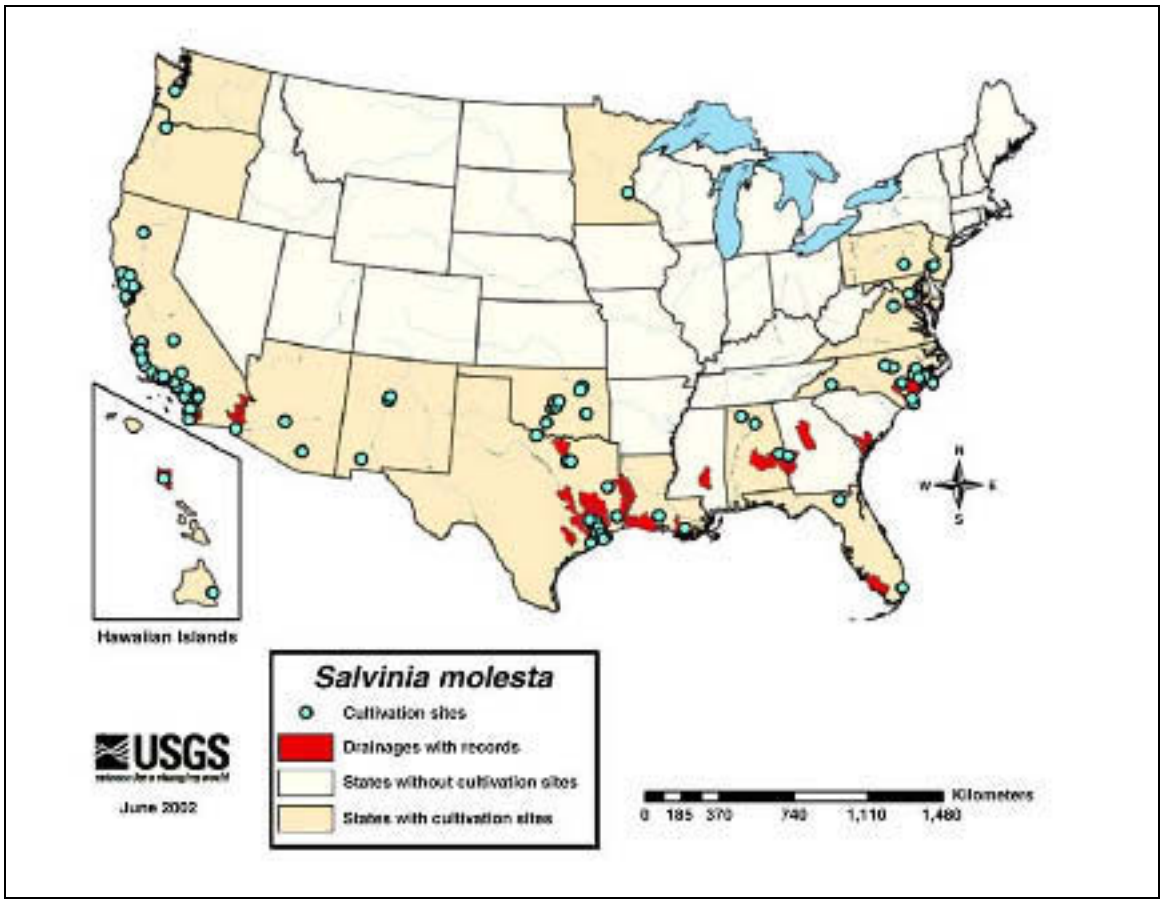

Figure 2. Recorded distribution of *S. molesta* in the United States.

By 1999, naturalized *S. molesta* populations were confirmed in over 50 localities in southern tier states (Texas, South Carolina, Louisiana, Georgia, Florida, Alabama, Mississippi, Arizona, California) and Hawaii. A rapidly expanding infestation was documented in April 1999, in Hawaii, where *S. molesta* in Enchanted Lake, Kailua threatened the habitat of three endangered waterbird species, i.e., the Hawaiian coot (*Fulica alai*), Hawaiian gallinule (*Gallinula chloropus sandivicensis*), and Hawaiian stilt (*Himantopus mexicanus knudseni*). Other major infestations were discovered later that year (August 1999), in the Lower Colorado River, at the Imperial National Wildlife Refuge bordering Arizona and California. Plants from the Palo Verde Irrigation District apparently initiated colonies, which have since penetrated the Mexican border via the Colorado River (Jacono and Pitman 2001). Many smaller outbreaks were chronicled in 1999 for various aquatic systems in Seale and Auburn, Alabama; Moselle, Mississippi; Houma, Louisiana; Houston (vicinity), Lovelady, Freeport, Alvin, Mont Belvieu, and Flower Mound, Texas; Atlanta (vicinity), Georgia; Oahu, Hawaii; and Naples, Florida (see Jacono 2002 for details).

The year 2000 marked the first sightings of *S. molesta* in North Carolina in low-lying areas near Burgaw and Jacksonville, and in ponds in Wilmington on the Cape Fear Peninsula. Since then, new reports of the species have become less frequent, though the severity of my infestations great has remained problematic. Today, the most widespread infestations occur in Texas and Louisiana, where for the two states, four public reservoirs, seven rivers and streams, two large marshland and over 25 ponds have been affected (Jacono and Pitman 2001). The Swinney Marsh Complex on the Lower Trinity River, in Liberty County, Texas, continues to support the most severe infestation of *S. molesta* in the United States. Current accounts by U.S. Geological Survey (USGS) list *S. molesta* naturalized in ten states (North Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, Texas, Arizona, California, Hawaii), with South Carolina being the only one where the plant has been eradicated (Jacono 2002).

Field Recognition:

S. molesta forms free-floating colonies of potentially independent modules (ramets) each held together by a horizontal stem (rhizome) just below the water surface (Figure 1). The rhizome of an intact module bears three distinct leaves, along with 4 or 5 buds that are relatively inconspicuous. Two leaves are green, emergent or floating, and ovate to oblong, while the third is brown, highly dissected, and hangs underwater. The upper surface of each floating leaf has a prominent midrib and is covered by rows of white, bristly hairs, topped with four branches united distally to form a structure resembling an "eggbeater" or "kitchen whisk." These hairs give the leaves a velvety appearance, and serve as air traps to repel water and aid in plant flotation. The submersed leaf resembles "root mass"and can elongate to great depths, and by creating a drag, functions as an axis for stabilizing the plant. Sori or sporocarps develop in long chains among filaments of the submersed leaves, and in mature plants, are formed in large quantities but are functionally sterile (Loyal and Grewal 1966). Bonnet (1955), Croxdale (1978, 1979, and 1981), and Harley and Mitchell (1981) have provided detailed descriptions of the anatomy and development of *S. molesta* ramets.

Three main phenotypes or growth forms of *S. molesta* have been recognized with a continuum of intermediate morphologies (Figure 1):

1) The *primary* (or *primary-invading*) *stage* occurs in isolated or widely spaced plants, during the initial invading stage of infestation. The plants produce small, delicate, oval leaves, from (2) 10 mm to 15 mm wide, that lie flat upon the surface of the water. This growth form may also be observed in plants recovering from damage or in uncrowded conditions in shade or rich nutrient culture (Harley and Mitchell 1981).

2) The *secondary* (or *openwater-colonizing*) *stage* is evident in plants that have grown in open water for some time, either freely or on the edge of stable mats. Stem internodes are longer and larger than in the primary stage; leaves are slightly cupped but do not overlap, with the entire lower leaf surface in contact with the water. Sizes of the leaves vary widely from ~20 to 50 mm in diameter.
3) The *tertiary* (or *mat*) *form* occurs under crowded conditions typically associated with a mature infestation. This form is a relatively robust with short internodes; the leaves are large (up to 60 mm in diameter), heart-shaped or oblong, and deeply keeled. As crowding increases the leaves are pushed upward to erect, and may become packed into dense mats up to a meter thick.

Ashton and Mitchell (1989) have described a *survival form* that occurs in *S. molesta* growing in harsh environments. In this growth form, which may result when nutrients conditions are low, the plant grows slowly, bearing up to five pairs of leaves that are flat, sometimes yellowish, and typically small (5 to 8 mm in diameter).

Reproduction:

S. molesta produces sporocarps but spores are rarely found, and when present are deformed and nonviable. Because the plant is pentaploidal (2n = 45) and thus genetically unable to produce fertile spores, reproduction in *S. molesta* is believed to be solely asexual (Loyal and Grewal 1966). Rhizomes of the plant can break very easily and daughter plants arise from buds numbering up to five per node. In still water, fragmentation occurs when older ramets senesce, causing the plant to break into two or more new plants. Fragmentation may also result from mechanical damage from human activities (e.g., harvesting and boating) or from friction between plants being moved by winds and water currents (Harley and Mitchell 1981; Room1983, 1990).

Dispersal:

Vegetative spread of *S. molesta* by fragmentation is thought to be the major means of intralake and interlake dispersal. High mobility of the plant is facilitated by aerenchyma tissue that causes buoyancy and enables ready movement over vast areas, particularly during flooding. Rises in water level as during flooding can loosen and break up dense mats, allowing strong winds and water movements to disperse parts of the mat and plant fragments. Rhizome and bud growth expands the colony laterally over smaller distances, while fragments appear the dominant means of long-distance dissemination. Fragments may be spread as a result of water-based recreation when parts of the plant adhere to fishing equipment, boats, trailers, or other vehicles. Animals may also contribute to vegetative spread: hippos in Africa and water buffalo in

Australia have been recorded to carry *S. molesta* over short distances (Miller and Wilson 1989; Storrs and Julien 1996). Waterfowl, raccoons, and turtles could possibly serve as natural vectors, but their role in spreading of *S. molesta* has not been investigated.

The attraction of *S. molesta* as an ornamental plant and as one of particular botanical interest has led to its spread to a far greater extent through intercontinental transport in aquarium and landscaping trades. Its introduction to North America, Asia, Africa, and other continents has been linked to cultivation activities of botanical gardens and commercial horticulture sites. Plants initially introduced to the U.S. probably arrived in Florida from Sri Lanka, as cargo for direct sale or as a contaminant in an aquatic plant shipment (Oliver 1993; Jacono 2002). A long-standing assumption has been that naturalized populations of the plant are due to plants being dumped into nearby waterways or being "seeded" deliberately in the wild for future marketing.

Recent surveys by various agencies have discovered *S. molesta* in cultivation in public and private aquatic gardens, and nurseries in 17 states (Figure 2). These sites are potential sources of release into natural systems and interestingly many are located in areas where infestations have been documented. To date, among the 11 states with records of *S. molesta* in nature, eight have known sites where the species is being cultivated (Jacono 2002).

As a Federally Noxious Weed, Federal Law prohibits *S. molesta* from transport across state lines and from being imported to the U.S. Yet, for the species to be restricted from sale, cultivation, and ownership within a given state, the plant must be listed by the state as a State Noxious Weed. Presently, *S. molesta* can be freely cultivated and sold within the 42 states (including Hawaii) as long as it is not transported across state lines. It is restricted as a State Listed Noxious Weed in Arizona, California, Florida, Georgia, Louisiana, North Carolina, South Carolina and Texas, but should be prohibited by others, especially those states with a history of infestation within their boundaries (e.g., Mississippi, Alabama, and Hawaii; Jacono 2002).

***Productivity*:**

Perhaps the most formidable characteristic of *S. molesta* is its incredibly high rate of growth and reproduction. Plants in the laboratory doubled in ~ 2 to 4 days (Gaudet 1973; Mitchell and Tur 1974; Mitchell 1979a), and in ~ 1 to 8 days under field conditions (Finlayson 1984; Room 1986a). Rates of leaf and ramet production strongly reflect changes in season. In mid-summer, the number of leaves doubled in 2.2 to 2.7 days, and in 40 to 60 days in winter in Lake Moondarra, Mt. Isa, Australia (Farrell 1979; Harley and Mitchell 1981; Finlayson 1984). Mitchell and Tur (1975) reported that in Lake Kariba, Zimbabwe, Africa, doubling time was reduced from 14.3 days in winter to 8.1 days in summer. Averaged across all seasons, growth

rates vary with life form with plants doubling faster the secondary (8.6 days) than in the tertiary form (11.6 days).

Rapid growth rates of *S.molesta* enable it to cover still and slow-moving waters with dense surface mats, up to 1 m thick, depending on mat age and degree of compaction (Harley and Mitchell 1981; Thomas and Room 1986a). In Lake Kariba, the number of plants was as high as 4672 m^{-2} in stable mats and ranged between 200 to > 10,000 km^{-2} (mean = 3290) in plants drifting in open water (Mitchell 1970). Live biomass in the mats was found to vary considerably, ranging from 250 to 600 g m^{-2} dry wt, which approaches the 670 to 1620 g m^{-2} dry wt observed for *E. crassipes* (Mitchell 1979a). Some of the highest rates of doubling in percent cover (1.3 days), leaf number (1.4 days), and fresh weight (1.8 days) have been recorded for *S. molesta* in a sewage lagoon near Lake Moondarra, with no evidence of toxicity (Finlayson 1984). Mitchell and Tur (1975) estimated that a mat growing at a conservative rate of 5% d^{-1} (doubling about every 14 days) would produce ~ 45.6 to 109.5 t ha^{-1} yr^{-1}. However, since this estimate was based on the lower end of the range of growth rates in Lake Kariba, they speculated that even greater production in *S. molesta* might result under more favorable conditions.

***Requirements for Growth*:**

Temperature. Results of numerous laboratory and field studies (Gaudet 1973; Rani and Bhambie 1983; Cary and Weerts 1983a and b; 1984; Finlayson 1984; Room 1986b) have enabled the development of a predictive model for the growth of *S. molesta* in relation to temperature conditions (Room 1988). According to the model, growth of *S. molesta* follows a bell-shaped curve, increasing to near 30 ºC, with upper and lower limits of about 40º and 5 ºC. More recently, Whiteman and Room (1991) showed that temperatures < -3 ºC or > 43 ºC are lethal to buds in exposures > 2 hrs. Their findings are consistent with temperature regimes within the plant's distribution, which extends from the equator to regions that experience frost but not the formation of ice on the water. While freezing temperatures could potentially kill the exposed plants, the population could recover and persist from underlying protected plants. Whiteman and Room (1991) concluded that near its limits in hot and cold climates, *S. molesta* is more likely to survive in larger bodies of water whose larger thermal capacity dampens temperature fluctuation.

Based on results of the above studies, the USDA has formulated an "expected range" for the expansion of *S. molesta* within the U.S. This range, as reported by Jacono (2002), includes the Atlantic coastal plain, from southeastern Virginia to southern Florida, the Gulf coast states, north to central California and southern Arizona. These areas generally coincide with regions in Zone 8 of the USDA Plant Hardiness Map (U.S. National Arboretum 2001). Emergent growth of

the plant dies back in winter in North Carolina (Zone 8, at latitude 34.4ºN), and in north Texas (Zone 7b, at latitude 33ºN), but recovers to dense levels the next growing season.

Light. As a floating aquatic plant species with access to light at the water surface, *S. molesta* in most cases may be less affected by light as compared with other environmental factors, e.g., temperature and nutrients. This may explain in part why so few studies have been conducted to assess growth of *S. molesta* in relation to light conditions. Current findings indicate that growth of this species is light saturated at ~ 4500 kcal m^{-2} d^{-1} then is inhibited with further increase in light intensity (Rani and Bhambie 1983). Under favorably high light conditions, its growth is increased with increases in temperature up to about 30 ºC (Mitchell and Tur 1975; Rani and Bhambie 1983). Significant interactive effects of light and temperature are reflected in seasonal changes in the rates of growth and biomass production in *S. molesta*. For example, out-door studies of this species showed that during August to September, growth rates were 0.06 to 0.07 g g^{-1} d^{-1} and doubling time was 9.8 days in full sun and 11.8 days in shade. However, under cooler temperatures that existed from December to February, growth rates were 0.01 to 0.02 g g^{-1} d^{-1}, and doubling time was 23 days under both light conditions (Rani and Bhambie 1983).

pH. Cary and Weerts (1984) found that over a range in pH from 5 to 8, *S. molesta* produced the greatest amount of biomass at pH 6. Total biomass at that pH was 11, 54, and 59 percent greater than at pH 5, 7, and 8, respectively. The preference of *S. molesta* for slightly acidic or near neutral pH is supported by reports that it grows well in nature at pH 6.0 to 7.4 (Johnson 1967; Gaudet 1973; Holm et al. 1977; Mitchell et al. 1980). Recent comparisons between two research ponds in Lewisville, Texas revealed more extensive infestation of the pond with pH < 7.5 than the one with pH 8.5 or greater (Owens et al. 2003). The ability of the plant to tolerate a wide range in pH is evidenced in its occurrence at pH 5.2 in Malaysia, pH 6.0 in Singapore, pH 7.4 in Zimbabwe, and pH 6.5-9.5 in other waters of Africa (Johnson 1967, as per Gaudet 1973; Holm et al. 1977; Storrs and Julien 1996).

Conductivity. Field surveys indicate *S. molesta* to infest waters with conductivities ranging from 239.3 (± 77.9) to 503.5 (± 446.2) µS cm^{-1} (Room and Gill 1985). Sewage lagoons supporting dense growth of the plant had conductivities as high as 1375.4 (± 149.5) µS cm^{-1} (Room and Gill op. cit.). Although thick mats have been observed in waters with low conductivity (~ 100 µS cm^{-1}), the leaves appeared chlorotic probably due to low availability of nitrogen (Mitchell et al. 1980). Small infestations are reported to survive at about 2000 µS cm^{-1} (Storrs and Julien 1996) but higher conductivities (~ 4800 µS cm^{-1}) damage plant tissues and diminish chance of survival (Divarkaran et al.1980).

Salinity. *S. molesta* is clearly a freshwater plant, with low tolerance of saline conditions, and does not colonize marine or brackish-water environments. The plant is able to survive at

salinities up to 20% that of seawater, with growth rate decreasing with increases in total dissolved salt concentration. Divakaran et al. (1980) demonstrated a 25% reduction in rate of growth of *S. molesta* in water having a salinity of 3 ppt (or 10% that of sea water). Plants in solution with a salinity of 7 ppt had a doubling time of 108 days as opposed to 3.8 days for the control plants (King and Mitchell unpubl. data, as per Harley and Mitchell 1981). Salinities > 7 ppt have been found to be lethal, and death occurred at 11 ppt after 20 hrs of exposure, and at 34 ppt (full strength seawater) after only 30 min of exposure (Divakaran et al. 1980; Harley and Mitchell 1981).

Nutrients. Since *S. molesta* is not rooted in sediment, nutrients required for growth must be obtained through portions of the plant that are in contact with the water column. Dissolved nutrients, especially nitrogen (N) and phosphorus (P), play a key role in determining morphological characteristics and rates of growth *S. molesta* colonies (Room and Thomas 1986a and b). Concentrations of nutrients in aquatic systems can fluctuate widely and, in heavily infested areas, are frequently below limits for accurate quantification (Storrs and Julien 1996). Therefore, measurements of nutrients in plant tissues, as compared to water samples, can provide a better assessment of nutrient availability for plant uptake over time.

Previous studies of nutrient relationships have shown that *S. molesta* can accumulate high concentrations of nutrients to sustain growth when nutrient supplies become deficient (Gaudet 1973; Cary and Weerts 1984). Its growth ceased to be limited by N and P availability when tissue concentrations reached approximately 5 % or more for N and 0.5% or more for P under laboratory conditions (Cary and Weerts 1983a and b; Room 1986b). In >1700 samples of *S. molesta* collected from field sites in Australia and Papua New Guinea, tissue N concentrations ranged from 0.62 to 4.0% and tissue P from 0.03 to 1.07% dry wt (Room and Thomas 1986a and b). The Australian average for concentrations of N in tissues of *S. molesta* was 1.59 %, while that for tissues from Papua New Guinea was 1.12%. Based on these low values, N was suggested to be the primary limiting nutrient, accounting for 40 and 80% of the variance in growth rates of *S. molesta* in the field (Room and Thomas, op. cit.).

S. molesta grows more rapidly when provided dissolved inorganic N as NH_4^+ rather than NO_3^- ions (Gaudet 1973; Cary and Weerts 1983a). In solution with NH_4-N or NH_4NO_3-N as a source of N, growth of *S. molesta* was twice the amount achieved with equivalent quantities of NO_3-N or urea-N (Cary and Weerts 1983a). Optimal levels of dissolved N depend on levels of other dissolved nutrients, especially P. High levels of biomass production and doubling times < 4 days occurred in *S. molesta* in solutions with N and P combinations varying from 2 to 20 mg NH_4-N L^{-1} and from 2 to 10 mg PO_4-P L^{-1} (Cary and Weerts 1984).

Availability of nutrients in the water is an important determinant of the survival strategy demonstrated by *S. molesta* colonies. Plants in infertile water were found to have tough rhizomes with few if any branches and fragmented when the oldest segments deteriorated (Mitchell and Tur 1975; Room 1983; Julien and Bourne 1986). Survival was enhanced under infertile conditions by the retention of senescing ramets so that the nutrients they contained could be reallocated elsewhere in the colony (Room, op. cit.). In contrast, S. *molesta* in fertile water had highly branched and brittle rhizomes, that fragmented sooner than in infertile water due to pressure from overcrowded ramets (Room 1983; Room 1990). Senescing ramets were not retained probably because proliferation of dispersal units has been selected under fertile conditions over retention of nutrients (Storrs and Julien 1996).

Impacts on the Environment:

Detrimental. On virtually all affected waters, extensive mats of *S. molesta* threaten a multitude of environmental, economic, and human health interests. Dense growth of the plant forms a physical barrier on the surface of the water that prevents or impedes water use for recreation, fish and wildlife habitat, and navigation. Even when the mats are not fully impenetrable, the clusters of rhizomes and masses of "roots" quickly become entangled around boat propellers, so that the watercraft may sooner or later be immobilized. Wind and water movements can bank the plants into thick stabilized mats that may accumulate in grids and sluices of dams and electrical generating installations, and plug up irrigation systems (Sculthorpe 1985). Where water flow is restricted and rates of silt deposition correspondingly increase, dredging operations may be needed to minimize potential adverse effects of flooding. In addition to causing the loss of crops, and water for domestic and power supplies, flooding is a prominent mechanism in breaking up the mats and distributing fragments that can produce new infestations.

Occasionally, other plants will colonize thick mats of *S. molesta,* forming "floating islands" of vegetation or mixed sudd communities (Sculthorpe 1985; Holm et al. 1977). The colonizing species often include water pepper and knotweeds (*Polygonum* spp.), water primrose (*Ludwigia peploides*, *L. lepticarpa*, and *L. ascendens*), grasses (*Leersia hexandra*, *Hymenachne acutigluma*, and *Panicum repens*), sedges (*Cyperus platystylis*), bulrush (*Scirpus cubensis*) and even trees, particularly paperbarks (*Melaleuca* spp.). Boughey (1963) documented more than 40 plant species that colonized *S. molesta* mats in Lake Kariba, central Africa. These deceptive islands have caused a number of livestock deaths by livestock sinking or breaking through the mats and drowning in deep water (Harper 1986).

S. molesta can have other detrimental effects on the ecology of aquatic systems by restricting light penetration and exchange of gases between the water and atmosphere. By

curtailing availability of light, the plant can successfully outcompete submersed and smaller floating vegetation, thus reducing populations of organisms they support. Water quality beneath the mats is almost always degraded by decreases in dissolved oxygen and pH, and increases in CO_2 and H_2S concentrations (Mitchell 1969). As the plants die, organic debris accumulates on bottom sediments and can threaten fisheries by creating a shallow-water environment less suited for fish breeding and netting. Furthermore, decomposition of organic materials may reduce dissolved oxygen supplies to levels insufficient to sustain fish, insects and other invertebrates. Rapid rates of nutrient uptake combined with relatively slow rates of decomposition enable *S. molesta* to tie up nutrients that could be used by other primary producers that contribute complex food chains. The theoretical maximum rate of N uptake, calculated from rates of growth of *S. molesta*, is about 8 mg N g^{-1} dry plant tissue d^{-1} or about 6000 kg N ha^{-1} yr^{-1} (Room 1986b).

Public health and economic concerns are raised due to heavy infestations serving as breeding habitat for vectors of human disease, and interfering with food production and market transport. The stagnant, shallow-water conditions and dense foliage provided by *S. molesta* mats are favored by many species of mosquitos that transmit rural filariasis (elephantiasis; Room et al. 1989), encephalitis, dengue fever, and malaria (Creagh 1991/1992 as per Oliver 1993). In Lake Kariba (Zambia and Rhodesia), the mats fostered the build up and spread of *Biomaphalaria boissyi*, the snail that is the intermediate vector of bilharzia (schistosomiasis; Bennett 1975). In Sri Lanka, India, and Borneo, the plant is a serious pest in ricelands, while its encroachment into other Asian and African waterways has led to declines in tourism, hunting, and fish industries. Yet nowhere have the adverse effects of rapid growth of *S. molesta* been as dramatic as in the floodplain of the Sepik River, Papau New Guinea. There, entire villages, dependent on aquatic transportation, were abandoned because thick mats of the weed eliminated access to food, markets, schools, and hospital care (Mitchell et al. 1980; Thomas and Room 1986a).

Beneficial. As a positive note, investigative attention has been given to finding value in the large amounts of biomass *S. molesta* produces. The plant has been used as a compost and mulch, and as a supplement to fodder for livestock in some Asian countries (Oliver 1993). A few studies have examined its suitability in treating sewage effluent (Finlayson et al. 1982), papermaking, and the generation of biogas (Thomas and Room 1986a). However, none of these efforts has led to large-scale utilization probably due to high costs associated with labor and mechinery. For such strategies to be viable, a continued supply of *S. molesta* must be available, which could exacerbate problems for aquatic weed management (Thomas and Room op. cit.).

MANAGEMENT OPTIONS

Chemical Methods:

Background -- Herbicide Investigation and Use Overseas. Numerous studies worldwide have evaluated and documented the use of chemical products to control *S. molesta*. According to Thomas and Room (1986a), the first attempts to chemically manage the plant were made in Sri Lanka in the 1940's, where high volume applications of emulsifiable oils containing pentachlorophenol (a chemical wood preservative) were used in rice paddies and waterways. In the years to follow (1960-70's), a variety of chemicals were tested against *S. molesta* including: monuron (a herbicide), anhydrous ammonia, formalin (a fish parasiticide), niclosomide (a molluscicide), and thiram (a fungicide) (Thomas and Room 1986a). While some of these products showed herbicidal activity against *S. molesta* in laboratory trials, most were never used on an operational scale.

Kam-Wing and Furtado (1977) assessed the effectiveness of the herbicides paraquat, diquat, nitrophen (as the coded compound, TOK E-25), and dalapon for control of *S. molesta* in Malaysia. Of these products, only paraquat and diquat showed potential in laboratory studies. Paraquat applied as a foliar spray at a rate of 1.1 kg ha^{-1} (1 lb ac^{-1}) controlled 100% *S. molesta* in one week. Diquat at 4.5 kg ha^{-1} (4 lb ac^{-1}) controlled 99% of plants, but at such a high rate, was considered cost prohibitive. Lower rates of both products were less effective (< 85% plant kill) and were considered unacceptable since the quantity of surviving plant material would lead to a recurrence of the weed problem. Thomas and Room (1986a) also reported that scientists in Zimbabwe successfully demonstrated the efficacy of paraquat against *S. molesta*. As a result of these studies, paraquat was used from the late 1960's through the 1970's to control *S. molesta* in Kenya, Sri Lanka, Botswana, Australia, and Papua New Guinea (Mitchell 1979b; Miller and Pickering 1980; Thomas and Room 1986a; Oliver 1993).

Diatloff et al. (1979) investigated the use of kerosene plus surfactant (calcium dodecylbenzene sulfonate) mixed with and without the herbicides 2,4-D, dichlorprop, and diuron. Kerosene and surfactant were added to maximize herbicide penetration into the plant, since upper frond surfaces are covered with numerous cage-like trichomes or hairs, which can impede optimal herbicide coverage (Holm et al. 1977; Oliver 1993). Although kerosene plus surfactant alone inhibited *S. molesta* by 80%, the data showed that addition of herbicide significantly improved treatment performance. Rates as low as 0.15 kg ha^{-1} diuron added to the kerosene-surfactant mixture controlled 100% of salvinia plants. Dichlorprop and 2,4-D controlled 92 to 95% of *S. molesta* in these trials, however higher rates of both products (0.75 to 3.00 kg ha^{-1}) were required to achieve results. As a result of these studies, a commercial product known as AF 101 (diuron

mixed with kerosene and calcium dodecylbenzene sulfonate) was formulated and used successfully for large-scale treatment of *S. molesta* and other nuisance floating plants (e.g., *Azolla filiculoides* var. *rubra* and *Pistia stratiotes*) in Australia.

Scientists in New Zealand evaluated fluridone for herbicidal activity against *S. molesta* in outdoor tank studies (Wells et al. 1986). Both the granular and liquid formulations of fluridone were tested at concentrations ranging from 0.003 to 100 mg L^{-1} (ppm). Fluridone symptoms (bleaching of new tissues) were noted on plants treated with concentrations $\geq$ 0.1 mg L^{-1} fluridone however, plant death only occurred when plants were subjected to 100 mg L^{-1} fluridone. Both fluridone formulations performed similarly in these trials. In contrast to results by Wells et al. (1986), aquatic plant managers in Florida have recently reported successful control of giant salvinia in small ponds with fluridone concentrations of 45 to 90 µg L^{-1} (ppb) (J. D. Schardt, personal communication)[1]. The rates used in Florida are an order of magnitude lower than those tested in New Zealand. The current maximum allowed label rate of application for fluridone in U.S. waters is 150 µg L^{-1}.

Herbicide Investigation and Use in the U.S. As *S. molesta* gained notoriety in the late 1990's as an established and noxious weed in the U.S., concern for identifying management options escalated. While the results of early studies conducted overseas identified several herbicides that were effective against this noxious water fern, only a few of these products were registered by the U.S. Environmental Protection Agency (USEPA) for use in aquatic environments. It was apparent that updated information on the use and efficacy of U.S.-labeled aquatic herbicides was needed.

Currently there are seven herbicides that are available in the U.S. for controlling weeds in aquatic habitats. They include: diquat, copper (as copper chelates), endothall, fluridone, glyphosate, 2,4-D, and triclopyr. Triclopyr is the most recent addition to this list; receiving full aquatic registration from the USEPA in December 2002. To date, there is no published information on the effectiveness of triclopyr on *S. molesta*. Current information documenting the efficacy of the other available aquatic herbicides against *S. molesta* is summarized below.

Nelson et al. (2001) compared the response of six herbicides (diquat, 2 formulations of endothall, glyphosate, copper, and imazapyr) applied alone and in combination against *S. molesta* in an outdoor tank experiment. Type of surfactant, rate of application, and application technique were also examined. Of the 32 treatments evaluated, diquat (1.12 kg ha^{-1}) and glyphosate (8.97 kg ha^{-1}) were equally effective for controlling *S. molesta* (99 to 100% reduction in plant biomass). Copper (as the formulation Komeen™) provided 81% control of *S. molesta* 42 days after treatment. Treatment with endothall (both formulations) showed significant plant control (80 to 86%) shortly after treatment, however, remaining plants were healthy and actively growing,

resulting in a steady decline in percent control over time. *S. molesta* was minimally affected by the rates of imazapyr evaluated in this study.

Fairchild et al. (2002) determined the effectiveness of glyphosate mixed with several surfactants for control of *S. molesta*. Five concentrations of glyphosate (0, 0.45, 0.91, 1.82, and 3.60 % v:v) and five surfactants were evaluated under outdoor conditions. Results indicated that a 0.45% solution of glyphosate with or without surfactant significantly reduced plant biomass compared to untreated plants. Of the surfactants tested in this study, only glyphosate (0.45% v:v) mixed with Optima™ (0.25% v:v) resulted in complete mortality of plants with no regrowth. The results of this study demonstrated that *S. molesta* was sensitive to lower doses of glyphosate than was previously reported. Similar results with low-dose glyphosate treatments have been confirmed in larger-scale outdoor experiments conducted by L. Nelson (unpublished data).

Glomski et al. (2003) investigated the use of the chelated copper formulation, Clearigate™, for control of *S. molesta*. Results showed that Clearigate™ mixed as a 15 to 20% solution (v:v) was effective for reducing biomass by 84 to 88%. Regrowth of surviving plant tissues was observed indicating follow-up applications may be necessary to maintain acceptable containment. Although 100% plant mortality was not observed, the authors commented that the use of Clearigate™ may be a feasible alternative for managing *S. molesta* in areas where water use restrictions would prohibit the use of either diquat or glyphosate.

Overall, the results of these recent studies demonstrate that registered aquatic herbicides can be used to effectively manage *S. molesta* infestations in the U.S. While research on chemical management strategies for *S. molesta* is ongoing, to date, glyphosate and diquat show the most promise. If used properly (correct rate, application equipment, and application technique), either product can be expected to provide >95% control of sprayed plants. Future research will continue to investigate new products and formulations, herbicide combinations, application techniques, and the potential for integrating management strategies.

Biological Control Methods:

Background. One insect species, the weevil *Cyrtobagous salviniae* Calder and Sands, is recognized throughout the world as the method of choice for *Salvinia molesta* management. The use of this agent has resulted in control in the tropical areas of 12 countries on three continents including but not limited to Australia, Fiji, India, Kenya, Namibia, South Africa, Sri Lanka, Zambia, and Zimbabwe (Room et al. 1981; Forno 1985a and b; Giliomee 1986; Joy et al. 1986; Thomas and Room 1986b; Forno 1987; Julien and Griffiths 1998).

While never intentionally released, *Cyrtobagous salviniae* is found in the U.S. in many areas of southern Florida. It was accidentally introduced from South America in the early 1960's

based on existing records and is commonly found feeding on *S. minima* Baker (a close relative to *S. molesta*). Until only recently, the Florida strain of *C. salviniae* was mistakenly identified as *C. singularis,* the species first used for *S. molesta* control but proved to be non-effective. Attempts to use the Florida strain of *C. salviniae* in the late 1990's and early 2000's to manage *S. molesta* have not been successful, therefore, researchers petitioned the Technical Advisory Group (TAG) and the United States Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine (USDA, APHIS, PPQ) for the release of the Australian strain of *C. salviniae*, a strain proven to be highly effective. Permission was granted in 2001 by APHIS, PPQ allowing the release of the Australian strain of *C. salviniae* in western Louisiana and east Texas only.

Host-Specificity Testing. Before *C. salviniae* could be released intensive host-specificity experiments were conducted. Host-specificity testing consists of a series of experiments where various plants are offered to adults and immatures to document if feeding, oviposition, and survival can occur. Because of the extensive range of plants used by the Australians and South Africans in documenting host-specificity no additional testing was performed in the U.S. with approval for release based on the work of both the Australians and South Africans (Forno et al. 1983; Tipping and Center 2001).

The following is a list of plants used in host-specificity testing and used for U.S. release approval (Tipping and Center 2001):

Species Name	Common Name	Family
Pteridophyta		
Salvinia molesta	Giant Salvinia	Salviniacea
Salvinia minima	Common Salvinia	Salviniacea
Salvinia hastate		Salviniacea
Azolla caroliniana	Water Fern	Azollaceae
Azolla filculoides		Azollaceae
Azolla pinnata Africana		Azollaceae
Adiantum hispidulum	Rough Maidenhair	Pteridaceae
Pteridium esculentum	Bracken Fern	Dennstaedtiaceae
Marsilea drummondii	Nardoo	Marsileaceae
Schizaea dichotoma	Comb Fern	Schizaeceae
Christella dentate	Binung	Thelypteridaceae
Monocotyledons		
Sagittaria graminea	Arrow Head	Alismataceae
Allium cepa	Onion	Amaryllidaceae

Pistia stratiotes	Waterlettuce	Araceae
Ananas comosus	Pineapple	Bromeliaceae
Zea mays	Maize	Poaceae
Orzya sativa	Rice	Poaceae
Saccharum officinarum	Sugarcane	Poaceae
Asparagus officinalis	Asparagus	Liliaceae
Musa x paradisiacal	Banana	Musaceae
Eichhornia crassipes	Waterhyacinth	Ponterderiaceae
Potamogeton tricarinatus	Floating Pondweed	Potamogetonaceae
Typha orientalis	Bullrush	Typhaceae
Zingiber officinale	Ginger	Zingiberaceae
Dicotyledons		
Carica papaya	Papaya	Caricaceae
Beta vulgaris	Beetroot	Chenopodiaceae
Spinacia oleracea	Spinach	Chenopodiaceae
Lactuca sativa	Lettuce	Asteraceae
Ipomoea batatas	Sweet Potato	Convolvulaceae
lpomoea aquatica	Potato Vine	Convolvulaceae
Cucurbita maxima	Pumpkin	Curcurbitaceae
Rorippa nasturtium-aquaticum	Water Cress	Brassicaceae
Brassica oleracea var. *botrytis*	Cauliflower	Brassicaceae
Medicago saliva	Lucerne	Fabaceae
Trifolium subterraneum	Subterranean Clover	Fabaceae
Gossypium hirsutum	Cotton	Malvaceae
Nymphoides indica	Water Snowflake	Menyanthaceae
Eucalyptus tereticornis	Forest Redgum	Myrtaceae
Eucalyptus maculata	Spotted Gum	Myrtaceae
Nymphaea gigantea	Purple Waterlily	Nymphaeaceae
Ludwigia peploides	Water Primrose	Onagraceae
Polygonum lapathifolium	Pale Knotweed	Polygonaceae
Polygonum hydropiper	Water Pepper	Polygonaceae
Polygonum sp.	Smartweed	Polygonaceae
Rumex brownii	Swamp Dock	Polygonaceae
Rumex crispus	Curled Dock	Polygonaceae
Fragaria x ananassa	Strawberry	Rosaceae
Citrus sinensis	Orange	Rutaceae
Citrus limon	Lemon	Rutaceae
Citrus reticulata	Mandarin	Rutaceae
Lycopersicon esculentum	Tomato	Solanaceae

Based on these experiments it was apparent that *C. salviniae* is highly host-specific to *S. molesta* with only minor feeding occurring on *Pistia stratiotes* L. (another introduced and problem plant). *Cyrtobagous salviniae* was found to feed extensively on all *Salvinia* spp. tested which is not surprising. However, this is not a problem since native *Salvinia* do not occur in the continental U.S. or Hawaii.

Plant Hosts. *Salvinia molesta* and *Salvinia minima*; most likely all other *Salvinia* spp. as well.

Description. *Cyrtobagous salviniae* is a small weevil ranging in length from 1.5 to 2.0 mm (USACE 2001; Center et al. 1999). Adults are typically black but newly emerged individuals may often be brown. Legs are reddish-brown in coloration. The dorsal surface of the weevil is covered with numerous shallow depressions or punctures as well as yellow peltate scales. The larvae are white and attain lengths of only 3 mm. The pupa forms a cocoon in the "roots"; i.e., the modified fronds.

Biology. Adults typically reside on or beneath the leaves or fronds of *S. molesta* (USACE 2001; Center et al. 1999). A thin film of air adheres to the bottom of the weevil allowing for respiration during periods of submergence. Eggs are laid individually in cavities formed by the female's feeding activity. Egg hatch occurs in approximately 10 days. Total larval development requires 3 to 4 weeks. The pre-pupal and pupal periods last about 2 weeks.

Feeding Damage. Adults will feed on the fronds leaving small irregularly shaped holes but prefer feeding on newly formed buds. Larvae feed within the roots, rhizomes, and buds and their feeding action can be devastating. Initial establishment is highly dependent on the nitrogen content of the plants. Australian scientists have found that applying nitrogen in the form of urea either directly or indirectly to the plants significantly increases the chance for establishment and initial population build-up (Forno 1985b; Forno and Bourne 1985; Room and Thomas 1985).

Plant Impacts. Feeding action of both the adults and larvae can be devastating with reported impact to field populations in other countries observed in several months instead of years as typically seen with other biological control agents (Room et al. 1981; Forno 1987). During the early damaging phase plants turn brown and subsequently begin to sink. Such browning action has been reported to appear as small patches initially until the brown patches coalesce and the entire mat appears brown and damaged. Following this stage the mat begins to sink.

U.S. Operational Status. As indicated previously, *C. salviniae* is commonly collected in southern Florida feeding on a close relative to *S. molesta*; i.e., *S. minima*. Recent efforts to release the Florida strain of *C. salviniae* on Texas populations of *S. molesta* were not successful. Reasons for the failure are unknown but are believed related to conditioning of the Florida strain to *S. minima* for many years. This prompted researchers to obtain permission to release the Australian strain of *C. salviniae*. Permission was received in 2001 and weevils of the Australian strain were released shortly thereafter at sites in Texas and western Louisiana. While it is too early to confirm long-term establishment and impact early evidence indicates that the weevils are established, expanding in distribution, and beginning to impact *Salvinia* locally in the release areas (T. Center, personal communication)[2].

Physical Control:

Conventional Methods for Floating Aquatic Plants. Physical management alternatives for controlling free-floating aquatic plants have generally involved the following management practices: 1) removing the target species directly by hand, or by water-based or land-based mechanical harvesters; 2) destroying the infestation by inflicting physical damage by cutting, shredding, or chopping plants in situ; 3) placing barrier material to confine nuisance vegetation to prevent colonization of other areas, and 4) altering the aquatic environment to eliminate habitat conducive to growth of the target species. Among these different practices, the use of cutters/shedders/choppers is least effective due to potential spread of *S. molesta* by generating large numbers of fragments. These machines are also likely to kill nontarget biota and create water quality problems from decaying plant material. Pros and cons of each method are discussed in greater detail by Miller and Wilson (1989), Madsen 1997, Wade (1990) and Chilton et al. **(**1999).

Direct Removal. Manual removal of *S. molesta* has been successful in small-scale operations when the plant is in the initial stages of infestation (Thomas and Room 1986a; Miller and Wilson 1989). Once the plant has become established, hand removal and harvesting are less practical due to the plant's rapid rate of growth and production of large amounts of biomass. The cost of equipment can be extremely high because the machinery is specialized to collect and remove large quantities of biomass (Chilton et al. 1999; Thomas and Room 1986a). *S. molesta* is heavy, with > 95% water content, and typically doubles its weight in < 10 days under favorable conditions. In the tropics, it may accrue up to 200 tons (wet wt) ha^{-1} and in extreme cases, > 400 tons ha^{-1} (Room and Julien 1994; Storrs and Julien 1996). In order to be effective, the harvester must be able to deal with such bulk and remove it at rate exceeding regrowth (Storrs and Julien 1996). Even in winter, in Australia, when *S. molesta* doubling rate was 40 to 60 days, the capacity of a large infestation for regrowth exceeded the removal capacity of the machines (Mitchell 1979a). Furthermore, in many cases, the shape of natural waterways, inaccessibility, and presence of other vegetation and obstacles makes large-scale mechanical removal impractical.

Barriers. Floating booms have been used successfully to restrict migration of *S. molesta* downstream in rivers, streams, and other flowing systems (Farrell 1978; Finlayson and Mitchell 1982; Miller and Wilson 1989). They may also be deployed in very localized areas to prevent the plant from entering into and clogging water intakes, boat launches, swimming areas, and marinas (Chilton et al. 1999). However, booms require continuous upkeep and maintenance and are subject to breakage under pressure of large windblown mats (Oliver 1993). In some cases, a series of nets has been constructed as insurance against breakage of one or more during flooding

(Miller and Wilson 1989). In Lake Moondarra, mesh netting supported on a boom of wire hawser, held afloat with 200 L drums and anchored to concrete blocks was successful except in high water flows when the boom was pushed free by the build up of *S. molesta* (Finlayson and Mitchell 1982). In Lake Kariba, booms slung on 5 cm diameter steel cables were abandoned after being broken several times by windblown *S. molesta* accumulations (Thomas and Room 1986a).

Habitat Alteration. Water-level drawdown may be an effective means to reduce *S. molesta* growth in some selected areas. This technique is relatively inexpensive when applied in lakes with water-level control structures but can be exorbitantly expensive if used in large systems elsewhere. The object of the drawdown is to control the plant by exposure to freezing temperatures and/or dessication. Yet the success of this procedure will depend in large part on the structure of the *S. molesta* mat and its ability to protect and insulate embedded plants. Where the mat is thick and dense, the most exposed plants and plant parts are subject to desiccation and freezing while plants close to the sediment may survive. Unless the sediment becomes dry (and/or frozen) for a sufficient period, plants deep in the mat may regenerate the colony at the onset of favorable conditions.

Water-level manipulation is a primary method of controlling nuisance plants in many reservoirs in Louisiana (Cooke et al. 1986). Effects of drawdown on vegetation in several Louisana lakes have been summarized by Lantz et al. (1964), Lantz (1974), and Cook et al. (1986). Their findings suggest drawdown to be useful in reducing growth of many aquatic plant species but cannot be used for eradication. In addition, its use as a management tool has been somewhat controversial due to adverse impacts on secondary uses of the aquatic system, e.g., boat access, hunting, fishing (Chilton et al. 1999). In northern Louisiana, autumn/winter drawdown is most effective and can reduce nuisance species including *E. crassipes*; but the effectiveness of this technique on other species and in other locations may improve (or be lessened) by climatic conditions. Recent evidence from pond studies in Lewisville, Texas has shown winter drawdown to be successful in reducing populations of *S. molesta* (Dick et al. 2003). However, further study is needed to determine efficacy of drawdown on *S. molesta* in other areas and in combination with other control methodologies.

Ecosystem Approach:

Obviously, the most effective, economical, and environmentally compatible method for dealing with an invasive plant like *S. molesta* is prevention. This plant is being spread via the water garden trade. There have been many separate introductions within the U.S. and will likely be many more, if more stringent monitoring methods are not employed.

Barring prevention, early detection followed by prompt management action, would facilitate eradication of *S. molesta* within a particular water body. However, given our past history with this and other invasive aquatic plants, eradication, even within any single system, is unlikely for the foreseeable future. It seems more likely that we will have to develop management approaches that seek to reduce the extent of *S. molesta* infestations to acceptable levels.

When eradication is no longer a viable alternative, integrated plant management, has proven effective in control of other invasive aquatic plant species, including *E. crassipes*. A balanced, integrated plant management (IPM) approach utilizing all appropriate control methods (including chemical, biological, physical, and public outreach) will likely be required to "manage" the spread of *S. molesta*. This approach, while it might include attempts at local eradication, and would almost certainly include attempts at containment (prevention of spread), would seek to suppress the growth or extent of infestations, thereby reducing the harmful environmental or economic effects of the offending species.

The IPM approach utilizes knowledge of the biology and ecology of the target plant, knowledge of the efficacy and environmental effects of available control technologies, and continual monitoring of the infested system to allow managing agencies to minimize the impacts of the offending plant. Ideally this approach would rely heavily on the use of host-specific biocontrols to provide long-term, sustainable control.

A key component of any long-term management strategy has to be sustainability. The most effective way to achieve sustainable control is by "filling the niche" with a beneficial, native species that will help to prevent a recurrence of invasive species. Unfortunately, the niche occupied by *S. molesta*, a free floating aquatic plant, is one that generally causes problems for managing agencies, whether filled by an exotic or native species. Given the high nutrient loading rates suffered by most of our aquatic systems, the development of any floating plant species will likely be excessive. However, riparian wetlands and well-developed littoral plant communities in lakes and reservoirs would intercept excess nutrients before they could accumulate and promote the excessive growth of problematic species. Because they do not often have to compete with other plants for light, and because they are dependent on the water column for their nutrient supply, floating plants are more likely to be limited by nutrients than are submersed and floating-leaved forms. Thus any reductions in nutrient supply are likely to provide corresponding reductions in biomass or growth rates of floating plants such as *S. molesta*.

DISCLAIMER

Citation of trade names does not constitute an official endorsement of the use of such commercial products.

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FOOTNOTES

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