Can Failure be Turned into Success for Biological Control of Mile-a-Minute Weed (*Mikania micrantha*)?

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Abstract

Research into biological control of *Mikania micrantha* Kunth (Asteraceae) started in 1978, concentrating on insect agents. Host specificity studies on the first agent, *Liothrips mikaniae* (Priesner) (Thysanoptera, Phlaeothripidae) from Trinidad were completed by 1982, and the thrips was released in the Solomon Islands in 1988 and, subsequently in Malaysia in 1990. Neither release led to establishment, and possible reasons for this are discussed, including the impact of generalist thrips predators and the effectiveness of different release strategies. Other insect natural enemies were considered worth evaluating for host specificity and effectiveness, but failure of the thrips discouraged further investment. A new initiative started in 1996, in collaboration with the Kerala Forestry Research Institute (India) and Viçosa University (Minas Gerais, Brazil), to assess the weed problem in the Western Ghats of India and to develop classical biological control based on exotic coevolved fungal pathogens as part of an IPM programme. A rust pathogen, *Puccinia spegazzinii* de Toni (Uredinales), has been selected as the prime candidate for introduction and a broad range of neotropical isolates is currently under glasshouse evaluation. The rust has demonstrated total specificity to *M. micrantha* (38 non-target species currently screened), is highly damaging (leaf, petiole and stem infections leading to cankering and death) and has a broad environmental tolerance. Progress on biological control of this and other weeds of developing countries is discussed in light of the availability and continuity of funding. Comparisons are drawn between the developed world where a long-term commitment with adequate funding is now generally recognised as necessary, and the developing world, where short-term donor funding makes long-term funding difficult or impossible to obtain. In future, those concerned with funding solutions to invasive weeds in developing countries need to recognise the long-term nature of this work.

Keywords: Biological control, *Mikania micrantha*, *Liothrips urichi*, *Puccinia spegazzinii*

The weed *Mikania micrantha* Kunth (Asteraceae) originates from Central and South America. It is a fast growing perennial creeping vine that colonizes agricultural land and badly damages tree crops and agroforestry / multipurpose trees in moist tropical forest zones of Asia, particularly South-east Asia (Choudhury 1972, Parker 1972, Holm *et al.*

1977, Muniappan and Viraktamath 1993, Waterhouse 1994).

Mikania micrantha was deliberately introduced into the Old World, probably on several occasions, some of which have been documented. Choudhury (1972) suggests that *M. micrantha* was present in Calcutta (presumably in the Botanical Gardens, via Kew Gardens) as early as 1918, and there is considerable anecdotal evidence concerning the introduction and use of *M. micrantha* in Assam as an airfield camouflage in World War II. Material from Paraguay was received by the Botanical Garden Bogor in 1949 and subsequently introduced as a ground cover for rubber plantations in 1956 (Wirjahardja 1976). Cock (1981) mentions a verbal communication that *M. micrantha* was introduced into the Philippines from Acapulco, Mexico, but we have not been able to substantiate this report. There are considered to be at least two biotypes in West Malaysia, one hairy and the other smooth, suggesting separate introductions. Without doubt, *M. micrantha* is variable in both the Old and the New World. Scientists of CABI Bioscience have been examining the DNA taxonomy of individuals from diverse localities in the Neotropical and Oriental Regions, and this will be reported at a later time.

The weed has a vigorous vegetative and sexual reproductive capacity (Swarmy and Ramakrishnan 1987), but cannot tolerate dense shade (Holm *et al.* 1977). Seeds are dispersed long distances by wind and the plant can grow vegetatively from very small sections of stem (Holm *et al.* 1977). Growth of young plants is extremely fast (8-9 cm in 24 hours; Choudhury 1972) and it will use trees and crops to support its growth; the weed rapidly forms a dense cover of entangled stems bearing many leaves (Holm *et al.* 1977). Areas freed from the weed can be recolonized within a fortnight (Choudhury 1972). Damage is caused to crops because the weed can smother, penetrate crowns, and even pull over plants. In tea plantations it seriously disrupts picking as it grows amongst the new tea shoots which are harvested. The weed also successfully competes for soil nutrients and sunlight. Finally, there is evidence from studies on rubber in Malaysia that the weed can retard plant growth probably through the production of allelopathic substances (Holm *et al.* 1977, Cronk and Fuller 1995).

Teoh *et al.* (1985) summarised research on the impact of *M. micrantha* in Malaysia and reported the results of a questionnaire survey on its distribution and impact. They report potential yield losses over the first 32 months of rubber production of 27-29% compared to a legume cover crop, and losses of 20% in the first five years of oil palm production. Over half the respondants to the questionnaire considered *M. micrantha* highly competitive in immature rubber, oil palm, cocoa and coconut, but in rubber and oil palm at least it was considered tolerable in mature plantings. About 5% of the total weed control costs in rubber and oil palm plantations were directly attributable to control of *M. micrantha*; in 1982 this amounted to about Malaysia $10-12 million.

The weed has been present in India since the early 1940s but since that time has dramatically increased its range within India. Tree crops and agroforestry / multipurpose trees particularly badly affected include plantains, tea, (Choudhury 1992, Parker 1972, Holm *et al.* 1977, Sen Sarma and Mishra 1986), bamboo (Nair 1988), reeds (for thatching), teak (Palit 1981) and eucalyptus. *M. micrantha* also affects subsistence crops grown in short rotation shifting agricultural systems in northeast India (Swarmy and Ramakrishnan 1987) and forest plantation and disturbed natural forest in northeast and southwest India (Choudhury 1992, Parker 1972, Palit 1981, Sen Sarma and Mishra 1986, Muniappan and Viraktamath 1993, Nair 1988). It has been observed recently invading national park ecosystems in Nepal and poses a threat to such habitats throughout the Old

World tropics.

Several methods of weed management have been considered and sometimes tried to keep *M. micrantha* populations in check. All of these methods have been developed for tree crops or forest trees grown in plantations; methods which are applicable for the control of the weed in more rural situations (for example, plots of land used by small scale farmers for agricultural purposes) do not seem to have been evaluated.

Attempts have been made to hand weed or to use slashing in plantations but this has been found to be ineffective and costly in labour terms (Sen Sarma and Mishra 1986, Muniappan and Viraktamath 1993). All the stems need to be destroyed because of the weed's ability to grow from even the tiniest fragments (Holm *et al.* 1977). Also, the creeping and climbing habits of *M. micrantha* enable it to penetrate into the crowns of bushes or trees where it is difficult to apply mechanical methods without damage to the crops.

The herbicides 2,4-D and paraquat have been tried against the weed in tea plantations but this has only been met with partial success because applications are uneconomical and sometimes unsafe because of the problems caused to young tea bushes and the flushes of tender buds (Choudhury 1972, Parker 1972, Sen Sarma and Mishra 1986, Muniapppan and Viraktamath 1993). Nevertheless, herbicides are routinely applied in tea plantations in Assam for control of *M. micrantha* despite problems with tainting of the tea (H.C. Evans and S.T. Murphy, unpublished observations). Both Choudhury (1972) and Palit (1981) report successful trials of 2,4-D against *M. micrantha* in plantations of the forest tree *Shorea robusta* in northern India. Again, there is no evidence that herbicides are used for the sustainable management of the weed in forest plantations in any part of India.

Mikania micrantha would seem to be an ideal target for classical biological control. Of particular significance, is the fact that none of the closely-related, indigenous *Mikania* spp. are weedy in South-east Asia, once the earlier erroneous reports and the taxonomic confusion had been analysed (Cock 1982a) – i.e. there is only one target species. Conversely, *M. micrantha* is highly invasive in Asia, but only a minor ruderal species in its neotropical native range (Barreto and Evans 1995). Thus, there is strong circumstantial evidence to suggest that coevolved natural enemies (probably specific to a single host taxon) play a significant role in regulating *Mikania* populations. Classical biological control is particularly suited to weed problems affecting a wide range of farming systems (including rural farmers) because it is cheap, environmentally safe, and self-sustaining.

Previous Attempts at Biological Control

In light of the problems which *M. micrantha* was causing in Asia and the Pacific, the UK Government Department for International Development (DFID; Overseas Development Administration at that time) funded CABI Bioscience (Commonwealth Institute of Biological Control at that time) to carry out a three year project based in Trinidad to survey and assess the natural enemies of *M. micrantha* in the Neotropical region. This project was carried out by the first author who intensively surveyed the insects associated with *M. micrantha* in Trinidad, and extensively surveyed in Colombia, Costa Rica, Ecuador, Panama, Peru and Venezuela (Cock 1982a). Pathogens were largely neglected in these surveys. Although several insects seemed potentially useful biological control agents, in the time and funding available only one could be screened for host specificity. *Liothrips mikaniae* (Priesner) was selected because:

- the congeneric *Liothrips urichi* Karny had successfully controlled *Clidemia hirta* (Linnaeus) D. Don (Melastomataceae) in Fiji;

- *L. mikaniae* is widespread in the Neotropics, and therefore is likely to be adapable to a wide range of habitats in the Old World;
- it attacks and damages the youngest leaves, and therefore likely to have substantial effect on the aggressive vegetative growth, which is the most weedy aspect of *M. micrantha*;
- it is heavily attacked by parasitoids, predators and entomopathogenic fungi in the Neotropics, and freed of these natural enemies should be more effective in the Old World. (Entomopathogenic fungi were not recorded by Cock (1982b) but the first author found an undescribed species of *Hirsutella* with characteristic sclerotia (Mitosporic fungi; identified by the third author) on field collections in Trinidad in 1988, which subsequently caused problems in the UK culture of *L. mikaniae* until it was eliminated).

Host-range screening was carried out using 37 test species: 3 *Mikania* spp., 13 other Asteraceae, and 21 further species from 15 other plant families. Although there was slight feeding on a few other species, *L. mikaniae* was shown to be host specific to *Mikania*, and would only feed on species closely related to *M. micrantha* within the genus *Mikania* (Cock 1982b). Thus, by the end of the three year project, one biological control agent was ready for use, and several others had been identified as having potential but had not been studied for host specificity. Fungi had not been studied except on a casual basis.

There followed a delay for six years until two initiatives to release *L. mikaniae* came to maturity, one in the Solomon Islands, and the other in west Malaysia.

Solomon Islands. Waterhouse and Norris (1987) rank *M. micrantha* as the second most serious weed in the South Pacific, second only to nutgrass, *Cyperus rotundus* ; it ranked amongst the top ten weeds in six South Pacific countries – Cook Islands, Fiji, Guam, Western Samoa, Solomon Islands and Vanuatu. Thus, following the initial research 1978-81, interest was high in the Pacific (e.g. Cock 1987) but there was no programme of release until the UK ODA funded an implementation project to release *Liothrips mikaniae* in the Solomon Islands in 1988-89. The following summary is taken from Greenwood and Mills (1989) and reports cited therein, and Williams *et al.* (1990).

Liothrips mikaniae was collected from Trinidad in January 1988, and established in third country quarantine at CABI Bioscience UK Centre (Ascot). Medium scale rearing techniques were developed, and a further 14 plant species of economic importance in the Solomon Islands were screened for host specificity. *L. mikaniae* was first imported into the Solomon Islands in August 1988, and a local culture set up. The culture did not thrive, and only two releases of a total of 57 mated females were made at one site on Guadalcanal on 19 October and 1 November 1988 (Tubutu, an oil palm plantation of SIPL – Solomon Islands Plantation Limited). Exceptional rainfall in November and December led to flooding of this site, and there was no sign of establishment in 1989. Accordingly a fresh collection was made in Trinidad in January and February 1989, and about 1,000 nymphs and pupae hand carried to the Solomon Islands at the end of February.

Half of these were then taken to the Lowlands Agricultural Research Station, Papua New Guinea, to establish a culture for further host range testing, and the other half were used to establish a culture in the Solomon Islands at the Dodo Creek Research Station, Solomon Islands. As far as we know, the culture in PNG failed; certainly no releases have been documented.

The new culture under Dr. C.T. Williams at Dodo Creek was initially very successful, and approximately 5,000 F1 were obtained, and releases made of young adults. In April-June 1989, 1,438 were released at a site near Dodo Creek, on a Lever Solomons Limited coconut plantation and 2,731 in another area at the original SIPL Tubutu site. The culture declined after this, but a further release of 221 was made into a thrips-proof field cage at the SIPL Tubutu site in November 1989, to eliminate the possibility of rapid dispersal from the release site causing failure to establish.

Monitoring of 1,000 young and 1,000 old leaves from a 3 x 3 m area was carried out at approximately fortnightly intervals from May until September. No recoveries were made at the Levers site, but thrips and damage were observed through to July at the SIPL Tubutu site. Thereafter no recoveries were made at either site, in spite of checks in October at the SIPL Tubutu site, and February 1990 at both sites when over 14,000 leaves were sampled from a 15 x 15 m area at both sites, and 1,000 leaves from the field cage. The field cage was removed in May 1990 by which date dry weather had caused partial die-back of the *M. micrantha*; a further 840 leaves were sampled without success.

It was concluded that the thrips had failed to become established, although annual checks should continue to be made.

West Malaysia. The rearing and release programme in Malaysia was organised and coordinated by by the Working Group on Biological Control of *Mikania micrantha* (WG-BCMM) which included scientists from the plantation industry, the Department of Agriculture, the Malaysian Agricultural Research and Development Institute, the ASEAN Plant Quarantine Centre and Training Institute and CABI Bioscience (the fourth author). Their achievements were reported by Teoh *et al.* (1985) and Liau *et al.* (1991, 1994) in conference proceedings not readily available outside Malaysia and unpublished internal reports. The programme is summarised here.

Some additional host range testing of *L. mikaniae* was completed in quarantine in Malaysia in 1990, and releases started later that year. Following some initial culture problems, improved culture methods were developed, and *L. mikaniae* was cultured in Malaysia from 1990 to 1992. Early on in this process it became apparent that plants of *M. micrantha* were variable and this could have an impact on the culture. In particular, plants could be characterised as glabrous or hairy; the culture proceeded well on the glabrous variety, but the thrips had great problems on the hairy variety, the nymphs getting stuck between and on the hairs. In 1991 a further problem arose when it was realised that the culture had become contaminated by a predatory thrips, *Xyloplothrips inquilinus* Priesner, and production of *L. mikaniae* plummeted from an average of over 600 adults per week to 20. The culture was painstakingly cleaned up and built up again, and production proved very effective, as can be seen from the release programme described below.

Releases were made from April 1991 until June 1992, and a total of 32,660 adults were released during this period. In the first phase from April 1990 until June 1991, 13,160 adults were released in 25 small batches of 99-1400 adults at five different sites. There was no evidence of establishment. These results were reported at the International Conference on Biological Control in Tropical Agriculture, Genting Highlands, Malaysia, in 1991, and the resulting discussion led to a new strategy of making a single large release and monitoring its fate closely.

This was done in 1992, when two releases of 18,000 and 1,500 adults were made in May and June respectively in a three year old oil palm replant at Tanuh Merah Estate, Negri Sembilan. These releases were made from 36 potted plants set out in a grid of four rows, approximately "two feet" (0.6 m) apart.

For the 1992 releases, samples were taken in April prior to release, and sweep net and pitfall samples taken following release. Vegetation was monitored using a ten pin point quadrat. Inspection and sample data showed that the population of *L. mikaniae* gradually disappeared, and after eight months it was concluded that it had failed to establish and there had been no impact on the vegetation.

The sweep net and pitfall traps also yielded data on natural enemies. Generalist predators such as spiders (Oxyopidae, Salticidae, Lycosidae), coccinellids, the predatory thrips, *X. inquilinus* and various ants were present. Some of the common predators were evaluated in the laboratory (Ooi 1993). The spiders, coccinellids and most of the ants did not feed on *L. mikaniae*. In contrast, *X. inquilinus* and one species of ant (?*Pheidole* sp.) fed readily on *L. mikaniae*. The ants were very efficient at removing adults, larvae and pupae, but less effective at finding and removing ova. *X. inquilinus*, on the other hand preferred ova as food.

It was concluded that the action of generalist predators, including certain ants and the predatory thrips, *X. inquilinus*, were responsible for the failure of *L. mikaniae* to become established in Malaysia.

A New Pathology Initiative with India

A pathology programme was initiated in 1996 for a project in the Western Ghats of India, funded by DFID and led by Dr. Sean T. Murphy (CABI Bioscience, UK) and Dr. K.V. Sankaran (Kerala Forest Research Institute [KFRI], India). *M. micrantha* has been an on-going problem for some decades in North-east India (Choudhury 1972, Parker 1972), but it appears to have arrived only recently in the Western Ghats where it now poses an actual and potential threat to forest ecosystems (Muniappan and Viraktamath 1993). The project, as well as monitoring the spread of the weed and its socio-economic impact on subsistence agriculture at the forest interface, also aims to evaluate the potential of both local pathogens as mycoherbicides, and neotropical, co-evolved pathogens as classical biological control agents.

Pathogens already present in India include *Cercospora mikaniicola* Stevens which was recorded on seedlings of *M. micrantha* in Kerala State. This species had previously been reported from Malaysia as an aggressive pathogen of *M. "scandens"* (= *M. micrantha* fide Parker 1972), which was originally used as a cover crop in rubber and oil palm plantations (Thompson 1939, Evans 1987). Slow growth and poor sporulation in culture, however, does not permit the exploitation of this fungus as a mycoherbicide and other fungi are currently being evaluated at KFRI (e.g. *Myrothecium roridum* Tode and *Corynespora cassiicola* (Berk. & M.A. Curtis) C.T. Wei), but with limited success.

The main thrust of the pathology component of the project has been towards a classical approach. On the basis of herbarium and literature surveys, Evans (1987) concluded that two neotropical rust species, *Endophylloides portoricensis* Whetzel & Olive and *Puccinia spegazzinii* de Toni, appeared to offer the most potential as classical biological control agents of *M. micrantha* since they are restricted to the Neotropics and cause significant host damage. The biocontrol potential of *P. spegazzinii* was further emphasised following field surveys in Brazil (Barreto and Evans 1995), when the rust was observed infecting both old and young leaves, as well as petioles, leading to premature senescence. Although a number of other damaging leaf pathogens were recorded during these surveys, it was considered that defoliation alone of a vigorous climbing plant, such as *M. micran-*

tha, would not be sufficient for long-term sustainable control. This is well illustrated by the lack of overall impact of *C. mikaniicola* on this host in both India and Malaysia, even though in certain months of the year it appears to be causing serious damage. As shown above, it was first implicated as a disease of agricultural significance (Thompson 1939), at a time when *M. micrantha* was considered to be a valuable cover crop. Ironically, this "crop", because of its rapid growth rate, proved to be so effective in suppressing weeds, despite the presence of *C. mikaniicola*, that it in turn became a weed of both agricultural and ecological importance.

Thus, at the start of the present project, neotropical rusts were targeted as the most suitable candidates for control of the weed in India. Extensive surveys were undertaken in Latin America and the Caribbean in collaboration with local institutions, including the University of Viçosa (Minas Gerais, Brazil), the Institute of Ecology (Xalapa, Mexico) and the CABI Bioscience Regional Centre in Trinidad and Tobago. The rust, *P. spegazzinii* proved to be widespread, highly damaging throughout most of its range in the Neotropics, from southern Brazil to Costa Rica, and apparently specific to *M. micrantha*.

A second rust, *E. portoricensis* (=*Dietelia* fide Buritica and Hennen 1980), overlaps with *P. spegazzinii* in the most northerly range of *M. micrantha*. Both are microcyclic species, possessing telia and basidiospores only *(P. spegazzinii* with telioid telia and *E. portoricensis* with aecioid telia), which produce pustules not only on the leaves, but also on petioles and stems. The pustules frequently aggregate and induce growth changes in the infected tissues, such as hyperplasia and hypertrophy, leading to the formation of swollen or distorted stems and petioles. Necrosis of the tissues results in cankering, girdling and ultimately to die-back. Stunted growth and even plant death may be observed in the field and is frequent in the greenhouse.

A total of 13 rust strains from Brazil, Ecuador, Trinidad, Costa Rica and Mexico are currently held under quarantine at CABI Bioscience UK Centre (Ascot), and are being screened for pathogenicity and specificity. All the evidence from cross-inoculation studies indicates that both rust species are extremely host-specific and exist as strains or pathotypes. Thus far, a strain of *P. spegazzinii* from Trinidad has proven to be the most pathogenic across the range of weed biotypes tested, including collections from Malaysia, Nepal, Sri Lanka, Australia as well as from the north-east and south-west of India.

From the work to date, including exhaustive field observations and greenhouse assessment, the prospects for successful control of *M. micrantha* using rust fungi appear to be good. These pathogens are:

- highly host-specific, apparently restricted to *M. micrantha*,
- highly damaging; causing cankering and host death,
- highly effective in the weed's native range; restricting its occurrence and abundance despite significant pressure from mycoparasites.

Discussion

Work on biological control of *M. micrantha* started more than 20 years ago, and as yet, only one insect has been released in two countries, and the problem is still unresolved and increasing.

Solomon Islands experience with *Liothrips mikaniae*. Reasons for the failure of *L. mikaniae* in the Solomon Islands were not investigated in detail, but possibilities suggested at the time included:

- Impact of indigenous natural enemies.
- Disruption of dispersal, mate location or host finding behaviour because of the continuous distribution of *M. mikania* compared to its distribution in small patches in the area of origin.
- Unidentified pupal mortality.
- Host plant incompatability.

No observations were made on natural enemies so this cannot be assessed. Although none were noted in the Solomon Islands cultures, the cultures did not thrive, and natural enemies may have been present but overlooked. The results from the field cage release suggest that behaviour disruption is unlikely to be the cause of failure. No observations could be made on pupal mortality, but the only likely culprit would be predatory ants. Host plant incompatability seems unlikely to be an adequate explanation, since under the right conditions the culture on Solomon Islands plants did thrive. On balance the impact of indigenous natural enemies seems to be the only explanation which cannot be discounted on the available information.

Malaysian experience with *Liothrips mikaniae.* Releases were made in Malaysia over a period of more than a year, and in large numbers, yet there was no evidence of establishment. Observations on laboratory cultures offer two possible explanations: incompatability with the host plant, and the effects of generalist natural enemies.

Although there are at least two morphological biotypes of *M. micrantha* in Malaysia, the common glabrous variety is clearly susceptible, and releases were made onto this variety. The impact of a generalist thrips predator, *X. inquilinus* on the laboratory culture was striking, and the presence of this and other predators of thrips at the release site, laboratory observations on their feeding capacity, and field observations of predation, all point to these predators having a significant impact. At present this is the most likely explanation for the failure of *L. mikaniae* to become established in Malaysia.

Comparison with *Liothrips urichi.* Biological control of *Clidemia hirta* in Fiji was successful using *Liothrips urichi* introduced from Trinidad in 1930 (Simmonds 1933). Details of the release programme are not well documented, but Simmonds mentions that 20,000 thrips were taken from the culture received in Fiji (by sea) before it was destroyed. Some of these were released directly to the field, and others used to establish a culture for release. Releases were made from culture throughout the affected areas during 1930. From this scanty evidence, we suggest that the releases probably came to a total of thousands, perhaps tens of thousands of thrips released at dozens, but probably not more than 100 localities. Initial impact was thought to be adversely affected by dry weather, and by January 1931 dispersal from the points of release was not more than “300-400 yards” (277-369 m). However, heavy rain followed by warm moist conditions was considered to tip the balance and the colonies rapidly expanded and joined up. This description implies that there was no difficulty with establishment of the colonies at different sites. It was concluded that the impact of *L. urichi* was through decreasing the competitive ability of *C. hirta* particularly in open situations, with the result that it was displaced by other plants, of which *M. micrantha* was one of the most conspicuous.

Liothrips urichi was successfully introduced into Oahu, Hawaii, and established for the biological control of *C. hirta* in 1953 (Julien and Griffiths 1998). Again there is scanty published information on the release programme. *L. urichi* causes significant damage to *C. hirta* in the field by stunting its growth and killing juvenile plants in sunny situations

(Reimer and Beardsley 1989), but is adversely affected by two predators: an anthocorid, *Montandoniella moraguesii* (Puton) which was deliberately introduced for the biological control of *Gynaikothrips ficorum* (Marchal) (Davis and Krauss 1965), and the alien ant, *Pheidole megacephala* (Fabricius) (Reimer 1988). *C. hirta* remains a major weed problem in forests of Hawaii (Wester and Wood 1977).

Several unsuccessful introductions of *L. urichi* were made into the Solomon Islands (Julien and Griffiths 1998) but we have traced no suggestions as to why they failed. In 1972, *L. urichi* was introduced into Palau, and is reported to be established and effective in sunny areas (Julien and Griffiths 1998).

Comparing the fortunes of the two species of *Liothrips* spp., the contrast in establishment records is striking. Overlooking the possible differences in biology and ecology between the two and what impact that might have, there is one obvious difference. Releases on oceanic islands with relatively impoverished natural enemy faunas led to establishment and control (Fiji, Hawaii) while those on the mainland or highly diverse islands led to failure of establishment and no control (Malaysia, Solomon Islands). From this one might conclude that *L. mikaniae* would stand a better chance of becoming established and having impact in oceanic islands such as Fiji and Vanuatu. This hypothesis can be tested.

Alternative release strategies. One possible reason for *L. mikaniae* failing to become established which has not been considered in detail is whether the optimal release strategy was used. In the Solomon Islands over 4,000 thrips were released at two sites, whereas in West Malaysia 32,660 were released at no more than six sites. The failure of the initial releases in Malaysia led to the development of a strategy of a single very large release to maximise the chances of establishment. Recent research by Memmott *et al.* (1998) suggests this may not have been the best startegy.

Memmott *et al.* (1998) carried out a manipulative experiment to investigate the relationship between the probability of establishment and the number of individuals released for a weed biological control agents: the gorse thrips, *Sericothrips staphylinus* Haliday in New Zealand. They made replicated releases of 10, 30, 90, 270 and 810 thrips onto separate isolated gorse bushes, and sampled for establishment after one year. Although the smaller releases more frequently failed to become established than the larger releases, they concluded that an optimum release size could be calculated to maximise the number of colonies established with a limited number of thrips available for release. In this case, the optimum was around 100 thrips per release site and perhaps less.

One cannot extrapolate directly from the gorse thrips to the mikania thrips, but the obvious conclusion is that more releases of small numbers of thrips at many sites would be a more robust strategy to obtain establishment of the agent in the field. Furthermore, when one considers the population dynamics of *L. mikaniae* in South America (Cock 1982b), it should be remembered that small scattered populations on discrete growing shoots of *M. micrantha* is the norm for this species. A release strategy which mimics this is not unreasonable.

Hence, we suspect that there is fundamentally no reason why *L. mikaniae* should not have become established, particularly if many small releases had been made at a wide range of sites. However, the observations on predator pressure argue that even if it had become established, *L. mikaniae* would have been maintained in low populations in small, dispersed temporary patches, as it is in the Neotropics, and is most unlikely to have substantial impact on *M. micrantha*, at least in Malaysia. It is possible that it could be more effective in Pacific island countries with a poorer fauna of thrips predators, as was the case for *L. urichi* in Fiji.

Funding of biological control. The failure of *L. mikaniae* at this time led more or less directly to a loss in interest in the potential of biological control of *M. micrantha.* No other potential insect biological control agents for *M. micrantha* had been screened for host specificity, although there were many which were potentially of value as biological control agents. Effectively, the failure of the first biological control agent stopped any further investment in screening further biological control agents, until the new initiative with India to look at fungi as potential biological control agents was proposed.

There are several examples of successful biological control of weeds in the developing tropics, but most of these are programmes which have benefited from the research and implementation programmes of developed countries such as the USA and Australia, e.g. water weeds, *Opuntia* spp., *Tribulus* spp. The number of programmes funded entirely for the benefit of a developing country are very limited if South Africa's exemplary record is excluded (Table 1). Programmes against *Cuscuta* spp. *Cyperus rotundus* L.*, Phthirusa adunca* (Meyer) Maquire and *Striga hermonthica* Bentham might have been included in this list, but were based on research at the IIBC India and Pakistan Stations funded by US PL-480 funds.

Table 1.
Biological control programmes of weeds entirely for developing countries (South Africa not included).
From Julien and Griffiths (1998).

Target weed	Target area	Funding	First Releases	Number of agents	Result
Mikania micrantha	South-east Asia and the Pacific	Donor, plus industry and government	1988	1	Failure
Cordia curassavica	Mauritius (Malaysia and Sri Lanka)	Industry with CABI subsidy	1947	3	Success
Chromolaena odorata	West Africa, South Asia, etc.	Industry with CABI subsidy, subsequently government and donor support	1973	5	Partial success
Elephantopus mollis	Fiji	?Government	1957	1	Not known
Galega officinalis	Chile	?Government	1973	1	Failure
Clerodendrum chinense	Thailand	?Government	1990	1	Not known
Clidemia hirta	Fiji	?Government	1930	1	Success

This table shows that:

- there has been very little original research funded purely for the benefit of developing countries;
- the two successful programmes were carried out over 50 years ago, and succeeded with one and three insects respectively;
- the more recent unsuccessful programmes have been rather small and surely have not exploited all the opportunities.

Why is it that weed problems specific to developing countries have been neglected? Partly, it is because the most important invasive tropical weeds have also invaded USA, Australia or South Africa. *M. micrantha* is an exception to this, although it has recently been found in tropical Australia. It may be that Australia will be a significant beneficiary of the UK-DFID aid investment in biological control of this weed.

The fact that most of the important and widespread alien weeds have also spread to developed countries had led to many opportunities for implementation projects based on developed country research. There have been many significant successes by this route, but one of the drawbacks is that it does not develop national capability and ownership of the process in the developing countries. The success of this approach has also perhaps led to the perception that weed biological control is quick and cheap. Hence perhaps there is a reluctance to fund basic research on invasive alien weeds which have not been previously studied.

The results reported at this series of international symposia have shown that many, if not most, alien weeds are amenable to biological control. However, it has also become apparent that to achieve the maximum benefits – and these are large – persistence and a series of different biological control agents are often needed. Donor projects usually operate in three to five year cycles; weed biological control programmes can take decades.

Conclusions for donors. The most cost effective way to exploit biological weed control is to exploit the research and experience of developed countries, to make known biological control agents available to developing countries. The more challenging approach is where a weed is not already a developed country biological control target, and no research has been done. In this case, short term projects carry the risk that the first agents introduced may fail, but that if a long term investment can be made it is likely to pay dividends. Such an approach would offer considerably more opportunity for capacity building in the target (and source) countries.

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