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A Review of the Biology of Giant Salvinia (*Salvinia molesta* Mitchell)[1]

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INTRODUCTION

Giant salvinia (Salviniaceae) is a potentially serious aquatic weed that is native to Brazil. It has been reported in more than 20 countries, but is not established in the U.S. at this time. Mitchell and Tur (1975) reported that three years after the formation of the Kariba Reservoir in Africa, giant salvinia blanketed 21.5% or 1003 km^2 of the reservoir surface area. Creagh (1991/1992) wrote, "A single small plant may grow to form a thick mat covering more than 100 sq. km. in just three months - choking lakes and waterways, reducing populations of aquatic plants and animals and in some countries threatening the livelihoods of . . . thousands of people".

Dense mats of giant salvinia interfere with rice cultivation, clog fishing nets, and disrupt access to water for humans, livestock, and wildlife (Mitchell 1979), and recreation, transportation, irrigation, hydroelectric generation, and flood control are also hampered (Holm et al. 1977). Thick mats of giant salvinia form large floating islands which support secondary and tertiary colonizing plants and fill in waterbodies (Thomas 1979).

Common names of *S. molesta* include giant salvinia, African pyle, and Kariba weed (Mitchell and Thomas 1972). These names allude to this species' relatively large size and to its successful invasion of Lake Kariba and other waters of Africa.

The plant was originally reported as a form of *S. auriculata* Aubl. It was later reclassified as *S. molesta*, based on details of the male sporocarps (Mitchell 1972). This review reports on the pertinent scientific literature concerning giant salvinia.

DISTRIBUTION AND DESCRIPTION

Giant salvinia is indigenous to southeastern Brazil (Forno and Harley 1979) and first became established outside its native range in 1939 in Sri Lanka, via the University of Colombo, Botany Department (Room 1990). It continued to be spread by man to other warm regions of the world in the following decades. For example, in the Sepik River floodplain of Papua New Guinea, a few plants introduced in 1972 grew in eight years into mats covering 250 km^2 and weighing 2.2 million tons (2 million tonnes). The lives of about 80,000 people who were almost entirely dependent on canoes for transport and food were severely affected (Thomas and Room 1986b, Room 1990).

Giant salvinia has been introduced to other parts of the world as an aquarium plant (Room et al. 1981, Australian National Parks and Wildlife Service 1992) and has become established in India (Cook 1976), Australia (Creagh 1991/1992) and Papua New Guinea (Mitchell 1979). It has been reported from the Caribbean (Cuba, Trinidad, Holm et al. 1979), South America (Columbia, Guyana, Holm et al. 1979), Africa (South Africa, Cilliers 1991; Botswana, Kenya, and Zambia, Mitchell and Tur 1975), Asia (Indonesia, Malaysia, Baki et al. 1990), Fiji and New Zealand (Considine 1984/1985, Farrell 1978, Holm et al. 1979, Mercado et al. 1974). Major infestations and problems have occurred in the Chobe-Linyata-Kwando River system, the Zambezi River, and Lake Naivasha in Africa, Lake Moondara in Australia, the Sepik River in Papua New Guinea, and the Kakki Reservoir in India (Mitchell 1979). Giant salvinia is on the U.S. Department of Agriculture (USDA) Noxious Weed List and the Florida Department of Environmental Protection Prohibited Aquatic Plant List and is illegal to import into the U.S.

Giant salvinia has been discovered and eradicated in several botanical gardens and was detected and destroyed at two aquatic plant nurseries in Florida, where it had apparently been part of a contaminated aquatic plant shipment from Sri Lanka (Nelson 1984). The species occasionally contaminates shipments of other aquatic plants, and in spite of careful inspection and control, it is likely to again be discovered in the U.S.

MORPHOLOGY

Giant salvinia is a fern which can be identified by floating fronds that are broadly rounded and green (Ramey 1990). The upper frond surface bears a prominent midrib and is covered with close parallel rows of long, stiff leaf hairs that make the leaf buoyant. Slender brown feathery structures extend beneath the plant and reproductive sporangia occur on submersed stalks below the fronds.

In all growth stages, giant salvinia and the USDA Noxious Weed, *S. auriculata*, can be distinguished from common salvinia (*S. minima*) by the presence of unwettable hairs on the upper leaf surface which form cage-like structures (Cook et al. 1974 and Figure 1). Giant salvinia can be distinguished from other members of the *S. auriculata* group by the presence of straight chains of sessile to subsessile male sporocarps, 1 mm or less in diameter, containing mostly empty sporangia (Mitchell 1972). Further keys to identification were given in Forno (1983).

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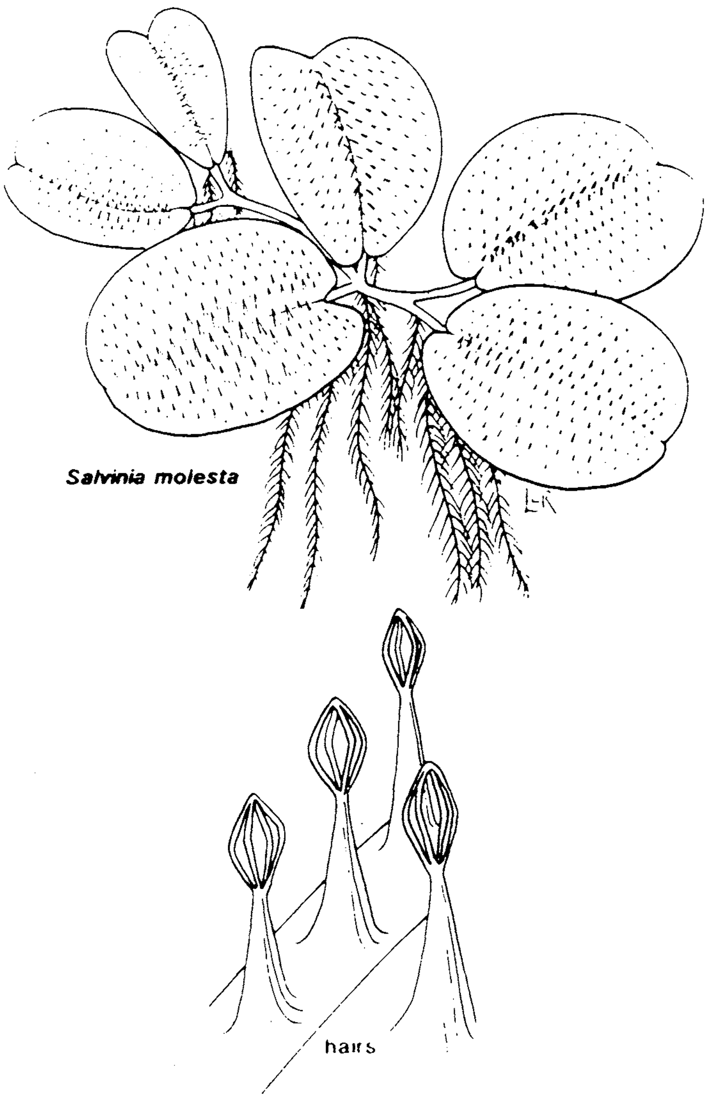

Figure 1. Giant salvinia, illustrating details of hairs on upper surface of frond. Reprinted with permission from Ramey 1990.

BIOLOGY AND IMPORTANCE

Giant salvinia possesses three different phenotypes or growth stages (Ashton and Mitchell 1989). The survival stage is typically found in adverse conditions, e.g., where nutrient supplies are low. At this stage, the plant grows slowly, and bears four to five pairs of flattened leaves that are each 0.5 - 0.8 cm in diameter. During the colonizing stage, it is found in open water and capable of high growth rates, and has flat leaves that are 2 - 4 cm in diameter. During the mat stage, the plant is present in established mats where growth is restricted and relatively slow. Plants have erect pairs of leaves on a long (15-20 cm) rhizome. When individual giant salvinia plants are transferred from one environment to another, they adapt their growth form to suit the surrounding conditions and thus maximize dominance.

Giant salvinia spreads at a rapid rate by vegetative reproduction. When the plant is introduced to new habitats, it produces the colonizing stage plants which have thin stems and fragment easily, thus further producing new plants. As plant density becomes greater, larger mature plants are formed which produce tight, intertwined mats. Giant salvinia appears unable to reproduce sexually (Mitchell and Gopal 1991) and does not produce viable spores. It exhibits anomalies at meiosis which prevent production of fertile haploid gametes. The fact that the plant is asexual and perennial means that the millions of tonnes of the plant worldwide may be clones of a single genetic individual (Werner 1988, Barrett 1989).

Giant salvinia is a highly aggressive, competitive species. Kammathy (1968) states that in the backwaters, canals, and rice paddies of Kerala, India, it successfully competes with and even replaces water hyacinth (*Eichhornia crassipes* (Mart.) Solms) and water lettuce (*Pistia stratiotes* L.) Gaudet (1973) found that when giant salvinia and the naturalized species common salvinia were grown together, giant salvinia maintained a greater dry weight and larger leaf area. The larger leaf area corresponds to a greater light absorptive area and is a factor in the success of giant salvinia as a troublesome aquatic plant. Doubling times of leaves of 3.4 days have been recorded in sterile culture, and 8.1 days in Lake Kariba (Mitchell 1979, Gaudet 1973). In greenhouse studies, a leaf doubling time as low as 2.2 days has been reported (Cary and Weerts 1983a).

The plant can completely cover water surfaces and form mats up to 1 m thick (Thomas and Room 1986a). Live biomass ranges from 250-600 g m^{-2} dry wt, which approaches the 670-1620 g m^{-2} dry wt observed for water hyacinth (Mitchell 1979). Giant salvinia growing in good conditions with a sustainable growth rate of 5% d^{-1} (doubling time of about 14 d) would produce 45.6 - 109.5 dry tonnes ha^{-1} yr^{-1} (Rani and Bhambie 1983, Mitchell and Tur 1975).

Giant salvinia combines a high growth rate with a slow rate of decomposition (0.0033 d^{-1}, Sharma and Goel 1986), so that nutrients absorbed into the plants are only slowly made available to phytoplankton, periphyton, macrophytes, and the higher trophic levels which depend on these primary producers. Thus, giant salvinia potentially alters the natural nutrient dynamics of water bodies in which it colonizes.

High mobility has allowed giant salvinia to spread over vast areas. This mobility is facilitated by formation of aerenchyma tissue which gives stems and leaves buoyancy (Barrett 1989). Plants float with wind or water currents to uninfested waters where they can grow and propagate vegetatively.

Common habitats are mostly disturbed areas, but undisturbed areas are also colonized. Disturbed habitats include flood canals, rice paddies, artificial lakes, and hydroelectric facilities (Barrett 1989). In its native Brazil, giant salvinia occurs in artificial reservoirs, swamps, drainage channels, and along the margins of rivers (Forno and Harley 1979). In central Java in Indonesia, the plant is a pest in rice paddies, where it competes for water, nutrients, and space, resulting in poor crop production (Anonymous 1987). In India, giant salvinia has invaded wetland habitats and reportedly replaced native flora (Gopal 1988).

This species has a low tolerance for saline and dry environments. It does not colonize brackish or marine environments, and a 30-minute exposure to full strength sea water is lethal (Mitchell 1979). Individual plants are readily killed by desiccation, but plants shaded by others on moist substrates have remained viable in excess of one year.

Growth of giant salvinia is promoted by high light intensities, relatively high water temperatures, and a plentiful supply of nutrients (Mitchell and Tur 1975). Increasing the water temperature up to 30 C results in elevated growth rates, as does increasing the concentrations of nutrients, especially nitrogen and phosphorus (Cary and Weerts 1983b). Eutrophic habitats such as nutrient-rich springs and phosphate-mine reclamation wetlands and ponds in the U.S. would be particularly suitable for rapid growth and colonization.

The species is known to dominate in warm-temperate to tropical areas that are climatologically similar to Florida. Giant salvinia is killed when its buds are exposed to temperatures less than -3 C, but leaves can survive freezing air temperatures if they are under the water surface (Whiteman and Room 1991). Because the lower and upper thresholds for growth are about 10 C and 40 C respectively (Room and Kerr 1983, Room 1986b), all freshwater areas of Florida, especially in central and south Florida, are potential habitats for the plant.

On the basis of environmental, economic, and human health problems, giant salvinia ranks second behind water hyacinth on a list of the world's most noxious aquatic weeds (Barrett 1989). Human health costs in Sri Lanka have been increased by giant salvinia since infestations provide an ideal environment for the reproduction of disease-carrying organisms. Giant salvinia is an important plant host of *Mansonia* mosquitos, which serve as one of the principal vectors of rural elephantiasis (Pancho and Soerjani 1978). Other mosquito species sheltered by giant salvinia have been responsible for the transmission of encephalitis, malaria, and dengue fever (Creagh 1991/1992).

Thick, floating mats of giant salvinia sometimes become colonized by other plants (Bennett 1975). Roots of other species bind the mats firmly so that navigation by small boats becomes impossible. In Kariba Lake, small harbors have become clogged and the mats aided in spreading snails which are the intermediate vectors of schistosomiasis (Thomas and Room 1986a). Giant salvinia and associated floating species have restricted light penetration and when resulting organic matter decomposes it reduces oxygen for young fish (Hattingh 1961). These environmental factors potentially impact commercial fishing by inhibiting breeding of fish in shallow areas. Dead giant salvinia plants have been observed to fall to the bottom of the water column and to cause organic matter build-up, as well as depletion of oxygen. Benthic fauna are typically decreased under permanent mats (Coates 1982).

The multitude of economic, health and environmental costs due to giant salvinia far outweigh any economic values that it possesses. These values include utilization as a compost and mulch, and in Asia, supplementation to regular livestock fodder (Thomas and Room 1986a). Giant salvinia is not suitable as a sole source for fodder because high contents of crude ash, lignin, and tannins reduce digestibility (Moozhiyil and Pallauf 1986).

Giant salvinia would probably occupy a similar niche to the naturalized species, common salvinia, if it became established in the U.S. (Nelson 1984). However, because it is a more aggressive colonizer of open water, it has the potential to become a more serious weed species. If uncontrolled, it would probably form large monotypic mats which would shade out native submersed vegetation, increase organic sedimentation, decrease water quality and provide substrate for successional species.

MANAGEMENT OPTIONS

The cage-like arrangement of bristles on the upper surface of giant salvinia fronds (Figure 1) forms a waterproof barrier to herbicides (Hattingh 1961). In order to breach this barrier with contact herbicides, it is necessary to use a wetting agent. In Australia, repeated applications of paraquat (at an unspecified treatment rate, Miller and Pickering 1980) and a wetting agent have been used successfully to control giant salvinia. Glyphosate was reported to be ineffective in controlling giant salvinia by Mitchell (1979) and fluridone was also not effective (Wells et al. 1986). Diquat was reported by Mitchell (1979) as only one-eighth as effective on giant salvinia as paraquat, however. In Malaysia, diquat at 4.5 kg/ha was effective in controlling the plant (Kam-Wing and Furtado 1977). Individuals of the species were successfully reduced by hand removal and spraying remaining plants with herbicides such as diquat and 2,4-D along the edges of the Adelaide River, Australia (Miller and Pickering 1988). Thomas (1979) states that 2,4-D has been successfully employed to control giant salvinia in India, but he does not state the effective dosage.

In the laboratory, detergent has been shown to damage giant salvinia. Spraying the plant with a 0.05% aqueous solution of the household detergent LAS (linear alkyl benzene sulfonate) resulted in a decrease in total chlorophyll content of 85% and a decrease in total protein of 75%, 48 h after treatment (Chawla et al. 1989). Giant salvinia was more sensitive to LAS than were the other species tested, water lettuce, coontail (*Ceratophyllum demersum* L.), hydrilla (*Hydrilla verticillata* (L.f.) Royle), giant duckweed (*Spirodela polyrhiza* (L.) Schleid.), and common duckweed (*Lemna minor* L.) A mixture of detergent and kerosene developed in Australia and formulated as AF101, causes rapid toxicity to giant salvinia. It has been used to help control the plant, but early claims for its effectiveness were overstated (Thomas and Room 1986a).

Cook (1976) reported that manual control was successful in controlling 1500 ha of giant salvinia on an Indian hydroelectric reservoir. Thirty men removed about half of the infestation over a three-month period and it required annual repetition to maintain acceptable levels of control (Murphy 1988). In the Adelaide River, Australia, hand removal and erection of nets at the water's surface were used in the management of giant salvinia (Miller and Pickering 1980). Typically, floating booms and wire nets have some value in confining giant salvinia and maintaining adjacent waters weed-free, but booms are subject to breakage under the pressure of large windblown mats (Thomas 1976). Booms slung on 5-cm diameter steel cables have been known to break, and anchor points on the banks are pulled out (Thomas and Room 1986a).

Economic constraints are the main reason for a general inadequacy of mechanical control measures (Thomas and Room 1986a). Manual removal is only practical in the early stages of invasion. After the plant is established, biomass to about 80 tonnes/ha and rapid regrowth make harvesting and hand removal impractical. In Australia, even in winter, the regrowth of large infestations exceeded the removal capacity of harvesting machines. Mechanical harvesting is not cost-competitive with chemical control (Thomas and Room 1986a).

Reducing the concentration of nutrients in a waterbody may help slow the growth of giant salvinia. Cary and Weerts (1983a and 1983b) found that in laboratory tests, the plant grew most rapidly in high concentrations of nitrogen and phosphorus (2-20 mg N l^{-1} and 2 mg PO_4-P l^{-1}), however, the species can grow in concentrations as low as 0.02 mg N l^{-1} and 0.02 mg PO_4-P l^{-1}.

The salvinia weevil (*Cyrtobagus salviniae*) has been used to control giant salvinia in several parts of the world. In India, South Africa, and Botswana, in waterways where the weevils have been introduced, the plant has been reduced to about 1% of its former area (Room 1986a, Creagh 1991/1992, Cilliers 1991). The most dramatic control by *C. affinis* was in the Sepik River, Papua New Guinea, where 250 km^2 of the plant were reduced to 3 km^2 in 1.5 yr (Thomas and Room 1986b). However, in Australia's tropical Northern Territory, high water temperatures in seasonal waterbodies have been associated with a failure of the weevil to control giant salvinia. In areas such as New South Wales, Australia, control by the weevil has been variable, since the cooler climate is also not favorable for the insect. Insect damage to giant salvinia generally increases as water temperature increases from 16 to 30C (Forno and Bourne 1986). Because much of Florida's climate is similar to New South Wales, it is uncertain how well the salvinia weevil could control the plant. Room (1990) reportedly collected this species on common salvinia in Florida.

Feeding and larval damage by the salvinia weevil also depends on levels of nitrogen in the plant. Insects in Sri Lanka were distributed to most lowland areas in 1987 (Room et al. 1989) and establishment occurred at all sites, but increase in numbers of the weevil was low due to low levels of nitrogen in giant salvinia tissue until the end of a drought. In 1988, after water and nitrogen levels increased, major infestations of giant salvinia were destroyed by the insect.

An aquatic grasshopper (*Paulinia acuminata* De Geer), has been evaluated as a possible biocontrol of giant salvinia (Sands and Kassulke 1986). Adults and nymphs fed on giant salvinia, water lettuce, and azolla (*Azolla* sp.) and adults heavily damaged strawberry (*Fragaria* x *ananassa* Duchesne), but oviposition did not take place and the life cycle was only completed on the three former aquatic plants. This grasshopper is of questionable value as a biocontrol because it is not monophagic and because it has not been conclusively shown to control giant salvinia.

The pyralid moth (*Samea multiplicalis* Guenee) and the salvinia weevil have been released for the biological control of giant salvinia in northeastern Australia (Forno 1987). Although the weevil was successful at destroying large areas of the plant, the moth did not reduce plant growth permanently at any site. (However, it is common for biocontrol organisms and their food plants to undergo cycles of varying abundance). Of the insects tested to date, only the salvinia weevil has proven effective in controlling giant salvinia (Room 1986b).

The grass carp (*Ctenopharyngodon idella* Val.) is a possible biological control agent for giant salvinia. In Indonesian ponds, it feeds on rhizomes and leaves of the species and can inhibit the plant's growth (Soewardi and Muchsin 1977).

Stress factors such as falling water levels or flooding damage to giant salvinia apparently contribute to biological control of the plant (Toerien et al. 1983). Successful control by the salvinia weevil might only be feasible where the plant's growth is severely limited or stressed by one or more environmental factors.

Giant salvinia remains one of the most serious plant management problems in the world. It is expected to enter the U.S. and cover large areas of aquatic systems unless it is continually excluded.

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