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Salvinia molesta D. S. Mitchell (Giant Salvinia) in the United States: A Review of Species Ecology and Approaches to Management

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June 2004

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Final report

ABSTRACT: Over the past 70 years, the free-floating aquatic fern *Salvinia molesta* D. S. Mitchell (giant salvinia) has spread from its native range in Brazil to many tropical and subtropical regions. Though innocuous within its native range, elsewhere this species is an aggressive menace that has had devastating ecological and socioeconomic impacts on aquatic systems in parts of Africa, Sri Lanka, India, Australia, New Guinea, and the Philippines. In the United States, the plant is established in waterways in at least 10 states (mainly in the south) and is expected to continue to expand in areas generally where *Eichhornia crassipes* (Mart.) Solms (water hyacinth) persists. Listed as a Federal Noxious Weed since 1984, *S. molesta* is prohibited from importation to the United States and from transport across state lines. Dense mats of *S. molesta* can suppress growth of native vegetation and degrade water quality, fish and wildlife habitat, and numerous other ecological values. Notably, massive infestations have occurred in the Swinney Marsh Complex, Texas, in the Lower Colorado River, Arizona/California, and in Lake Wilson and Enchanted Lake, Hawaii.

This report presents a review of available information on the growth, distribution, and ecology of *S. molesta*. Information is provided on the plant's taxonomic status, its field characteristics, phenology, and spread overseas and in the United States. Growth responses of *S. molesta* in relation to environmental variables (e.g., temperature, nutrients, light, pH, conductivity) are emphasized as are impacts of the species on the environment and other aquatic organisms. Different technologies (i.e., physical, chemical, biological, and integrated) applied to control *S. molesta* infestations are discussed along with information on the effectiveness of these procedures and their need for further study.

Contents

Preface

1 Introduction

Background

Salvinia molesta D. S. Mitchell (giant salvinia), a free-floating aquatic fern, is one of the world's worst aquatic 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 number and biomass in less than 3 days (Farrell 1978, 1979; Harley and Mitchell 1981; Barrett 1989). Problems caused by *S. molesta* result from rapid vegetative reproduction in which rhizomatous colonies are produced and disseminated through fragmentation (Room 1986a, 1990). Excessive growth of this species prevents light penetration of the water column by forming dense floating mats that can shade out favorable vegetation and degrade habitat for fish and wildlife. Dense mats of *S. molesta* can impede water-based transport and recreation, reduce water quality and aesthetic values, and clog irrigation and power generation intakes (Thomas and Room 1986a; Room et al. 1989). Public health problems have also been associated with nuisance growth of the plant, which restricts access to potable water supplies and harbors mosquitoes 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 tropical and subtropical regions around the world (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 (Oliver 1993; Chilton et al. 2002). 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). In the United States, severe infestations 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 invasion of many U.S. waterways by *S. molesta* in recent years has increased the demand for information on the ecology and management of this weed. To improve programs to control *S. molesta* and prevent its rapid spread,

knowledge is needed of current management practices, their levels of efficiency, and vulnerabilities of the species in different conditions.

The objective of the present report is to review available information on the growth, distribution, and management of *S. molesta*. Information is provided on the plant's taxonomic status, field characteristics, life history, and occurrence overseas and in the United States. Ecological information on *S. molesta* is also included, emphasizing environmental tolerances, growth requirements, and impacts on the environment. Efforts toward managing this nuisance species using different control technologies (e.g., physical, chemical, and biological) are discussed with an indication of degree of efficacy, operational status, and/or need for further investigation.

2   Plant Description and Ecology

Taxonomic Status

Kingdom: Plantae; Subkingdom: Tracheobionta; Division: Pteridophyta; Class: Filicopsida; Order: Hydropteridales; Family: Salviniaceae; Genus: *Salvinia* Séguier; Species: *Salvinia molesta* Mitchell (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). Up to 12 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*) originated in the neotropics (Mitchell and Thomas 1972; Sculthorpe 1985; Jacono and Pitman 2001). *Salvinia molesta* along with three other closely related species, i.e., *S. auriculata*, *S. herzogii,* and *S. biloba,* comprise the taxonomic assemblage known as "*S. auriculata* complex" (Forno 1983). 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 listed on the Federal Noxious Weed List which prohibits their introduction to the United States as well their interstate transportation. At present, *S. molesta* is the only one of these four species that occurs in the United States outside of culti-vation (Jacono 2003a).

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 noting the confusion over species identity indicate *S. auriculata* auct. non Aubl. (misapplied) as a probable synonym (Global Compendium of Weeds (GCW) 2004). *Salvinia molesta* is also known by a variety of common names (e.g., 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).
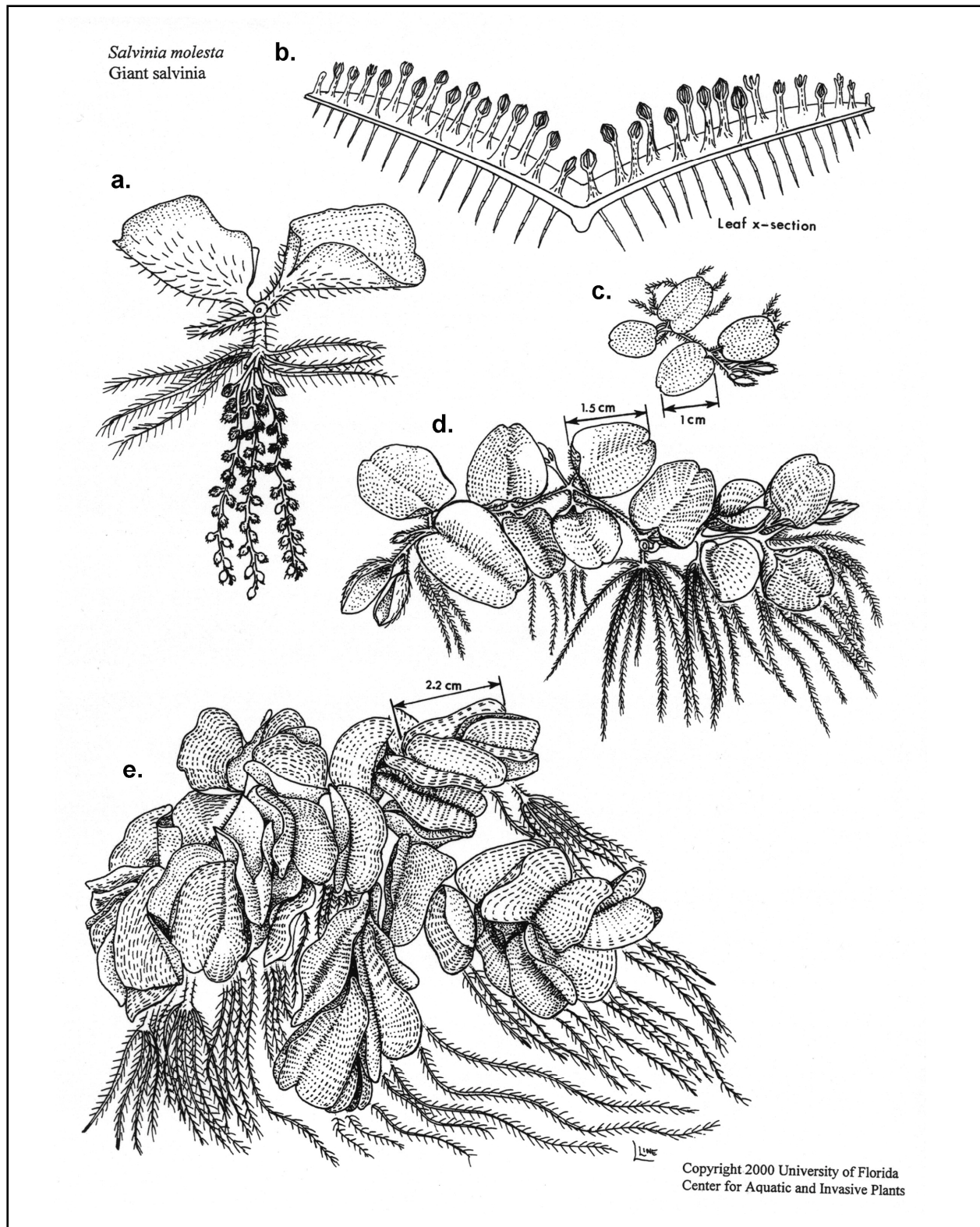
Figure 1. Morphology of *Salvinia molesta* D. S. Mitchell: a. Individual plant, showing sporocarps, floating leaves (i.e., fronds), and rootlike submerged leaf; b. Floating leaf, cross section; c. Primary form; d. Secondary form; e. Tertiary form (permission to reprint granted by University of Florida, Center for Aquatic and Invasive Plants 2000)

Geographical Distribution

Native and overseas distribution

Salvinia molesta is considered native to southeastern Brazil, in a subtropical zone (between latitudes 24º 05' S and 32º 05' S), extending inland to an elevation of about 900 m (Forno and Harley 1979; Forno 1983). It was first observed outside its native range in Sri Lanka in 1939 and has since become a serious nuisance in over 20 countries (Room 1986a; Room et al. 1989; Room 1990; Oliver 1993; Storrs and Julien 1996). Beyond the United States, *S. molesta* is presently established in Australia, New Zealand, Fiji, the Philippines, India, Indonesia, Malaysia, Singapore, and Papau, New Guinea. It also plagues aquatic systems in Africa (the Ivory Republic, Ghana, Zambia, Kenya, Namibia, Botswana, South Africa, and Madagascar), South America (Columbia and Guyana), and two Caribbean countries (Cuba and Trinidad; cf. syntheses by Oliver 1993; 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 are becoming increasingly overgrown (Jacono and Pitman 2001).

History of spread in the United States

For nearly 2 decades, *S. molesta* has been cultivated in the United States (Figure 2) as an ornamental plant provided by the horticulture industry (Harley and Mitchell 1981; Nelson 1984; Jacono 2003a). The species was first reported outside cultivation in this country in 1995 in a private 0.6-ha (1.5-acre) pond in southeastern South Carolina (Johnson 1995; Jacono and Richerson 2003). That same year, the plant was removed with chemical herbicide treatment and no further cases in South Carolina have been reported since then (Chilton et al. 2002; Jacono and Richerson 2003). However, in 1998, new outbreaks were discovered in Texas and Louisiana, initially in small ponds and later in Toledo Bend Reservoir, oxbow lakes of the Sabine River, and swamplands of Swinney Marsh (Chilton et al. 2002; Jacono and Pitman 2001; Jacono and Richerson 2003). The infestation of Toledo Bend Reservoir was the first in public U.S. waters and posed a significant threat for interstate dispersal because of the reservoir's large size, i.e., approximately 75,272 ha (186,000 acres), and location on the state line between Texas and Louisiana (Chilton et al. 2002). A primary concern was the reservoir's use by many thousands of sportsmen who could inadvertently transport the weed on their boating equipment across these two states and elsewhere. During the year 2000 growing season, 485.6 ha (1,200 acres) of Toledo Bend were chemically treated, but these efforts appear to have been only marginally successful (Jacono and Pitman 2001; Chilton et al. 2002).
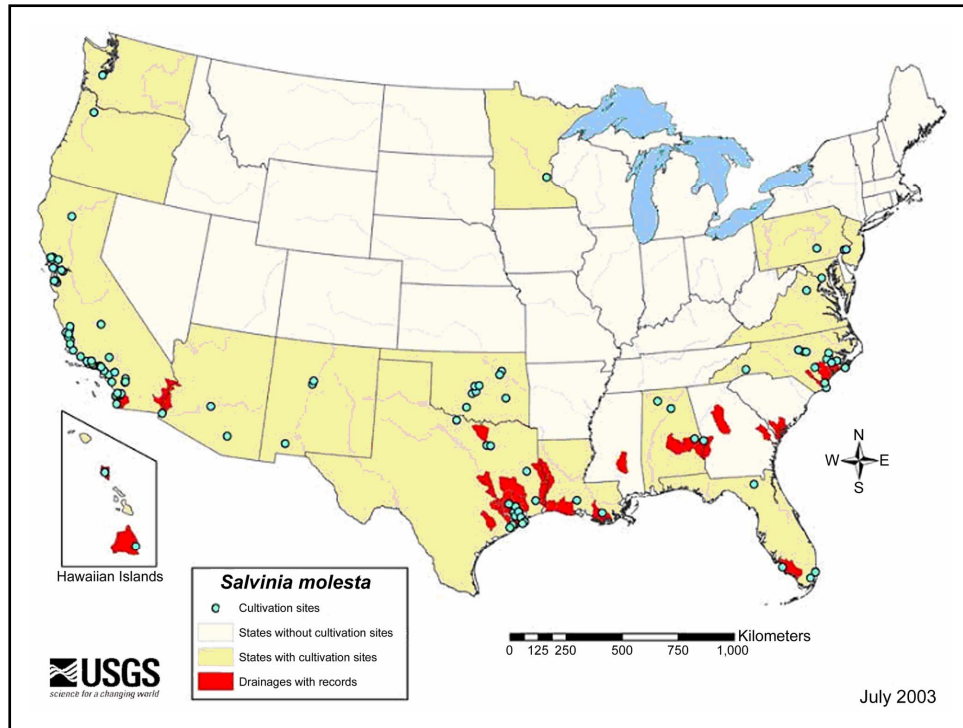
Figure 2.   Recorded distribution of *Salvinia molesta* in the United States

By the end of 1999, *S. molesta* had invaded over 50 localities in southern tier states (Texas, South Carolina, Louisiana, Georgia, Florida, Alabama, Mississippi, Arizona, California) and Hawaii (Jacono 2003a). A rapidly expanding infestation was documented in April of that year, when *S. molesta* in Enchanted Lake, Kailua, Hawaii, 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*) (Jacono and Richerson 2003). The following August, major infestations were discovered 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 that have since penetrated the Mexican border via the Colorado River (Jacono and Pitman 2001). Many smaller infestations were chronicled in 1999 for various aquatic systems in Seale and Auburn, AL; Moselle, MS; Houma, LA; Houston (vicinity), Lovelady, Freeport, Alvin, Mont Belvieu, and Flower Mound, TX; Atlanta (vicinity), GA; Oahu, HI; and Naples, FL (see Jacono and Richerson 2003 for details).

The year 2000 marked the first sightings of *S. molesta* in North Carolina in low-lying areas near Burgaw and in Jacksonville, and in ponds in Wilmington on the Cape Fear Peninsula (Kay 2002; Jacono and Richerson 2003). New reports of the species have since become less frequent, though many existing infestations have remained problematic. Today, the most widespread infestations occur in Texas and Louisiana where 4 public reservoirs, 7 rivers and streams, 2 large marshlands, and over 25 ponds have been impacted (Jacono and Pitman 2001). Swinney Marsh Complex on the Lower Trinity River, in Liberty County, Texas, continues to support one of the most serious infestations of *S. molesta* in the

United States (Jacono 2002; Jacono and Richerson 2003). Accounts by the U.S. Geological Survey (USGS) now show *S. molesta* naturalized in 10 states (North Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, Texas, Arizona, California, Hawaii), with South Carolina being the only state where the plant has been eradicated (Chilton et al. 2002; Jacono 2003a; Jacono and Richerson 2003).

Field Recognition

Salvinia 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 (or fronds), along with four or five buds that are relatively inconspicuous. Two leaves are green, emergent or floating, and ovate to oblong, while the third (a modified submerged leaf) 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 (trichomes), 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 flotation (Harper 1986). The submerged leaf resembles "root mass" and can elongate to create resistance to the water and thus helps to stabilize the plant. Sori or sporocarps develop in long chains among filaments of the submerged 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):

a. The *primary* (or *primary-invading*) stage occurs in isolated or widely spaced plants, during the initial invading stage of the infestation. The plants produce small, delicate, oval leaves, from (2) 10 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).

b. The *secondary* (or *open water-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, and the entire lower leaf surface is in contact with the water. Sizes of the leaves vary widely from about 20 to 50 mm in diameter.

c. The *tertiary* (or *mat*) stage 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 mats up to 1 m thick.

Ashton and Mitchell (1989) have described a *survival form* that occurs in *S. molesta* populations growing in harsh environments, e.g., under poor nutrient conditions. In this form, 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

Salvinia molesta produces sporocarps but spores are rarely found, and when present, the spores are generally 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 that number up to five per node. In calm waters, fragmentation occurs when older ramets senesce, causing the plant to break, as a result of deterioration of the rhizome, into two or more daughter plants (Room 1983). 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; Room 1983, 1990).

Dispersal

Vegetative spread by fragmentation is thought to be the major means of intra- and inter-lake dispersal of *S. molesta*. High mobility of the plant is facilitated by aerenchyma tissue that increases buoyancy and enables movement over vast areas, particularly during flooding (Barrett 1989; Oliver 1993). Rises in water level during flooding can loosen and break up *S. molesta* mats, allowing wind and water movement to disperse parts of the mat and plant fragments (Barrett 1989). Colonies can expand laterally over small distances by rhizome and bud growth, while fragments appear to be the dominant means of long-distance dispersal. Fragments may spread, for example, when parts of the plant adhere to fishing equipment, boats, trailers, or other vehicles (Chilton et al. 2002). Animals may also contribute to vegetative spread: hippos in Africa and water buffalo in Australia reportedly have carried *S. molesta* over short distances (Miller and Wilson 1989; Storrs and Julien 1996). Raccoons, wildfowl, turtles, and other wetland animals could possibly serve as vectors, but their role in spreading *S. molesta* has not been investigated extensively.

The attraction of *S. molesta* as an ornamental plant has led to its intercontinental transport via 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 (Harley and Mitchell 1981; Nelson 1984; Thomas and Room 1986a; Oliver 1993; Jacono 2003a). Plants initially introduced to the United States probably arrived in Florida from Sri Lanka, as cargo for direct sale or as a contaminant in an aquatic plant shipment (Nelson 1984; Oliver 1993; Jacono 2003a). A long-standing assumption has been that naturalized populations of exotic plants occur by these plants being dumped into nearby waterways or being "seeded" deliberately in the wild for future marketing.

Jacono (2003a) has reported *S. molesta* in cultivation in public and private aquatic gardens and nurseries in 17 states in the United States (Figure 2). These sites are potential sources of release into natural systems, and interestingly, many are located in areas where *S. molesta* infestations have been documented. To date, among the 11 states with records of *S. molesta* in nature, 8 states contain sites where the species is in cultivation (Jacono 2003a).

Salvinia molesta is prohibited, as a Federal Noxious Weed, from transport across state lines and from being imported to the United States (Chilton et al. 2002; Jacono and Pitman 2001; Jacono 2003a). However, 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 (Jacono 2003a). Presently, *S. molesta* can be freely cultivated and sold within 42 states (including Hawaii) as long as it is not transported across state lines (Jacono 2003a). It is listed as a State 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 2003a).

Productivity

Rates of growth and reproduction are formidably high in *S. molesta*. In the laboratory, its leaf doubling time ranged from ~ 2 to 4 days (Gaudet 1973; Mitchell and Tur 1975; Mitchell 1979a), and from ~ 1 to 8 days under field conditions (Finlayson 1984; Room 1986a). Rates of leaf production strongly reflect changes in season. In midsummer, the number of leaves were found to double 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 (in terms of leaf number) was reduced from 14.3 days in winter to 8.1 days in summer. Averaged across all seasons, doubling time varied with growth form – being shorter in *S. molesta* in 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 $4,672/m^2$ in stable mats and ranged between 200 to > $10,000/km^2$ (mean = 3,290) 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 1,620 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 percent per day (doubling about every 14 days) would produce ~ 45.6 to 109.5 tons/ha/yr. 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, 1983b; 1984; Finlayson 1984; Room 1986b) have enabled the development of a predictive model for the growth of *S. molesta* in relation to temperature (Room 1988). According to the model, growth of *S. molesta* follows a bell-shaped curve, increasing to a maximum near 30 ºC, with upper and lower limits of about 40 and 5 ºC. More recently, Whiteman and Room (1991) showed that temperatures < -3 ºC or > 43 ºC are lethal to buds in exposures > 2 hr. 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 most 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 large bodies of water where thermal capacity dampens temperature fluctuation.

Based on results of the above studies, the U.S. Department of Agriculture (USDA) has formulated an "expected range" for the expansion of *S. molesta* within the United States. This range, as reported by Jacono (2003b), 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 2003). Emergent growth of the plant dies back in winter in North Carolina (Zone 8, at latitude 34.4º N), and in north Texas (Zone 7b, at latitude 33º N) but generally recovers to dense levels the following growing season (Jacono 2003b).

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 ~ 4,500 kcal/m^2/day 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, outdoor studies of this species showed that during August to September, growth rates were 0.06 to 0.07 g/g/day 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/day, 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 pH 6 was 11, 54, and 59 percent greater than at pH 5, 7, and 8, respectively. The predilection of *S. molesta* for slightly acidic or near neutral pH is supported by accounts 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, TX, showed more extensive infestation of the pond with pH < 7.5 than the one with pH 8.5 or greater (Owens et al. in preparation). 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 (Room and Gill 1985). Sewage lagoons supporting dense growth of the plant had conductivities as high as 1,375.4 (±149.5) µS/cm (Room and Gill 1985). Although thick mats have been observed in waters with low conductivity (~ 100 µS/cm), the leaves appeared chlorotic, very likely because of low availability of nitrogen (Mitchell et al. 1980). Small infestations can survive at about 2,000 µS/cm (Storrs and Julien 1996), but higher conductivities (~ 4,800 µS/cm) damage plant tissues and diminish likelihood of survival (Divakaran et al.1980).

Salinity

Salvinia molesta has a low tolerance for saline environments and does not colonize marine or brackish waters (Oliver 1993). This species can survive at salinities up to 20 percent that of seawater, with growth rate decreasing with increases in total dissolved salt concentration. Divakaran et al. (1980) demonstrated a 25-percent reduction in rate of growth of *S. molesta* in water having a salinity of 3 ppt (or 10 percent 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 control plants (King and Mitchell unpubl. data, as per Harley and Mitchell 1981). Salinities > 7 ppt appear to be lethal, with death occurring at 11 ppt after 20-hr exposure; *S. molesta* died after only 30 min of exposure when cultured at 34 ppt, i.e., full strength seawater (Divakaran et al. 1980; Harley and Mitchell 1981).

Nutrients

Since *S. molesta* is free-floating and is not rooted in sediment, nutrients required for growth must be obtained by portions of the plant 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 of *S. molesta* colonies (Room and Thomas 1986a, 1986b). 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 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 percent or more for N and 0.5 percent or more for P under laboratory conditions (Cary and Weerts 1983a, 1983b; Room 1986b). In > 1,700 samples of *S. molesta* collected from field sites in Australia and Papua New Guinea, tissue N concentrations ranged from 0.62 to 4.0 percent and tissue P from 0.03 to 1.07-percent dry wt (Room and Thomas 1986a, 1986b). The Australian average for concentrations of N in tissues of *S. molesta* was 1.59 percent, while that for tissues from Papua New Guinea was 1.12 percent. Based on these low values, N was suggested to be the primary limiting nutrient, accounting for 40 and 80 percent of the variance in growth rates of *S. molesta* in the field (Room and Thomas 1986a, 1986b).

Salvinia 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 and from 2 to 10 mg PO_4-P/L (Cary and Weerts 1984).

Availability of nutrients in the water is an important determinant of the survival strategy demonstrated by *S. molesta* colonies. In infertile water, *S. molesta* rhizomes are tough with few if any branches and fragment when the oldest segments deteriorate (Mitchell and Tur 1975; Room 1983; Julien and Bourne 1986). Survival is enhanced under infertile conditions by retaining senescing ramets so that the nutrients within them can be reallocated elsewhere in the colony (Room 1983). In contrast, *S. molesta* in fertile water has highly branched and brittle rhizomes that fragment sooner than in infertile water because of pressure from overcrowded ramets (Room 1983, 1990). Senescing ramets are not retained probably because proliferation of dispersal units is selected under fertile conditions over retention of nutrients (Storrs and Julien 1996).

Impacts on the Environment

Detrimental

By hindering the use of water resources, 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 water surface that prevents or impedes water use for recreational activities, such as swimming,

boating, water skiing, and fishing (Holm et al. 1977; Barrett 1989; Chilton et al. 2002). Even when the mats are not fully impenetrable, the clusters of rhizomes and submerged leaves quickly become entangled around boat propellers, so that the watercraft may sooner or later be immobilized (Sculthorpe 1985). 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 (Holm et al. 1977). Where water flow is restricted and rates of silt deposition increase, dredging operations may be needed to minimize potential adverse effects of flooding. In addition to causing the loss of crops and preventing agricultural operations, flooding is a prominent mechanism in breaking up the mats and distributing fragments that can produce new colonies (Sculthorpe 1985).

Occasionally, plants of various species will colonize thick *S. molesta* mats, 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. leptocarpa*, and *L. ascendens*), grasses (*Leersia hexandra*, *Hymenachne amplexicaulis*, and *Panicum repens*), sedges (*Cyperus platystylis* and *C. cephalotus*), bulrush (*Scirpus cubensis*) and even trees (*Melaleuca* spp.) (Holm et al. 1977; Mitchell et al. 1980; Storrs and Julien 1996). 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).

Salvinia 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 the availability of light, *S. molesta* can outcompete many native species of submersed and floating plants, consequently reducing community diversity (Sculthorpe 1985). 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 at the bottom of the water column and can threaten fisheries by creating a shallow-water environment less suited to fish breeding (Sculthorpe 1985). Furthermore, decomposition of the organic materials can greatly diminish dissolved oxygen supplies needed to support healthy fish populations and other biota (Hattingh 1961; Coates 1982; Oliver 1993). 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 to complex food chains. The theoretical maximum rate of N uptake, calculated from rates of growth of *S. molesta*, is about 8 mg N/g dry plant tissue/day or about 6,000 kg N/ha/yr (Room 1986b).

Heavy infestations of *S. molesta* raise public health and economic concerns by 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 produced by *S. molesta* mats are favored by many species of mosquitoes that transmit encephalitis, dengue fever, malaria (Creagh 1991/1992 as per Oliver 1993), and rural filariasis or elephantiasis (Room et al. 1989). In Lake Kariba (Zambia and Rhodesia), *S. molesta* mats fostered the buildup and

spread of *Biomaphalaria boissyi*, the snail that is the intermediate vector of bilharzia or 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 (Bennett 1975; Thomas and Room 1986a; Oliver 1993). Yet nowhere have the adverse effects of rapid growth of *S. molesta* been as dramatic as in the flood-plain of the Sepik River, Papau New Guinea. There, entire villages, dependent on aquatic transportation, were abandoned because thick mats of *S. molesta* eliminated access to health care, food, markets, and schools (Mitchell et al. 1980; Thomas and Room 1986a).

Beneficial

Despite limited possibilities, investigative attention has been directed toward 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 because high costs associated with labor and machinery. 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 1986a).

3   Management Options

Chemical Control

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's to 1970'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 lb/acre) controlled 100 percent of *S. molesta* in 1 week. Diquat at 4.5 kg/ha (4 lb/acre) controlled 99 percent of the plants, but such a high rate was considered cost prohibitive. Lower rates of either product were less effective (< 85-percent 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 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 percent, the data showed that addition of herbicide significantly improved treatment performance. Rates as low as 0.15 kg/ha diuron

added to the kerosene-surfactant mixture controlled 100 percent of *S. molesta*. Dichlorprop and 2,4-D controlled 92 to 95 percent of *S. molesta* in these trials, however higher rates of both products (0.75 to 3.00 kg/ha) were required. Because of the findings 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 (ppm). Fluridone symptoms (bleaching of new tissues) were noted on plants treated with concentrations $\geq$ 0.1 mg/L fluridone, but plant death occurred only when plants were subjected to 100 mg/L 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 *S. molesta* in small ponds with fluridone concentrations of 45 to 90 µg/L (ppb).[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.

Herbicide investigation and use in the United States

As *S. molesta* gained notoriety in the late 1990's as an established and noxious weed in the United States, concern for identifying management options escalated. While early studies conducted overseas identified several effective herbicides for *S. molesta*, 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, eight herbicides are available in the United States for controlling weeds in aquatic habitats. They include: diquat, copper (as copper chelates), endothall, fluridone, glyphosate, imazapyr, 2,4-D, and triclopyr. Triclopyr and imazapyr are the most recent additions to this list, receiving full aquatic registration from the USEPA in December 2002 and September 2003, respectively. To date, no information has been published 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 different herbicides (diquat, two 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) and glyphosate (8.97 kg/ha) were equally effective for controlling *S. molesta* (99- to

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[1] Personal communication, J. D. Schardt, Florida Department of Environmental Protection, Tallahassee, FL.

100-percent reduction in plant biomass). Copper (as the formulation Komeen™) provided 81-percent control of *S. molesta* 42 days after treatment. Treatment with endothall (both formulations) showed significant plant control (80 to 86 percent) shortly after treatment, however, remaining plants were healthy and actively growing, resulting in a steady decline in percent control over time. *Salvinia molesta* was only 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 percent v:v) and five surfactants were evaluated under outdoor conditions. Results indicated that a 0.45-percent 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 percent v:v) mixed with Optima™ (0.25 percent 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 (unpublished data) by Dr. L. Nelson, a co-author of this report.

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-percent solution (v:v) was effective for reducing biomass by 84 to 88 percent. Regrowth of surviving plant tissues was observed indicating follow-up applications may be necessary to maintain acceptable containment. Although 100-percent 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.

Several cases have been reported where operational-scale herbicide applications were successful in managing *S. molesta* infestations. State applicators in Texas reported excellent control of *S. molesta* using 4.54 kg/ha glyphosate (as Rodeo™) mixed with nonionic (Aqua-king™) and organo-silicone (Thorough-bred™) surfactants and applied in a total spray volume of 935 L water/ha (100 gal water/acre).[1,2] In 1995, officials in South Carolina used diquat (2.24 to 3.36 kg/ha) and follow-up applications of fluridone (1.46 kg/ha) to eradicate *S. molesta* from a small plantation pond.[3] As mentioned previously, fluridone has also been successfully used to control *S. molesta* populations in Florida. Most recently (March 2003), nearly 121 ha of *S. molesta* were cleared from Lake Wilson, Oahu, Hawaii, using glyphosate (as AquaMaster™) applied at 4.6 to 5.7 kg/ha and mixed with a nonionic surfactant. Multiple applications were necessary in some areas where plants had produced a thick, vegetative mat. In

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[1] Personal communication, B. Kellum, San Jacinto River Authority, Conroe, TX.

[2] Personal communication, H. Elder, Texas Parks and Wildlife, Jasper, TX.

[3] Personal communication, S. de Kozlowski, South Carolina Department of Natural Resources, Columbia, SC.

addition to herbicides, mechanical excavators were also used at Lake Wilson to aid in the removal of plant biomass.[1]

Overall, the results of recent research and large-scale field applications have demonstrated that registered aquatic herbicides can be used to effectively manage *S. molesta* infestations in the United States. 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 percent 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

Background

Use of one insect species, the weevil *Cyrtobagous salviniae* Calder and Sands (Figure 3), is recognized throughout the world as the method of choice for *S. molesta* management. Application of this agent has resulted in control in the tropical areas of 12 countries on 3 continents including, but not limited to, Australia, Fiji, India, Kenya, Namibia, South Africa, Sri Lanka, Zambia, and Zimbabwe (Room et al. 1981; Forno 1985; Forno and Bourne 1985; Giliomee 1986; Joy et al. 1986; Thomas and Room 1986b; Forno 1987; Julien and Griffiths 1998).

While never intentionally released, *C. salviniae* is found in the United States in many areas of southern Florida. Based on existing collection records, it was probably introduced accidentally from South America in the early 1960's. It is commonly found feeding on *S. minima* Baker, a close relative of *S. molesta*. Until recently, the Florida strain of *C. salviniae* was mistakenly identified as *C. singularis,* a species initially used for *S. molesta* control overseas but later proven to be noneffective. Attempts to use the Florida strain of *C. salviniae* in the late 1990's and early 2000's to manage *S. molesta* in Texas and western Louisiana 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 petition the Technical Advisory Group (TAG) and the USDA, Animal and Plant Health Inspection Service (APHIS), Plant Protection and Quarantine (PPQ) for approval to release the Australian strain of *C. salviniae* proven to be highly effective in oversea applications. Permission was granted in 2001, allowing the release of the Australian strain of *C. salviniae* in western Louisiana and east Texas only.

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[1] Personal communication, L. Nakahara, Hawaii Department of Agriculture, Honolulu, HI.

Figure 3. Photograph of *Cyrtobagous salviniae* on *S. minima* (from USACE 2001 and USDA, Agricultural Research Service (ARS))

Host-specificity testing

Before *C. salviniae* could be released, intensive host-specificity experiments were conducted. Various plants were offered to adults and immatures to document if feeding, oviposition, and survival could 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 United States with approval for release based on the work of researchers from both these countries (Forno et al. 1983; Tipping and Center 2001).

Table 1 lists the plants used in host-specificity testing of *C. salviniae* in Australia and South Africa and for approval for release in the United States (Tipping and Center 2001). 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 in the United States. *Cyrtobagous salviniae* fed 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 United States or Hawaii.

Table 1		
Plants Used in Host-Specificity Testing		
Species Name	**Common Name**	**Family**
Pteridophyta		
Salvinia molesta	Giant Salvinia	Salviniacea
Salvinia minima	Common Salvinia	Salviniacea
Salvinia hastata		Salviniacea
Azolla caroliniana	Water Fern	Azollaceae
Azolla filiculoides	Pacific mosquitofern	Azollaceae
Azolla pinnata Africana	Feathered mosquitofern	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
Oryza sativa	Rice	Poaceae
Saccharum officinarum	Sugarcane	Poaceae
Asparagus officinalis	Asparagus	Liliaceae
Musa x paradisiacal	Banana	Musaceae
Eichhornia crassipes	Waterhyacinth	Pontederiaceae
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
Ipomoea 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

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 about 3 mm. The pupa forms a cocoon in the modified submerged fronds.

Biology

Adults typically reside on or beneath the 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 prepupal 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 fronds, 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 buildup (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, the plants initially turn brown in small patches that coalesce until finally the entire mat appears brown and begins to sink.

U.S. operational status

As indicated previously, permission was received in 2001 and *C. salviniae* 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.[1]

[1] Personal communication, T. Center, U.S. Department of Agriculture, Agricultural Research Service, Aquatic Plant Management Laboratory, Fort Lauderdale, FL.

Recent controlled experimentation has indicated that previously observed differences between the Florida and Australian weevil strains were erroneous, and this has prompted researchers to petition USDA, APHIS, and PPQ to accept both the Florida and Australian strains as the same.

Physical Control

Conventional procedures for floating aquatic plants

Physical alternatives for controlling free-floating aquatic plants have generally involved the following management practices: (a) physically removing the target species directly by hand, or by using water-based or land-based mechanical harvesters; (b) destroying the infestation by inflicting physical damage by cutting, shredding, or chopping targeted plants in situ; (c) placing barrier materials to confine nuisance vegetation to prevent colonization of other areas; and (d) modifying the environment to minimize growth of the problem plant by eliminating or reducing suitable habitat (Chilton et al. 2002). Probably the least effective of these methods in controlling *S. molesta* infestations is the use of cutters, shredders, or choppers that could spread the species by generating a large number of fragments (Madsen 2000; Chilton et al. 2002). 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 and 2000), Wade (1990), and Chilton et al. (2002).

Direct removal

Manual removal has been successful in controlling *S. molesta* in the initial, uncrowded stage of population development (Thomas and Room 1986a; Miller and Wilson 1989). Once the plant has become established, hand removal and harvesting are less practical considering the plant's rapid rate of growth and production of large amounts of biomass. Generally, the cost of equipment is expensive because the machinery is specialized to collect and remove large quantities of biomass in an aquatic environment (Thomas and Room 1986a; Chilton et al. 2002). With > 95-percent water content, *S. molesta* can be very heavy and can typically double in weight in < 10 days under favorable conditions. In the tropics, its biomass has been recorded to reach approximately 200 tons (wet wt)/ha and in extreme cases, > 400 tons/ha within a 10-day period (Room and Julien 1994; Storrs and Julien 1996). In order to be effective, the harvester must be able to handle such biomass and remove it at rates exceeding regrowth of the targeted vegetation (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 machines (Mitchell 1979a). Furthermore, the morphometry of natural waterways may impose problems of inaccessibility and physical obstacles (e.g., other vegetation), to make large-scale mechanical removal impractical.

Barriers

Floating booms and nets 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 have also been deployed in very localized areas to prevent the plant from entering into and clogging water intakes, boat launches, marinas, and swimming areas (Chilton et al. 2002). However, booms and nets require continuous inspection and maintenance and are subject to breakage under the pressure of large windblown mats (Oliver 1993). In some cases, a series of nets must be installed as protection against breakage of one or more nets during periods of flooding (Miller and Wilson 1989). In Lake Moondarra, 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 buildup of *S. molesta* (Finlayson and Mitchell 1982). Booms slung on 5-cm-diam steel cables in Lake Kariba were abandoned after being broken several times by windblown *S. molesta* accumulations (Thomas and Room 1986a).

Habitat alteration

Water-level drawdown is a relatively inexpensive technique for controlling aquatic weeds in lakes with sufficient water-level control structures (Chilton et al. 2002). The primary goal of the drawdown is to destroy the target plant by thorough drying and/or exposure to lethal (freezing) temperatures (Cooke et al. 1986). The success of this procedure in controlling *S. molesta* would largely depend on the structure of the plant mat and its ability to protect and insulate embedded ramets. Where the mat is thick and dense, the most exposed plants and plant parts are subject to desiccation and/or being frozen, while plants close to the sediment may survive. Unless the sediment becomes dry (and/or frozen) for a long enough period, plants deep in the mat may regenerate the colony on the return of suitable conditions.

Lantz et al. (1964), Lantz (1974) and Cooke et al. (1986) have reported water-level manipulation to be an important technique for controlling nuisance plants in many Louisiana reservoirs. Their findings indicate this procedure to be highly species specific and suggest that while drawdown may curtail one plant nuisance, it may promote development of a resistant species. In northern Louisiana, autumn/winter drawdown is most effective in reducing dense growth of *E. crassipes*; however, the effectiveness of this technique on other plant species and in other locations may improve (or be lessened) by climatic conditions. In addition, water-level drawdown as a management tool has been somewhat controversial because of adverse impacts on secondary uses of the aquatic system, e.g., boat access, hunting, fishing (Chilton et al. 2002). Recent evidence from pond studies in Lewisville, TX, has shown winter drawdown to be successful in reducing growth of *S. molesta* (Dick et al., in review). Yet, further study is needed to determine efficacy of drawdown on *S. molesta* in other areas and when used in an integrated approach with other control methodologies.

Ecosystem Approach

Prevention

Obviously, prevention is the most effective, economical, and environ-mentally compatible method for dealing with an invasive plant like *S. molesta.* The spread of this aquatic weed in the United States (and in other countries) has been closely linked to the water garden trade where implementation of preventa-tive measures would be highly beneficial. Recently, *S. molesta* was found for sale in commercial nurseries in 12 states (Texas, Louisiana, California, Hawaii, Arizona, New Mexico, Alabama, Oklahoma, Oregon, Washington, Virginia, and Pennsylvania) and in cultivation in many sites including botanical gardens, aquatic plant nurseries, and private ponds (Figure 2; Jacono 2003a). These activities are widely agreed to be principal mechanisms of plant spread, for example, when the plant is thrown by gardeners into nearby waters, or floods carry it from cultivation sites into natural drainages (Jacono 2003a). Water resources could be better protected by closer monitoring of public areas (e.g., boat launches, beaches, and marinas) and by educating users of the potential harmful effects of *S. molesta* on aquatic systems and of the dangers of allowing this plant to escape cultivation. Additionally, State and Federal Agencies responsible for enforcing exotic species regulations (restricting the sale, trans-port, and cultivation of *S. molesta*) should be notified immediately of any possible violations and provided sufficient funding for inspection and enforce-ment personnel (Chilton et al. 2002).

Eradication

Barring prevention, early detection followed by prompt management action would help to eradicate *S. molesta* in its initial stages within a water body. However, given past experiences with this species and other invasive aquatic plants, eradication, even within any single system, is almost always unattainable. It seems more likely that management approaches will need to be developed that seek to reduce the extent of *S. molesta* infestations to acceptable levels.

Integrated pest management

When eradication is no longer feasible, integrated pest management (IPM) has proven effective in controlling weedy species, including *E. crassipes*. A balanced, IPM approach, employing all appropriate control methods (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 (preven-tion of spread)—would seek to suppress the growth or extent of *S. molesta* infestations, thereby reducing the plant's harmful environmental or economic effects.

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 weed control.

"Filling the niche"

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 the 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. It is important, nevertheless, to ensure the presence of a diverse community of aquatic plants as a defense against an overgrowth of an invasive species—whether submersed, free-floating, or emergent.

Nutrient management

Given the high rates of nutrient loading suffered by many aquatic systems, the development of any floating plant species potentially could be excessive. However, well-developed riparian wetland and littoral plant communities in lakes and reservoirs could intercept excess nutrients before they accumulate and promote the excessive growth of problematic species (Mitsch and Gosselink 1993). Since free-floating plants do not often have to compete with other plants for light, and because they depend on the water column for their nutrient supply, free-floating plants are more likely to be limited by the availability of nutrients than are submersed and floating-leaved forms that obtain nutrients mainly from sediment (Sculthorpe 1985; Barko et al. 1991). Thus, reductions in nutrient supply are likely to provide corresponding reductions in biomass or growth rates of floating plants such as *S. molesta*.

Normally, waterbodies receive inputs of nutrients and sediment from the surrounding drainage basin as a result of natural runoff and soil erosion (Gupta 1979; Miller 1994). Problems with aquatic weeds, such as *S. molesta,* tend to arise when nutrient loadings are accelerated by human activities, a process known as cultural or anthropogenic eutrophication (Gupta 1979; Wetzel 1983). Nutrient inputs may become excessive because of agricultural runoff, failing septic systems, deforestation, building and road construction, and effluents from sewage treatment facilities (Miller 1994; Park 1997). Management strategies to reduce nutrient inputs through wise land-use and conservation practices (e.g., the use of advanced sewage treatment technologies, diversion of animal wastes, strip cropping and contour farming, and wetland protection) would help to improve water quality and reduce the potential for proliferation of *S. molesta*.

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REPORT DOCUMENTATION PAGE

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1. REPORT DATE *(DD-MM-YYYY)* June 2004	2. REPORT TYPE Final report		3. DATES COVERED *(From - To)*
4. TITLE AND SUBTITLE *Salvinia molesta* D. S. Mitchell (Giant Salvinia) in the United States: A Review of Species Ecology and Approaches to Management			**5a. CONTRACT NUMBER**
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) D. G. McFarland, L. S. Nelson, M. J. Grodowitz, R. M. Smart, C. S. Owens			**5d. PROJECT NUMBER**
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Engineer Research and Development Center, Environmental Laboratory 3909 Halls Ferry Road, Vicksburg, MS 39180-6199; U.S. Army Engineer Research and Development Center, Lewisville Aquatic Ecosystem Research Facility 201 E. Jones Street, Lewisville, TX 75057			**8. PERFORMING ORGANIZATION REPORT NUMBER** ERDC/EL SR-04-2
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Corps of Engineers Washington, DC 20314-1000			**10. SPONSOR/MONITOR'S ACRONYM(S)**
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Over the past 70 years, the free-floating aquatic fern *Salvinia molesta* D. S. Mitchell (giant salvinia) has spread from its native range in Brazil to many tropical and subtropical regions. Though innocuous within its native range, elsewhere this species is an aggressive menace that has had devastating ecological and socioeconomic impacts on aquatic systems in parts of Africa, Sri Lanka, India, Australia, New Guinea, and the Philippines. In the United States, the plant is established in waterways in at least 10 states (mainly in the south) and is expected to continue to expand in areas generally where *Eichhornia crassipes* (Mart.) Solms (water hyacinth) persists. Listed as a Federal Noxious Weed since 1984, *S. molesta* is prohibited from importation to the United States and from transport across state lines. Dense mats of *S. molesta* can suppress growth of native vegetation and degrade water quality, fish and wildlife habitat, and numerous other ecological values. Notably, massive infestations have occurred in the Swinney Marsh Complex, Texas, in the Lower Colorado River, Arizona/California, and in Lake Wilson and Enchanted Lake, Hawaii.

This report presents a review of available information on the growth, distribution, and ecology of *S. molesta*. Information is provided on the plant's taxonomic status, its field characteristics, phenology, and spread overseas and in the United States. Growth responses of *S. molesta* in relation to environmental variables (e.g., temperature, nutrients, light, pH, conductivity) are emphasized as

(Continued)

15. SUBJECT TERMS
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are impacts of the species on the environment and other aquatic organisms. Different technologies (i.e., physical, chemical, biological, and integrated) applied to control *S. molesta* infestations are discussed along with information on the effectiveness of these procedures and their need for further study.

15. (Concluded)

African pyle
Aquarium watermoss
Aquatic systems
Australian azolla
Control, management
Disturbance
Environmental factors
Eutrophication
Invasive species
Kariba weed
Water fern
Water spangles