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Development of an Integrated Pest Management Approach for Controlling Giant Salvinia Using Herbicides and Insects

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PURPOSE

This bulletin outlines a general approach for developing integrated pest management (IPM) techniques and procedures to control the invasive free-floating plant giant salvinia (*Salvinia molesta* D. S. Mitchell) (Figures 1 and 2) using herbicides and the giant salvinia weevil (*Cyrtobagous salviniae* Calder and Sands).

BACKGROUND

Giant salvinia is a free-floating, mat-forming aquatic fern native to southeastern Brazil (Forno and Harley 1979) that has become invasive in many parts of the world. Giant salvinia was first detected in the United States in the 1990s and has since become problematic in water bodies throughout the southeastern United States, as well as Puerto Rico and Hawaii. Giant salvinia dominates coves and quiescent bays where dense infestations disrupt transportation, hinder irrigation, threaten desirable native plant communities, and increase mosquito breeding habitat (Oliver 1993; Jacono 1999; Jacono and Pitman 2001; Nelson et al. 2001; McFarland et al. 2004). It is estimated that under optimal growth conditions, giant salvinia can double every 36 to 53 hr (Cary and Weerts 1983; Johnson et al. 2010). The plant was first reported in the United States in 1995 as an established population in a small pond in South Carolina before later being eradicated (Johnson 1995). Plants were then observed in 1997 in a Houston, Texas pond, followed by infestations in Toledo Bend Reservoir in 1998 (Owens et al. 2004). By 2004, giant salvinia was reported in four reservoirs, five rivers (or streams), and 20 ponds in Texas (Owens et al. 2004). Although an estimate of current total acreage in Texas is not available, 17 major water bodies are confirmed

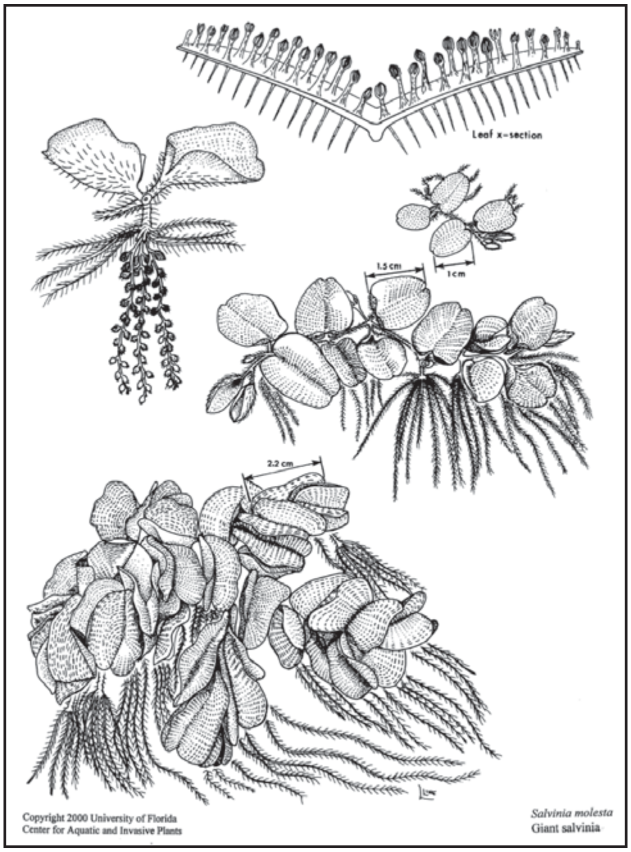

Figure 1. Morphology of giant salvinia (*Salvinia molesta* D. S. Mitchell). Permission to reprint granted by University of Florida, Center for Aquatic and Invasive Plants (2000).

Figure 2. Tertiary growth stage of giant salvinia.

to be infested by giant salvinia.[1] In 1999, an initial infestation in Louisiana estimated to be < 400 acres expanded to > 70,000 acres in 20 lakes, 7 bayous or rivers, the Atchafalaya Basin, the Red River, and the coastal fresh water marsh from Lafitte to Morgan City (Johnson et al. 2010).

Giant salvinia (Figure 3) can be difficult to control using conventional management methods including both herbicides and biocontrol techniques. Individually, herbicides[2] and weevils (Flores and Carlson 2006) have demonstrated the capacity, in some situations, to temporarily provide control of plant populations scattered throughout the southern regions of the United States. However, new giant salvinia infestations are reported each year and the cost to manage this plant continues to increase.

Various reasons account for failure to eradicate giant salvinia. For example, chemical applications are hindered by the size of the infestation, thickness of the plant mat, cost of application, and the number of herbicide applications needed to effectively manage this plant. Giant salvinia weevil success has been hampered by limited insect distribution, minimal large-scale releases, and limited overwintering of the biocontrol agent in more temperate climates. It is clear that a new, more effective management model is needed to improve long-term control of giant salvinia.

Figure 3. Dense infestation of giant salvinia in a Louisiana lake.

To develop an effective IPM technique against giant salvinia, several key questions need to be investigated, including: 1) impact of herbicides on weevil feeding with respect to palatability, nutrient availability, and reproduction; 2) optimal herbicide application rates in combination with weevil stocking rates; and 3) efficiency of these treatment techniques in combination versus each individually with respect to cost, efficacy, and speed of control.

CHEMICAL CONTROL METHODS

Giant salvinia has been managed using chemical, biological, mechanical, and physical control methods (Madsen and Wersal 2009), with chemical and biological methods being more widely used in the United States. Herbicides such as carfentrazone, diquat (6,7-dihydrodipyrido[1,2-α:2',1'c] pyrazinediium ion), glyphosate (N-(phosphonomethyl glycine), and penoxsulam (2-(2,2-difluoroethoxy)-6-(trifluoromethyl)-N-(5,8-dimethoxy[1,2,4]triazolo-[1,5c]pyrimidin-2-yl)-benzenesulfonamide) have been successfully used for management of this floating plant species (Glomski and Getsinger 2006, Nelson et al. 2007, Madsen and Wersal 2009, Mudge et al. 2010). When applied to smaller or less dense populations of giant salvinia, herbicide treatments can selectively and precisely target the weed species while providing rapid control. Surfactants are typically used in combination with foliar-applied herbicides. Surfactants are substances that improve the emulsifying, dispersing, spreading, and wetting processes, as well as increasing the spray coverage on the foliage to aid in herbicide uptake by the plant (Ferrell et al. 2008).

Since the inception of chemical control of giant salvinia, herbicides have traditionally been applied as foliar applications with moderate to good success (Figure 4), but chemical contact with all frond surfaces can be difficult, and repeated applications are often required to prevent re-growth. The small size of giant salvinia makes treatment with foliar-applied herbicides difficult, as plants form dense vegetative mats up to 1 m thick, sheltering plants from surface-sprayed herbicide applications (Thayer and Haller 1985, Thomas and Room 1986). In addition, the upper surface of each floating frond is covered by rows of white, bristly hairs

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[1] Personal communication. 2010. H. Elder, Aquatic Habitat Biologist, Texas Parks and Wildlife Department, Jasper, TX 75951.

[2] Personal communication. 2010. A.J. Perret, Aquatic Plant Control Coordinator, Inland Fisheries, Louisiana Department of Wildlife and Fisheries, Baton Rouge, LA 70808.

(trichomes), topped with four branches united distally to form a structure resembling an "eggbeater" (McFarland et al. 2004) (Figure 5). Subsurface injection techniques are currently being evaluated to increase plant uptake of herbicides via submersed fronds and under fronds in an effort to achieve more complete control. Giant salvinia exposed to penoxsulam at 20 µg active ingredient (a.i.) L^{-1} for 16 wk provided 100% control (Mudge et al. 2010). Unfortunately, the extended herbicide exposure requirements and associated costs of treating the entire water column may hinder the success of this application technique.

BIOLOGICAL CONTROL METHODS

Although herbicide programs have increased over the past few years, giant salvinia infestations have continued to increase in number and size (Sanders et al. 2010). In an effort to combat this problematic weed, efforts to rear, harvest, and release biological control agents have expanded in recent years (Harms et al. 2009; Sanders et al. 2010). The giant salvinia weevil (Figure 6), originally occurring in southeastern Brazil, Bolivia, Paraguay, and northern Argentina (Wibmer and O'Brien 1986, Calder and Sands 1985), was first released in the United States in 2001, at sites in Louisiana and Texas for the management of giant salvinia, with a subsequent reduction in plant populations observed at release sites (Tipping 2004, Tipping et al. 2008). Successful management of giant salvinia to the point where it is no longer considered a problem has also been achieved in Zimbabwe, South Africa, Senegal, Mauritania and India, often within two years after initial stocking (Jayanth 1987, Cilliers 1991, Diop and Hill 2009, Chikwenhere and Keswani 1997, Pieterse et al. 2003). Adult weevils, averaging 2.5 mm in length, are sub-aquatic in nature and can be spotted on or under fronds, within buds, or among the root-like modified leaves of giant salvinia plants (Johnson et al. 2010). Although young larvae spend periods feeding externally on the roots and buds before tunneling into the rhizome (Forno et al. 1983), the mobility of the immature stages is unknown. Adult weevils can disperse from stocking sites, but only do so when the local food supply is exhausted (Room and Thomas 1985). Although both larvae and adults damage giant salvinia plants, the larval stage provides a greater impact by tunneling within the stolons (Julien et al. 1987).

Figure 4. Aquatic herbicide application in Louisiana.

Figure 5. Giant salvinia trichomes or "eggbeater"-like structures located on the upper surface of each floating frond.

Figure 6. Giant salvinia weevil (*Cyrtobagous salviniae* Calder and Sands) on giant salvinia.

Despite the reported success of this biocontrol agent in other parts of the world, limited distribution of the weevil and minimal large-scale releases in the United States have likely hindered potential effectiveness in this country. In addition, severe winters can limit the increase and spread of weevil populations in the spring, and maintenance of populations may be necessary (Tipping et al. 2008). Adult weevils survive in areas where air temperatures range from 0 to 45°C (Room et al. 1984), but feeding increases as temperatures increase, especially above 20°C (Forno and Bourne 1985). Also, while mass rearing the giant salvinia has been examined and refined for efficiency, there are substantial upfront costs related to transporting/shipping the agents to the field (Harms et al. 2009). In fact, the costliest part of mass-rearing tends to be release-associated shipping costs. Despite this, there is the potential, once populations are established, to use release sites as nurseries and move weevils into new sites, thus decreasing associated transport costs.

IPM CONTROL METHODS

In order to maximize the potential of each control method, it seems prudent that true IPM techniques be employed using both chemical and biocontrol technologies. While information on the effectiveness of combining biological and chemical methods on giant salvinia is limited, numerous attempts using this approach have been made on other aquatic plant species (Nelson et al. 1998, Lindgren et al. 1999, Shabana et al. 2003) and IPM practices are common and often successful in agriculture and forestry (Chiras et al. 2002). The benefits of utilizing an IPM program include long-term sustainability of control as well as the flexibility to alter the management program based on field observations. For instance, in a biocontrol-herbicide IPM program, it may be necessary to spot-treat new infestations while allowing insect herbivore populations to grow and maintain low-priority weed populations.

In contrast to a management program focused on herbicides or biocontrol alone, IPM may be a more prudent approach, combining both chemical and biocontrol techniques to achieve rapid biomass reduction and long-term control of giant salvinia. Only minimal research has been conducted to determine the potential of an IPM approach combining herbicides and biological control agents for the management of aquatic plants, though examples do exist of combining chemical herbicides with mycoherbicides (Nelson et al. 1998). The aquatic herbicides 2,4-D ((2,4-dichlorophenoxy)acetic acid), fluridone (1-methyl-3-phenyl-5-[3-(trifluoromethyl)phenyl]-4(1H)-pyridinone), and triclopyr (3,5,6-trichloro-2-pyridinyloxyacetic acid) were used in combination with the endemic fungal pathogen *Mycoleptodiscus terrestris* (Mt) for control of hydrilla (*Hydrilla verticillata* (L.f.) Royle) and Eurasian watermilfoil (*Myriophyllum spicatum* L.) (Nelson et al. 1998; Nelson and Shearer 2005, 2008). This IPM approach was efficacious against these submersed weeds under controlled conditions and has shown promise for field use. Integrating a pathogen with herbicides for management of submersed vegetation is different than combining insects and herbicides. The pathogen Mt performs similar to a contact herbicide with little spread or drift from the site of infection (Shearer 1995). Unlike classical biological control, the pathogen is not expected to survive or to provide control beyond the growing season in which it is applied (Shearer 2002). In contrast, insects are expected to increase population size, overwinter, and continue feeding into the next growing season and beyond. Thus, an established insect population could continue to provide long-term and sustainable management of giant salvinia.

The floating plant water hyacinth (*Eichhornia crassipes* Solm) has been the subject of IPM discussion and research, and combinations of herbicides and insect herbivores have been evaluated for the control of the plant (Haag 1986, Haag and Habeck 1991, Center et al. 1999). Center et al. (1999) suggest that when biological control agents are present, water hyacinth colonies recover more slowly from the effects of other control measures, such as herbicides. In addition, combining pathogens and insect control agents has also been successful for controlling water hyacinth in Mexico where plants were completely eliminated from a small reservoir within three months of the IPM treatment (Martinez-Jimenez and Gomez-Balandra 2007).

Herbicides and insects can be incorporated into a plant management program in several ways, including treating biocontrol agent-infested plants with herbicide (Center et al. 1982) or treating a majority of the plant population, leaving untreated areas for biocontrol agent populations to persist and grow (Haag and Habeck 1991, Center et al. 1999). Many of the recently registered aquatic herbicides are considered to pose reduced risk. These newer chemistries are plant specific (no toxic impacts on animals), applied at very low use rates, and can be used selectively against target plants, minimizing damage to desirable vegetation. It would be beneficial to approach IPM of giant salvinia using these newer herbicides. New herbicides including flumioxazin[1] and penoxsulam (Richardson and Gardner 2007) are effective against giant salvinia; however, substantial regrowth may occur a few weeks after treatment if adequate coverage on foliage or concentration exposure time (CET) is not achieved. The moderately efficacious products will likely provide immediate injury (chlorosis and necrosis), but allow the weevil to continue feeding on the plants once the herbicide injury symptoms have subsided. Past studies (Mudge 2008 and 2009, unpublished data) have shown that some of these herbicides tend to be slightly less efficacious and slower in activity against non-surface matted infestations than the glyphosate plus diquat combination treatment commonly used in Louisiana and Texas, so they may lend themselves to combination with extant salvinia weevil populations. By choosing a slightly less efficacious set of herbicides, there is a likelihood of damage but not enough to result in total removal of plants (i.e. weevil food source). This will be important in trials in which the combined effects of herbicides and weevils are examined.

Foliar and subsurface herbicide applications can result in the desiccation or destruction of fronds and roots, but may also decrease plant nitrogen levels. Several unknown consequences of herbicide treatments in combination with weevil release need to be better understood in order to develop IPM approaches using this combination of techniques. The impact on weevil feeding preference, or frond and root palatability, may be immediately affected following a herbicide application, as was shown to be the case with the water hyacinth weevil (Pellisier 1989). The foliage and roots of treated plants may become undesirable to the insects following herbicide/surfactant application, and may decrease or deter feeding. The relationship between an insect and its host plant is primarily nutritional (Andres 1982). Consequently, herbicides may induce changes in host plant nutrient concentration and quality that can be either favorable or detrimental to an insect species (Messersmith and Adkins 1995). Herbicides may affect biosynthetic pathways for secondary plant metabolites that are feeding deterrents, attractants, or toxicants to insects (Campbell 1988). The herbicide penoxsulam, for example, inhibits acetolactate synthase (ALS) and prevents the production of the branched-chain amino acids isoleucine, leucine, and valine (LaRossa and Schloss 1984; Senseman 2007). In addition to a slow death due to the lack of key amino acids, it is unknown if the plants will be able to provide the nutrients and extractable compounds necessary for development or reproduction of the weevils.

The giant salvinia weevil can adapt to variations in nitrogen availability by having extremely long-lived (up to 60 days), almost sedentary adults with rapid fecundity response but little behavioral response to nitrogen levels (Forno and Bourne 1988). It has been found that while adult feeding does not appear to be influenced by nitrogen content of the plant tissue, larval feeding and development are affected by low nitrogen levels, thus increasing developmental times (Sands et al. 1983). In addition, nitrogen application (fertilization), either directly or indirectly, to the plants significantly increases the likelihood for establishment and initial population buildup of the weevil (Forno and Bourne 1985; Room and Thomas 1985), implying that high nitrogen levels are important to newly established weevil populations. Nitrogen levels may also be important to the reproductive maturity of females because ovary functionality and fecundity most likely increase with increasing nitrogen content in host plants, as demonstrated for water hyacinth weevils (Center and Dray 2010).

As herbicide-treated plants sink and die, weevils will eventually be forced to move to untreated plants or harborage. The amount of time available before the plants begin to sink will depend on the type of herbicide applied. Systemic herbicides will either growth-regulate the plant or slowly kill the plant over several weeks. Either scenario will likely provide the weevil adequate time to move to an untreated area; however, contact herbicides kill quickly, providing immediate control within a few days after application. Plant

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[1] Personal communication. 2010. L. S. Nelson, Program Manager, U.S. Army Engineer Research and Development Center, Vicksburg, MS 39180.

colonies that are a single layer thick will likely receive excellent herbicide coverage and the entire population will quickly become chlorotic and/or necrotic. In these cases, the weevils will have minimal time to find refugia before the plants lose buoyancy and sink.

The Louisiana Department of Wildlife and Fisheries (LDWF) began using weevils throughout the state in 2008 and positive results are now evident.[1] However, herbicides still constitute at least 90% of LDWF management efforts. It has been suggested that integrating biological control agents into a predominantly herbicide-dominated plant management program could be successful if, during application of herbicide, "pockets" of plants were left untreated to serve as refugia for existing biocontrol agent populations (Haag and Habeck 1991, Center et al. 1999). For the relatively mobile water hyacinth weevils, *Neochetina* spp., adult insects are able to move from treated plants to healthier plants, thus concentrating weevil densities in the untreated areas (Haag and Habeck 1991). Larvae, on the other hand, likely die because they are not able to escape damaged plants. Therefore, it has been recommended that, in addition to leaving untreated harborage, herbicide application should take place when the ratio of adults to larvae/pupae is high and when a high proportion of the females are in a high state of reproduction (Grodowitz and Cofrancesco 1990). How successful this type of management strategy would be with the relatively slow-dispersing giant salvinia weevil remains unknown. It is unclear whether the giant salvinia weevil would be able to move from injured/dying plants to fresh/healthy material before tissue collapse. Although the adults are able to disperse, albeit slowly, there is no evidence that larvae are able to move from treated plants.

Research to determine stocking rates of giant salvinia weevils is limited, but it is generally accepted that approximately 300 adult weevils per square meter is a sufficient density to provide control of giant salvinia (Room 1988). An initial weevil population of a few thousand in Australia successfully controlled giant salvinia when the weevil population grew and destroyed over 27,000 metric tons of salvinia in one year (Room 1990). Integrating biological and chemical weed control practices might result in decreasing the weevil stocking rate and/or decreasing the herbicide use rates. Levels of each management technique will need to be manipulated to determine the lowest and most successful combination. Lower stocking and herbicide rates could lead to less expensive and more efficient giant salvinia control.

Weevil population dynamics in relation to herbicide application timing will be an important component of developing an IPM approach. It is unknown if the integration of these management techniques should be in sequence or staggered. Herbicide application, followed by weevil stocking a few weeks after treatment and plant regrowth, allows the biocontrol agent to feed on any new healthy tissue. Conversely, by introducing weevils first, the biocontrol agent can decrease the plant stand, with herbicides removing remaining biomass. The later technique benefits the herbicide, as there will be less biomass present when plants are sprayed. Currently, if giant salvinia is managed with weevils, land managers use chemical maintenance control to eliminate any lingering plant populations. Regardless of when herbicides are applied, it seems prudent to spray when the insect population is high and reproductive health is good. This will allow a higher population of adults to be present, and a greater chance for their survival and movement to other sites.

FUTURE WORK

Evaluations will be conducted at the U.S. Army Engineer Research and Development Center, Vicksburg, MS in a tiered approach utilizing environmental growth chambers, greenhouses, and outdoor mesocosms. The objective of these evaluations will be to determine the compatibility of selected aquatic herbicides and the giant salvinia weevil when applied in an integrated fashion to control giant salvinia.

Herbicides that provide partial control (ca. 25 to 75%) of giant salvinia when used at low rates will be combined with the weevil. The focus will involve evaluations of the newer reduced-risk herbicides, such as bispyribac-sodium, flumioxazin, imazamox, and penoxsulam, which have been recently registered or received experimental use permits (EUPs) by the U.S. Environmental Protection Agency (USEPA) for use in aquatic sites. These newer chemistries are plant-specific, applied at very low use rates (g a.i. ha^{-1}) and

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[1] Personal communication. 2010. A. J. Perret, Aquatic Plant Control Coordinator, Inland Fisheries, Louisiana Department of Wildlife and Fisheries, Baton Rouge, LA 70808.

concentrations (µg a.i. L^{-1}), and can be used selectively against target plants, minimizing damage to desirable vegetation. Herbicides will be applied as foliar and subsurface applications at selected rates and concentrations, respectively, along with various insect stocking densities to determine the proper balance of the two management techniques required for optimal IPM practices. An approved aquatic surfactant will also be used to enhance herbicide uptake by the giant salvinia.

Other parameters to be evaluated include a) timing of herbicide application with respect to weevil stocking; b) treating entire plant stands versus treating a portion of the stand to determine impact on insect movement from treated to untreated plants; and c) examining impact to weevil reproductive development. Pre- and post-treatment response variables evaluated will include: 1) plant biomass data, 2) chlorophyll analysis to determine plant health, 3) visual percent control evaluations, and 4) insect population estimates.

If combinations of weevils and herbicides are determined to be an effective IPM tool for controlling giant salvinia, a number of benefits will be derived: a) reduction in overall treatment costs, b) minimal post-treatment plant recovery and longer-term plant eradication, c) maintenance of sustainable weevil populations reducing need for additional stocking, and d) limited herbicide treatments to manage lingering populations of giant salvinia.

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