Salvinia molesta D.S. Mitchell – salvinia

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ABSTRACT

Salvinia molesta, salvinia, is a sterile floating fern that has spread to most tropical and sub-tropical countries. Rapid growth rates allow it to blanket still or slow moving water bodies very quickly, causing environmental, sociological and economic problems. A small, black weevil, *Cyrtobagous salviniae*, from Brazil that is specialised on *Salvinia* species, was released in Australia in 1980 on Lake Moondarra, Mount Isa, and provided extraordinary control of the weed within 15 months. Thereafter releases elsewhere in Australia and in Papua New Guinea, Sri Lanka and many other countries resulted in extremely high levels of control, mostly within 3 years. There are situations where the weevil is not effective such us on multi-layered salvinia mats or when it grows as an understory plant, but integrated management strategies that including biological control can overcome these restrictions. Recent studies have confirmed the value of this agent in temperate regions. Other control methods for salvinia are impractical, ineffective and costly, whereas biological control has provided long-term, sustainable management with very positive benefit to cost ratio estimates from 11 to 53:1 in monetary terms. The control of salvinia by the salvinia weevil is a classic contemporary example of the benefits of biological control of weeds

Key words: biological control, *Cyrtobagous salviniae, Samea multiplicalis, Paulinia acuminata*, benefit:cost,

INTRODUCTION

Salvinia molesta DS Mitchell (Salviniaceae), salvinia (Figure 1), is a floating aquatic fern. It has a pair of floating leaves at each node and a submerged leaf that is modified to act as a root. Amongst the filamentous roots hang sporocarps, however salvinia is a sterile pentaploid (chromosome number of 45) and no viable spores are produced. Population increase is by growth and fragmentation. Dispersal is mediated by downstream flow and wind, and by the movement on birds and animals of viable fragments, that is, nodes. It has been spread by man around the world as an ornamental and aquaria plant or contaminant of other plant shipments (Julien *et al.* 2009; Room and Julien 1995).

There is considerable morphological variation determined by age, crowding and available nutrients. Three forms were described (Mitchell and Tur 1975), but there is continuity of growth between them. The primary and secondary forms have leaves nearly flat on the water's surface, space between leaves and occur during early colonisation. The tertiary form (Figure 1) occurs when plants are crowded and the leaves become folded and upright (Julien *et al.* 2009; Room and Julien 1995).

Salvinia is native to south-eastern Brazil (Forno and Harley 1979), is widespread throughout the tropical world and was first recorded in Australia at Ludenham, NSW in 1952 and Bulimba Creek, Brisbane, QLD in 1953. The history of its distribution, world wide and in Australia was outlined in Room and Julien (1995). By the 1970s it had become a serious widespread weed and it now occurs in water ways from the NT (rivers near Darwin, Kakadu National Park, Nhulunbuy), QLD (Cairns to Brisbane including Atherton Tablelands and Lake Moondarra near Mt Isa) and NSW south to Sydney (Figure 2). It has been recorded from many locations south of Sydney in NSW, VIC and WA but because of low temperatures it is much less problematic and populations may not persist.

Salvinia grows best in still or slow moving water, can survive low nutrient levels, but rapidly takes up nutrients when they become available, for example, during increased flows. It has very rapid growth rates (double its number and dry weight in less than three days) under optimum conditions (tropical temperatures and unlimited nutrients) (Room 1986) and forms dense mats (Figure 3) that can be several layers of plants deep blanketing the surface of water. In Kakadu National Park dry weights doubled in 5 to 30 days (Storrs and Julien 1996) and on Lake Kariba, Zimbabwe, ramet numbers doubled in 9 to 17 days (Mitchell and Tur 1975). The range in durations was likely due to nutrient availability and temperature changes over time.

Salvinia has been used as a biological weapon to damage fisheries in Papua New Guinea (Gewertz 1983).

Details of its taxonomic relationships, biology, ecology, distribution, pest status and impacts can be found in Julien *et al*. (2009), Room and Julien (1995) and van Oosterhout *et al.* (2006) and references cited therein.

BIOLOGICAL CONTROL HISTORY

The first surveys for biological control agents for salvinia were conducted in the native range of *S. auriculata*, including Trinidad, British Guiana, and Brazil, during 1961 to 1963 (Bennett 1966; 1975). Of 25 phytophagous insect species found on the *S. auriculata* complex (Bennett 1975) three species, a curculionid weevil *Cyrtobagous singularis* Hustache, and pyralid moth *Samea multiplicalis* (Guenée) and a grasshopper *Paulinia acuminata* (De Geer), were selected for further study. Host specificity studies were conducted at Belem, Brazil and Curepe, Trinidad during 1964 to 1965 (Bennett 1966).

Cyrtobagous singularis, a small black weevil 2 mm long, has been collected from species in the *S. auriculata* complex from Brazil, Trinidad, Guyana, Paraguay and northern Argentina and from *S. oblongata* Mart. in Brazil (Bennet 1966; 1975). It was released in 1971 in Botswana and Zambia and established (Julien and Griffiths 1998), and spread to the Caprivi Strip of Namibia and to Zimbabwe. It was released in Fiji (1979) and established there (Julien *et al*. 2009). Its biology is described by Bennett (1966) and feeding behaviour by Sands and Schotz (1985). It has not contributed to control of *S. molesta*.

The moth *S. multiplicalis* has been collected from species in the *S. auriculata* complex in Trinidad, Argentina, Guyana, Brazil, Uruguay, Florida USA and Panama (Bennett 1966; Forno 1981). It was released in Zambia during 1970 and Botswana in 1972 but did not establish at either places. Releases in Fiji in 1976 resulted in establishment but no control of the weed. Though common in USA it was not deliberately released there and it provided no control of salvinia (Julien *et al*. 2009).

The grasshopper *P. acuminata* occurs widely in South America and following releases it established in Zimbabwe (1969), Zambia (1970), Botswana (1975), Sri Lanka (1973), India (1974), Fiji (1975), and but failed to establish in Kenya after releases in 1970. It wasn’t released but occurs in Mozambique, downstream from

Zambia and Zimbabwe. With the possible exception of the decline of salvinia on Lake Kariba in 1973, *P. acuminata* was not considered an effect biological control agent (Julien *et al*. 2009). Salvinia declined markedly four years after *P. acuminata* was released on Lake Kariba. Other factors contributed to that decline and it was not clear how much could be attributed to damage caused by the grasshopper (Mitchell and Rose 1979; Marshall and Junor 1981).

EXPLORATION

Before 1978 *S. molesta* was known only from outside South America. Since it was sterile and had the characteristic egg-beater shaped hairs on the upper leaf surfaces (see Julien *et al*. 2009), like other species in the *S. auriculata* complex, it was considered a hybrid of species from that complex, but without a native range (Mitchell 1972; 1978). Wendy Forno, CSIRO, based in Curitiba, Brazil from January 1978 to March 1982, to survey for potential biological control agents for salvinia found the native range of *S. molesta* within the latitudes 24°05'S and 32°05'S in south-eastern Brazil (Forno and Harley 1979). This knowledge permitted targeted surveys on salvinia in its native range which lead to the discovery of the salvinia weevil *Cyrtobagous salviniae* Calder & Sands that has been so important in the control of salvinia worldwide.

Surveys by Forno on species in the *S. auriculata* complex were conducted in Trinidad, Venezuela, Guyana, Brazil, Uruguay, Paraguay and Argentina. The natural enemies found, 31 insect and mite species, including those found by Bennett (1966) during earlier surveys were listed by Forno and Bourne (1984). Three of these were imported into Australia for study in quarantine at CSIRO Brisbane; the weevil *C. salviniae* (imported as *C. singularis*) the moth *S. multiplicalis* and the grasshopper *P. acuminata*. The first two were subsequently released in Australia.

CANDIDATES

Agents released in Australia

***Cyrtobagous salviniae* Calder & Sands (Coleoptera: Curculionidae).** Adults of this small (2 mm), black, long-snouted weevil (Figure 4) were very similar in appearance to adults of *C. singularis*. Calder and Sands (1985) described the adult and May and Sands (1986) described the larvae. When it was first collected from salvinia in south eastern Brazil it was thought to be *C. singularis*; a biotype adapted to *S. molesta* (Forno *et al*. 1983). It was only after it had been released in Australia that detailed comparative studies determined that it was a new, undescribed species, later to be named *C. salviniae* (Calder and Sands 1985). The comparisons showed why this species, which fed on buds and internal tissues and had higher rates of increase, became an effective agent while *C. singularis*, which fed externally and not on buds, did not (Sands and Schotz 1985; Sands *et al*. 1986).

C. salviniae was found on all species in the *S. auriculata* complex in South America. The material introduced into Australia was collected from salvinia at a site (26°3'S) near Joinville, Santa Catarina Province, Brazil. Host testing determined that it was specific to species in the *S. auriculata* complex (Forno *et al*. 1983). The biology and ecology of *C. salvinia* were presented in Forno *et al*. (1983), Sands *et al*. (1983), Forno and Bourne (1984), Sands *et al.* (1986), Julien *et al*. (1987), Room and Thomas (1985), Schotz and Sands (1988) and Hennecke and Postle (2006) and summarised in Julien *et al*. (2009). Some literature that was published before *C. salviniae* was recognized as a new species refers to *C. singularis* when the information actually refers to *C. salviniae*, e.g., Forno *et al*. (1983) and Room *et al.* (1981).

The first releases of the salvinia weevil as a biological control agent were at Lake Moondarra, Mount Isa, Australia in June 1980. Lake Moondarra had a 400 hectare mat of salvinia, weighting >50,000 tonnes fresh weight. The damage caused by the huge population of weevils that developed following release resulted in spectacular destruction of the mat within 15 months, reducing it to less than one tonne (Room *et al*. 1981) (Figure 5). Similar successes were repeated on impoundments, billabongs, rivers, creeks and dams throughout tropical and sub-tropical Australia (Forno 1987; Room and Julien 1995; Storrs and Julien 1996). Biological control of salvinia in temperate areas of Australia took longer than in tropical areas but was successful in coastal catchments in central NSW (Julien *et al.* 2009; Sullivan *et al.* unpublished). C. *salviniae* has been released on salvinia in at least 20 other countries with good to

excellent control occurring in one to five years in the 17 countries where the outcomes were known (Julien *et al*. 2009). The Australian research that lead to these successes was recognised with awards including; the 1985 UNESCO Science Prize (team), the AIDAB (now Ausaid) 1988 Award for Excellence in Overseas Development (team) and the 1991 CSIRO Chairman's Medal (team leader Peter Room).

***Samea multiplicata* (Guenée) (Lepidoptera: Pyralidae).** This moth had tan colouration with darker marking on the wings (Figure 6) and forewing length was 6.5 to 10.5 mm (Sands and Kassulke 1984). Eggs were laid singly among leaf hairs. Larvae had 5 to 7, usually 6, instars that fed on leaves under a canopy of silk and leaf hairs. When older larvae tunnelled through tertiary form salvinia they cause a 'shot hole' effect. When larvae were numerous they destroyed most leaves and the salvinia looked very ragged. Pupation occurred in a silk cocoon attached to a leaf. The life cycle took 50 to 60 days and development was influenced by host plant nutrition (Taylor and Sands 1986; Tayor 1984). The biology and host range of this moth was described by Bennett (1966), Khopf and Habeck (1976), DeLoach *et al*. (1979) and Sands and Kassulke (1984). Its main hosts included *S. molesta, Salvinia minima* Baker, *Pistia stratiotes* L. (Araceae), *Azolla caroliniana* Willd., and *Azolla pinnata* R. Br. (Azollaceae). It fed but could not complete development on *Lemna* species (Araceae) and *Eichhornia crassipes* (Mart.) Solms-Laub., (Pontederiaceae). It was heavily parasitised and predated upon in its native range (Bennett 1966) and has attracted parasites in Australia (Semple and Forno 1987). Though widely established on salvinia, it has rarely been found on *Pistia stratiotes* L., in the field in Australia (Waterhouse 1994).

The material imported, tested and released in Australia originated from Joinville, Santa Catarina State, Brazil. The first releases were at Mount Isa and Ingham, QLD, in January and February 1981 where it established. Dispersal was rapid and it caused considerable but patchy defoliation of salvinia. Although defoliation could be severe buds were not damaged and so plants continued to grow (Julien and Bourne 1988). In addition, *S. multiplicalis* adults sought undamaged plants for oviposition (Taylor and Forno 1987) and so there was no follow-up damage until the plants regenerated. *S. multiplicalis* has not contributed to control of salvinia in Australia.

Studied but not released in Australia

***Paulina acuminata* (De Geer) (Orthoptera: Pauliniidae).** The adults of this semi-aquatic, green and brown, grasshopper were 3-4 cm long and there were 5 or 6 nymphal stages. Population survival was dependant on high humidity. The biology and development were described by Sands and Kassulke (1986), Vieira and Adis (2000) and Thomas (1980). This grasshopper ate leaves of, preferably, the tertiary form of salvinia. Egg sacs were attached to leaves and life cycle development took 70 to 90 days. It completed development on a range of plants in Salviniaceae, Araceae and Hydrocharitaceae (Bennett 1966; Sands and Kassulke 1986; Vieira and Adis 2000).

A population of this grasshopper was imported into quarantine at Brisbane in March 1981 from Rio Guarguacu, Praia de Leste, Parana State, Brazil, where its biology and host specificity were studied (Sands and Kassulke 1986). The decision to release it was put off until the impacts of *C. salviniae* and *S. multiplicalis* were known. Following the success of the weevil in controlling salvinia no further consideration has been given to the release of *P. acuminata* in Australia.

DISCUSSION

The success of the salvinia weevil, *C. salviniae*, is a contemporary classic for biological control of weed because of the extraordinarily rapid (1 to 5 years) and high levels (up to 95% reduction in cover or biomass) of control of salvinia. It is a good example of the importance of knowing the native range of the weed. In this case new associations (biological control agents selected from other *Salvinia* species) were not useful, whereas, once the native range had been defined a useful agent was found. It is also an example of the importance of understanding each biological control agent. The useful agent, assumed to be *C. singularis*, was found to be a new species and named *C. salviniae*, with very important feeding and behaviour differences that lead to its controlling salvinia. Both of these were taxonomic issues that were solved by sound applied research; as part of exploration in the case of the native range of the weed (Forno and Harley 1979) and as part of post release studies in relation to insect taxonomy and behaviour (Sands and Schotz 1985; Sands *et al*. 1986).

Although the salvinia weevil had been successful in controlling salvinia in cooler climates in Australia in the 1980s, the technology was not taken up there (Julien *et al*. 2009). Salvinia infestations in temperate Australia at that time were small and

scattered and largely limited to small impoundments. It was easier to apply herbicides than to manage weevils and wait several years for control. It was not until a significant infestation occurred on the Hawkesbury River, north-west of Sydney that biological control was considered, and successfully implemented (Sullivan *et al*. unpublished), as part of a long term management strategy to maintain salvinia at low levels after huge amounts of biomass had been mechanically removed from the river (van Oosterhout *et al*. 2006). Concurrent studies have shown that oviposition by the salvinia weevil can adapt to cooler temperatures (Hennecke and Postle 2006).

The salvinia weevil could not develop large populations on multi-layered mats of salvinia (Storrs and Julien 1996). The reasons are likely to do with low host plant quality and the effects that this has on weevil population development (Room *et al*. 1984; Room and Thomas 1985). The adult weevils ate buds while larvae tunnelled in the stem and the amount of N available in these food sources regulated weevil population growth rates (Sands *et al*. 1986). Multi-layered salvinia tended to have low N content and therefore low growth rates, few buds and could support only low weevil numbers. Populations of the weevil increased most rapidly when numerous high quality buds were available. This occurred when salvinia grew rapidly in uncrowded situations and movement of assimilates concentrated N in the tips of the plants for bud development. Any activity, such as, strip application of herbicide physical control or downstream flushing, that removed part of the multi-layered mat stimulated rapid growth of salvinia and therefore population increase by *C. salviniae* that lead to control. Integrated strategies using herbicide and biological control have been used successfully in temperate regions (Sullivan *et al*. unpublished; G Popple, pers com. 2009), high altitude tropical areas (Forno 1987) and have been suggested for Magela Creek, Kakadu National Park, a tropical monsoon area where specific conditions can lead to very high biomass build-up on billabongs (Storrs and Julien 1996).

The salvinia weevil maintained populations on salvinia when it grew as an understory plant but failed to control the weed (Storrs and Julien 1996). Emergent plants on the fringes of water bodies or plants that used salvinia as a substrate may have helped to contain salvinia and so maintain weevil populations when all other salvinia was washed away. Those weevils could move to and control new salvinia growth on adjacent open water. Alternatively, non biological techniques could be used to remove the over-story plants to assist in the management of salvinia.

Following seasonal flushing of salvinia from water-bodies, re-colonisation may occur due to vector dispersal of propagules. The rapid growth of salvinia and the relatively low dispersal rate between catchments of the weevil has meant that mats of salvinia have developed quickly and covered water surfaces. To counteract this local and state government agencies have established rearing facilities to provide *C. salviniae* for use in their jurisdictions and to supply weevils to others on request (van Oosterhout *et al*. 2006). This has added considerable value to the biological control of salvinia while reducing the use of chemical and physical controls, methods that do not provide long-term solutions.

A study in Zimbabwe found that physical and chemical control of salvinia was less effective and more expensive than biological control, which provided a benefit to cost ratio of 10.6:1 (Chikwenhere and Keswani 1997). The *S. molesta* project in Australia cost AU$4.2 million over 11 years (1978 and 1993). An assessment of the combined cost of biological control of the three water weeds salvinia, *E. crassipes,* and *P. stratiotes* was AUD$5.1 (1974 to 1993), while the estimated combined benefit was 27.5:1 (Page and Lacey 2006). The value, in environmental restoration and protection, social and economic benefits, of transferring the salvinia weevil to many other countries continues to be enormous. In Sri Lanka the benefit to costs ratios for successful biological control of salvinia in the early 1980s was estimated to be 53:1 in financial terms and 1,671:1 in labour terms 1980s (Doeleman 1989).

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Figure 1. *Salvinia molesta*, salvinia, tertiary form (Photo M Julien CSIRO).

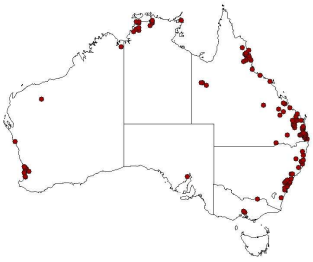

Figure 2. The distribution of *Salvinia molesta* in Australia. Specimen data reproduced from Australia's Virtual Herbarium with permission of the Council of Heads of Australasian Herbaria Inc.

Figure 3. *Salvinia molesta* covering a creek at Kaban, QLD Australia (Photo W Forno CSIRO).

Figure 4. ***Cyrtobagous salviniae*****, the salvinia weevil. (Photo M Julien CSIRO).**

Figure 5. Lake Moondara, Mount Isa, Australia, before and 15 months after release of the salvinia weevil. (Photos P Room CSIRO).

Figure 6. ***Samea multiplicalis*** **adult and larva. (Photos P Room CSIRO).**