# Session 5: Prospects for Weed Biological Control in Pacific Islands

# Weeds of Hawaii's Lands Devoted to Watershed Protection and Biodiversity Conservation: Role of Biological Control as the Missing Piece in an Integrated Pest Management Strategy

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## Summary

Despite Hawaii's reputation as an extinction icon, significant biological resources remain, especially in watersheds, natural areas, and specialized edaphic sites (e.g., lava dry forest, coastal). While direct habitat destruction by humans continues, human-facilitated biological invaders are currently the primary agents of continuing degradation. The ability of invasive plants to have prolific seed production, efficient dispersal systems, and to become established in dense vegetation, complicated by Hawaii's rugged topography, appears to render mechanical and chemical control as mere holding actions. Costly, 'environmentally unfriendly', and often ineffective, strategies using chemical and mechanical control on a large scale, despite the most valiant of efforts, can be viewed simply as attempts to buy time. Without increased levels of safely tested biological control, the seemingly inevitable result is the landscape level transformation of native forests, with potentially catastrophic consequences to cultural, biological, water, and economic resources. Increased levels of effective biological control for certain intractable invasive species appear to comprise a conspicuous 'missing piece' in our efforts to protect Hawaiian watersheds and other conservation lands.

## Evolution of Hawaiian Biota

The Hawaiian Islands are comprised of eight major high islands (19-22°N) and scattered small islands stretching northwest to 28°N. Hawaii is a world biodiversity hotspot and much like the Galapagos archipelago provides abundant textbook examples of evolutionary adaptive radiation in isolation, for decades having been a premier study site for evolutionary processes (Givnish et al., 2009; Baldwin and Wagner, 2010; Lerner et al., 2011). Substantial archipelago age, a highly isolated geographical position (ca. 4,000 km) from the nearest continent, and a remarkably wide range of microclimates from dry to very wet (with 200-10,000 mm mean annual precipitation) are all apparent drivers of the development of Hawaii's renowned biota and perhaps its relative vulnerability to invasions (Loope, 2011). Among animals, honeycreeper birds, drosophilid flies, long-horned and proterhinid beetles, crickets, microlepidoptera, and several groups of land snails are notable radiations, while among plants, the silversword alliance, lobelias, mints and gesneriads are conspicuous radiations. Among the most notable groups are the over 50 species of the extremely diverse Hawaiian honeycreepers evolved from a common cardueline finch ancestor, believed to have arrived from Asia just over 5 million years ago (Lerner et al., 2011). Biodiversity conservation challenges of the islands are perhaps best epitomized by these birds (Pratt et al., 2009), though similar challenges exist for many other endemic plants and animals.

## Value of Remaining Natural Areas and Watersheds

Though Hawaii is world renowned for its tremendous losses to biodiversity and natural communities, montane watersheds, natural areas, and specialized edaphic sites such as dry forest on lava and coastal vegetation on saline sands still continue to support communities of native species.

Losses of Hawaiian biota are significant not only biologically but also culturally. In Hawaiian culture, native biota and forests are critically important in both utilitarian and spiritual regards. They serve as indispensible sources of indigenous material culture, providing feathers, medicines, wood, fibers, and flowers and ferns for garlands (*lei*). The original native Hawaiian belief system recognized multiple gods, some dwelling in forested areas and taking earthly manifestations (*kinolau*) as particular plants within the forest. To Hawaiians, dense mountain forests were termed '*wao* '*akua*', literally 'place (of) god'.

In terms of human economics, the density of human populations living at first world standards on a limited land base in a highly isolated location has made Hawaii's watersheds, which are the sole sources of its potable and agricultural water, especially critical resources. With populations growing rapidly (predicted to double on Maui in the next 15-20 years), an increased and consistent water supply, especially in times of coming climate change, appears to be one of the islands' most important limiting factors. Not surprisingly, watershed conservation has traditionally received much attention in Hawaii, and the issue is now widely recognized as crucial. One recent economic study focused on aquifer recharge in Oahu's Koolau Mts. as the most direct benefit from tropical watershed conservation. The study calculated that if recharge to the aquifer from the Koolau Mts. ceased altogether, the reduction of inflow to the aquifer would be approximately 133 MGD/day, with a lost net present value of \$4.6 to \$8.6 billion (Kaiser et al., n.d.). In most Hawaiian watersheds, annual precipitation averages 4,000-6,000mm/yr. Watershed forest cover and composition is thought to largely determine how much of the water will run off, how much sediment it will carry, and how much it will recharge regional aquifers. Public agency awareness of the importance of watersheds was crucial to the establishment of Hawaii's Watershed Partnerships beginning some 20 years ago. The intent of these regional coalitions is to protect upland watersheds in order to facilitate water collection, promote water recharge and conservation, and prevent watershed degradation through erosion and siltation (http://hawp.org). An important concurrent goal is to protect native biological diversity to the extent practical.

## Threats to Remaining Natural Areas and Watersheds

Arriving about a millennium ago, Hawaiians deliberately introduced about 32 plant species for utilitarian purposes (Nagata, 1985) and, presumably inadvertently, about eight species of minor weeds (Wester, 1992). Since arrival of Europeans in 1778, approximately 13,000-15,000 species of non-native plants have been introduced; 1,200 of these are now naturalized, compared to a total native flora of approx. 1,200 species. Of introduced non-native species, about 100 non-native plant species in Hawaii are causing significant damage in natural areas (Smith, 1985; Stone et al.,1992). Invasive alien species may reach such high densities that they become community dominants, threaten entire native ecosystems and their component biodiversity, and threaten ecosystem services (Meyer and Florence, 1996; Denslow and Hughes, 2004). The International Union for the Conservation of Nature (IUCN) Invasive Species Specialist Group (ISSG) published a list of "100 of the World's Worst Invasive Alien Species" (Lowe et al., 2000). Of the 32 species among the hundred classified as 'land plants', Hawaii has 22.

While direct habitat destruction, first by Polynesians and now by modern humans, continues (especially of lowland and leeward ecosystems), human-facilitated biological invaders (weeds, non-native ungulates, rodents, and predators) are the primary agents of continuing degradation of biodiversity in Hawaii. A limited number of invasive plant species constitute the most important threat to extensive remaining native '*ohi'a lehua* (*Metrosideros polymorpha* Gaudich.) forests in Hawaii, which dominate moist, higher elevation areas (>ca. 900

m elevation). As a consequence, in many areas, this community is being progressively displaced by non-native plant species (Denslow, 2003; Medeiros 2004). Besides serving as refugia for native biota, *'ohi'a lehua* forests are also critically important economically as their distribution largely coincides with source areas of potable water. Research is only beginning to document the impacts of individual species (Asner and Vitousek, 2005; Kagawa et al. 2009) but three important vignettes are presented here to illustrate the magnitude of the problem.

Rapid invasion of Hawaiian watersheds by the quick growing Neotropical tree miconia (*Miconia calvescens* DC.) in the 1990s raised concerns about potential adverse hydrological impacts, especially on the steep slopes characteristic of Hawaii's watersheds (Conant et al., 1997). In part, these concerns were based on the behavior of the species in Tahiti – notably the formation of dense monotypic stands with little or no ground-covering vegetation (Meyer and Florence, 1996). Miconia's dense, large foliage dramatically reduces sub-canopy light levels and strongly inhibits survival and establishment of other plant species – often leaving near-barren soil surfaces. Giambelluca et al. (2009) demonstrated that the large leaves produce large through-fall drops during and after rain storms that reach high levels of kinetic energy and can result in substantial impacts to the soil, likely creating high rates of soil detachment, erosion, and reduced rates of infiltration.

The Brazilian tree strawberry guava (*Psidium cattleianum* Sabine) was introduced nearly two centuries ago and since has arguably achieved greater local dominance in Hawaiian watersheds and more negative effects on endemic species than any other invasive plant species (Medeiros, 2004; Asner et al., 2009). Invasion of *P. cattleianum* is currently being locally facilitated by the N-fixing invasive tree, *Falcataria moluccana* (Miq.) Barneby & J.W.Grimes (Hughes and Denslow, 2005). Takahashi et al. (2011), in a pioneering though preliminary study in Hawaii Volcanoes National Park, compared hydrologic properties of a *P. cattleianum* dominated stand to a comparable stand nearby comprised of native *M. polymorpha*. Cloud water interception at the native site was higher than in the invaded stand, likely because the characteristics of the native *M. polymorpha* tree facilitate more effective harvesting of cloud water droplets. Species invasion results in a lower proportion of precipitation reaching the forest floor and becoming available for groundwater recharge, suggesting that invasion by *P. cattleianum* may have significant negative effects on Hawaii's aquatic ecosystems and water resources.

Species brought from continental areas, having been separated from predators or pathogens of their native habitat (DeWalt et al., 2004), are often able to substantially outgrow Hawaii's endemic species. One dramatic well-documented example is the invasive Australian tree fern, *Cyathea (Sphaeropteris) cooperi* (Hook. Ex F. Muell.) Domin., that has been shown to be extremely efficient at utilizing soil nitrogen and is enabled to grow 6x as rapidly in height (15cm annually vs. 2-3cm), maintain 4x more fronds, and produce significantly more fertile fronds per month than the native Hawaiian endemic tree ferns, *Cibotium* spp. (Durand and Goldstein, 2001a, 2001b). Additionally, whereas *Cibotium* spp. provide an ideal substrate for epiphytic growth of many understory ferns and flowering plants, *C. cooperi* has the effect of impoverishing the understory and fails to support an abundance of native epiphytes with consequent reduction of local biological diversity (Medeiros and Loope, 1993).

## Conclusions

Current strategies of management agencies in Hawaii tasked with control of invasive plant species have focused on chemical and manual control methodologies, sometimes in conjunction with technical advancements such as directed herbicide application by helicopter. However, the ability of invasive plants to have prolific seed production, efficient dispersal systems, and to become established in dense vegetation, complicated by Hawaii's rugged topography, appears to render these primarily mechanical and chemical controls as mere holding actions for established species. An integrated pest management approach towards Hawaii's invasive species problems would include as its components: exclusion of new weed species and genotypes via quarantine and inspections, traditional management (fences and ungulate removal), expedient eradication/control of incipient invaders, research, public education, and a biological control program for the most problematic species.

In the Hawaiian Islands, invasive plant species which are beyond chemical and mechanical control yet are amongst the most serious habitat modifying species include the trees *Miconia calvescens*, *Morella* (*Myrica*) *faya* (Aiton) Wilbur (fayatree), *Psidium cattleianum*, *Falcataria moluccana* (albizia), and *Schinus terebinthifolius* Raddi (Christmas berry); tree fern *Cyathea cooperi*; shrubs *Clidemia hirta* (L.) D. Don (Koster's curse), *Ulex europaeus* L. (gorse), and *Rubus ellipticus* Focke (yellow Himalayan raspberry); forbs *Cortaderia jubata* (Lemoine ex Carrière) Stapf (pampas grass), *Hedychium gardnerianum* Ker-Gawl. (kahili ginger), *Rubus argutus* Link (Florida blackberry), *Tibouchina herbacea* (DC.) Cogn (cane tibouchina), and *Verbascum thapsus* L. (mullein); and the vine *Passiflora tarminiana* Coppens & Barney (banana poka).

Without increased levels of safely tested biological control, the seemingly inevitable result is landscape level transformation of native forests with potentially catastrophic consequences to cultural, biological, water, and economic resources. Increased levels of effective biological control for certain intractable invasive species appear to be the most conspicuous 'missing piece' in efforts to protect Hawaiian watersheds.

## References

Asner, G.P., Hughes, R.F., Varga, T.A., Knapp, D.E. & Kennedy-Bowdoin, T. (2009) Environmental and biotic controls over aboveground biomass throughout a tropical rain forest. Ecosystems **12**, 261–278.

Asner, G.P. & Vitousek, P.M. (2005) Remote analysis of biological invasion and biogeochemical change. Proceedings of the National Academy of Sciences, USA **102**, 4383–4386.

Baldwin, B.G. & Wagner, W.L. (2010) Hawaiian angiosperm radiations of North American origin. Annals of Botany **105**, 849–879.

Conant, P., Medeiros, A.C. & Loope, L.L. (1997) A multi-agency containment program for miconia (*Miconia calvescens*), an invasive tree in Hawaiian rain forests. In Assessment and Management of Invasive Plants (eds Luken, J. & Thieret, J.), pp. 249–254. Springer, Berlin.

Denslow, J.S. (2003) Weeds in paradise: Thoughts on the invasibility of tropical islands. Annals of the Missouri Botanical Garden **90**, 119–127.

Denslow, J.S. & Hughes, R.F. (2004) Exotic plants as ecosystem dominants. Weed Technology **18**, 1283–1287.

DeWalt, S.J., Denslow, J.S. & Ickes, K. (2004) Natural-enemy release facilitates habitat expansion of an invasive tropical shrub *Clidemia hirta*. Ecology **85**, 471–483.

Durand, L.Z. & Goldstein, G. (2001a) Growth, leaf characteristics, and spore production in native and invasive tree ferns in Hawaii. American Fern Journal **91**, 25–35.

Durand, L.Z. & Goldstein, G. (2001b) Photosynthesis, photoinhibition, and nitrogen use efficiency in native and invasive tree ferns in Hawaii. Oecologia **126**, 345–354.

Giambelluca, T.W., Sutherland, R.A., Nanko, K., Mudd, R.G. & Ziegler, A.D. (2009) Effects of *Miconia* on hydrology: A first approximation. In Proceedings of the International *Miconia* Conference, Keanae, Maui, Hawaii, May 4–7, 2009 (eds Loope, L.L., Meyer, J.Y., Hardesty, B.D., & Smith, C.W.), Maui Invasive Species Committee and Pacific Cooperative Studies Unit, University of Hawaii at Manoa. http://www.hear.org/conferences/miconia2009/proceedings/

Givnish, T.J., Millam, K.C., Mast, A.R., Paterson, T.B., Theim, T.J., Hipp, A.L., Henss, J.M.,Smith, J.F., Wood, K.R. & Sytsma, K.J. (2009) Origin, adaptive radiation and diversification of the Hawaiian lobeliads (Asterales: Campanulaceae). Proceedings of the Royal Society of London, B **276**, 407–416.

Hughes, R.F. & Denslow, J.S. (2005) Invasion by a N2-fixing tree alters function and structure in wet lowland forests of Hawaii. Ecological Applications **15**, 1615–1628.

Kagawa, A., Sack, L., Duarte, K. & James, S. (2009) Hawaiian native forest conserves water relative to timber plantation: Species and stand traits influence water use. Ecological Applications **19**, 1429–1443.

Kaiser, B., Pitafi, B., Roumasset, J. & Burnett, K. (n.d.) The Economic Value of Watershed Conservation. Honolulu: University of Hawaii Economic Research Organization, Online Report, http://www.uhero.hawaii.edu/assets/EconValueWatershed.pdf

Lerner, H.R.L., Meyer, M., James, H.F., Hofreiter, M. & Fleischer, R.C. (2011) Multilocus resolution of phylogeny and timescale in the extant adaptive radiation of Hawaiian honeycreepers. Current Biology **21**, 1–7.

Loope, L.L. 2011. Hawaiian Islands: invasions. In Encyclopedia of Invasive Introduced Species (eds. Simberloff, D. & Rejmánek, M.), pp. 309–319. University of California Press, Berkeley.

Lowe, S., Browne, M., Boudjelas, S. & De Poorter, M. (2000) 100 of the World's Worst Invasive Alien Species. The Invasive Species Specialist Group (ISSG), a specialist group of the Species Survival Commission (SSC) of The World Conservation Union (IUCN), 12pp.

Medeiros, A.C. (2004) Phenology, reproductive potential, seed dispersal and predation, and seedling establishment of three invasive plant species in a Hawaiian rain forest. Ph.D. dissertation, Department of Botany, University of Hawaii at Manoa.

Medeiros, A.C. & Loope, L.L. (1993) Differential colonization by epiphytes on native (*Cibotium* spp.) and alien tree ferns in a Hawaiian rain forest. Selbyana **14**, 71–74.

Meyer, J.-Y. & Florence, J. (1996) Tahiti's native flora endangered by the invasion of *Miconia calvescens* DC. (Melastomataceae). Journal of Biogeography **23**, 775–781.

Nagata, K.M.( 1985) Early plant introductions to Hawai`i. Hawaiian Journal of History **19**, 35–61.

Pratt, T.K., Atkinson, C.T., Banko, P.C., Jacobi, J.D. & Woodworth, B.L. (eds), (2009) Conservation of Hawaiian Forest Birds: Implications for Island Birds. Yale University Press, New Haven, CT.

Smith, C.W. (1985) Impact of alien plants on Hawaii's native biota. In Hawaii's Terrestrial Ecosystems: Preservation and Management. (eds. Stone, C.P. & Scott, J.M.) pp. 180–250. Cooperative National Park Studies Unit, Department of Botany, University of Hawaii, Honolulu, Hawaii.

Stone, C.P., Smith, C.W. & Tunison, J.T. eds. (1992), Alien Plant Invasions in Native Ecosystems of Hawaii: Management and Research. Cooperative National Park Resources Studies Unit, University of Hawaii, Honolulu, Hawaii. 887p.

Takahashi, M., Giambelluca, T.W., Mudd, R.G., DeLay, J.K., Nullet, M.A.& Asner, G.P. (2011) Rainfall partitioning and cloud water interception in native forest and invaded forest in Hawaii Volcanoes National Park. Hydrological Processes 25: 448–464,

Wester L. (1992) Origin and distribution of adventive alien flowering plants in Hawaii. In Alien Plant Invasions in Native Ecosystems of Hawaii: Management and Research. (eds. Stone, C.P.Smith, C.W. & Tunison, J.T) pp. 99–154. Cooperative National Park Resources Studies Unit, University of Hawaii, Honolulu, Hawaii.

# Biology, Field Release and Monitoring of the Rust Fungus *Puccinia spegazzinii* (Pucciniales: Pucciniaceae), a Biological Control Agent of *Mikania micrantha* (Asteraceae) in Papua New Guinea and Fiji

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## Abstract

*Mikania micrantha* Kunth (Asteraceae), mikania or mile-a-minute, is a neotropical plant species now found in all lowland provinces of Papua New Guinea (PNG) and all major islands of Fiji. The weed invades plantations and cropping areas, thereby reducing productivity and threatening food security of rural communities. As part of an Australian Government-funded biological control program, the rust fungus *Puccinia spegazzinii* de Toni was imported into PNG and Fiji in 2008 and released. Life cycle studies were conducted in PNG and inoculation techniques were evaluated. Field releases were made in areas where *M. micrantha* was abundant and monthly sampling at three sites determined the impact of the rust on *M. micrantha* in the field. *P. spegazzinii* is a microcyclic, autoecious rust, with a life cycle of 15-21 days. The most efficient inoculation method was to place 3-4 week old plants under infected plants in a perspex inoculation chamber for 48 hours at 26±1°C and 98% relative humidity. The most efficient field release method was to transplant about five infected 3-4 week old plants in amongst *M. micrantha* growing densely under canopy or in gullies where there is adequate water and humidity. The rust fungus has now been released at nearly 560 sites in 15 provinces in PNG and over 80 sites on four islands in Fiji. In PNG, the rust has established at over 180 sites in 11 provinces, spreading up to 40 km from some sites; while in Fiji, it has established at 25 sites on two islands. Detailed field monitoring has shown that *P. spegazzinii* reduces mikania density and therefore has the potential to control this weed in many parts of both countries.

## Introduction

*Mikania micrantha* Kunth (Asteraceae), mikania or mile-a-minute, is an aggressive neotropical vine. It has become a major weed throughout Asia and the South Pacific (Waterhouse and Norris, 1987; Waterhouse, 1994). It grows about 1 m/month and flowers profusely, producing thousands of light-weight barbed seeds. The seeds are spread by wind, by people on clothing and possessions, and by animals on their fur. *M. micrantha* is a particular problem on subsistence farms, where slash and burn agriculture is practiced. The plant can quickly invade cleared lands and smother crops. The main control method on subsistence farms is hand-pulling or slashing, as the use of herbicides is not economically feasible for resource-poor farmers (Day et al. 2011).

Plants can reshoot from broken stems and the vine's rapid growth rate means that land holders have to constantly clear land of the weed (Waterhouse and Norris, 1987; Holm et al., 1991). In subsistence farms, *M. micrantha* can grow over and kill crops such as taro, banana and papaw, while in plantations, it can smother cocoa, coconut seedlings or young oil palm trees, reducing flowering and productivity (Day et al., in press).

Biological control of *M. micrantha* was first attempted in the 1980s, with the introduction of the thrips *Liothrips mikaniae* (Priesner) (Thysanoptera: Phlaeothripidae) into the Solomon Islands in 1988 and Malaysia in 1990 (Cock et al., 2000). However, it failed to establish in either country (Julien and Griffiths, 1998; Evans and Ellison, 2005). The thrips was also sent to Papua New Guinea (PNG) in 1988 but the colony died out in quarantine before field releases could be conducted (Cock et al., 2000).

Renewed efforts into the biological control of *M. micrantha* commenced in 2005 with the release of the rust *Puccinia spegazzinii* de Toni (Pucciniales: Pucciniaceae) into India, mainland China and Taiwan, following exploration and host specificity testing by CABI Europe-UK (Evans and Ellison, 2005; Ellison et al., 2008; Ellison and Day, 2011). However, the rust appears to have established only in Taiwan (Ellison and Day, 2011).

Biological control of *M. micrantha* in the Pacific recommenced in 2006 following meetings of the Pacific Plant Protection Organization held in 2002 and 2004, where *M. micrantha* was rated as the second most important weed in the region behind the vine *Merremia peltata* L. (Convolvulaceae) (Dovey et al., 2004). A project, funded by the Australian Government and managed by the Queensland Government, aimed to introduce into PNG and Fiji safe biological control agents that were effective elsewhere (Pene et al., 2007).

Two butterfly species, *Actinote anteas* (Doubleday and Hewitson) (Lepidoptera: Arctiidae) and *A. thalia pyrrha* Fabr., were imported into Fiji in 2006 from Indonesia, where they were reported to aid the control of chromolaena, *Chromolaena odorata* (L.) King and Robinson (Asteraceae), and also damage *M. micrantha* (R. Desmier de Chenon pers. comm. 2006). However, colonies of both species died out before additional host-specificity testing could be completed. The rust *P. spegazzinii* was introduced into both PNG and Fiji in November 2008, following testing by CABI of additional plant species of concern to both countries. This paper reports on the biology, field release and monitoring of *P. spegazzinii* in PNG and Fiji.

## Materials and Methods

### Biology and culturing

Four small bare-rooted *M. micrantha* plants, each infected seven days prior with *P. spegazzinii* collected from Ecuador, were imported from CABI Europe-UK into quarantine facilities at the National Agriculture Research Institute, Island Regional Center, at Kerevat, East New Britain, PNG and the Secretariat of the Pacific Community, Fiji in November 2008. Plants were potted into clean pots with sterilized soil and held in a laboratory to aid recovery.

When the pustules on the imported plants reached maturity (about 15 days after inoculation), the infected plants were placed on a stand in a perspex inoculation chamber (60cm x 60cm x 45cm) within a quarantine laboratory (26±1°C, natural lighting). Healthy 3-4 week old *M. micrantha* plants, grown from 3cm long cuttings and containing 2-4 pairs of leaves, were placed under the infected plants. The chamber was sealed and the plants left for 48 hours for sporulation to occur and the fresh plants to be inoculated. After two days, the newly inoculated plants were removed and placed under a light bank in the laboratory for 48 hours prior to being placed in a shade house for pustules to develop. Plants were watered as necessary.

A culture of *P. spegazzinii* was maintained by repeating the above steps, using plants with mature pustules to inoculate young healthy plants. The life cycle of the rust was determined through daily observations of developing pustules.

To facilitate an increased number of field releases, small 3-4 week old plants were placed for 4-5 days in a field site where the rust had been established previously. The plants were then returned to the shade house for the pustules to develop. Using this field inoculation technique, in contrast with the laboratory procedure, many more plants can be inoculated.

### Field release and monitoring

Field releases of *P. spegazzinii* were conducted by transplanting infected potted plants amongst patches of actively growing *M. micrantha* such that the infected plants trailed over the field plants to encourage the inoculation process. Releases were generally conducted in areas where there was greater shade and damp soil to help keep the potted plants alive until infection of the field plants occurred. Release sites were inspected about three months after the rust was released, by which time the pustules had a chance to develop on the field plants and be more easily seen.

Two release sites near the research station at Kerevat were monitored in detail every month. At each site, ten $1m^2$ quadrats were placed randomly and the percent plant cover by *M. micrantha* was recorded in each. The number of infected leaves, petioles and stems in each quadrat was recorded.

## Results

### Biology

*P. spegazzinii* has a life cycle of 15-21 days. Tiny white spots appear on the upper leaf surface about six days after inoculation and the pustules continue to develop and grow, turning yellow by 11 days. Mature pustules become brown by day 15-17 when they are ready to infect other plants.

### Field release and monitoring

In PNG, the rust was released at over 560 sites in all 15 provinces infested with *M. micrantha*. Of the sites which were re-checked, the establishment rate was about 50%, with pustules being found at over 180 sites in 11 provinces. The rust established better in the wetter provinces of Oro (100% of release sites), Western (82%) and East New Britain (78%). Although the rust established at only three release sites out of seven checked in East Sepik Province, it spread up to 40 km in 16 months. The rust also spread widely in Oro and West New Britain provinces (Fig. 1).

Establishment was poor in Northern Solomons (4% of release sites), Sandaun (11%), Gulf (13%) and Madang (22%) provinces. To date, the rust has not established in Milne Bay, Morobe and New Ireland provinces, as well as around Port Moresby but recent release sites still need to be revisited (Fig. 1).

In Fiji, *M. micrantha* was found on all major islands. The rust was released at over 80 sites on the islands of Viti Levu, Vanua Levu, Taveuni and Ovalau. Pustules were found at 39% of sites checked on Viti Levu and 38% of sites on Vanua Levu (Fig. 2). Establishment was better on the wetter eastern side of Viti Levu than the drier western side of the island. On the eastern side of Viti Levu, the rust has begun to spread to other sites. No spread has been reported on Vanua Levu to date. Release sites on Taveuni and Ovalau are yet to be checked (Fig. 2).

In the field at one site near Kerevat, PNG, *P. spegazzinii* suppressed the growth of *M. micrantha*, allowing the growth of other plants (such as clycine *Glycine wightii*) over the *M. micrantha*, further reducing its cover. During a subsequent long dry season in 2010, the rust was not detected and *M. micrantha* began to increase again. However, the rust re-appeared after rains in early 2011 and the growth of *M. micrantha* is again beginning to be checked (Fig. 3).

At Tavilo, East New Britain (Fig. 4), the rust is suppressing *M. micrantha*, with cover decreasing from 100% to 40% following the release of the rust. Monitoring at both sites in PNG is continuing.

## Discussion

*M. micrantha* is considered a major weed in most wet lowland areas of both PNG and Fiji (Day et al., in press). The rapid growth rate of *M. micrantha* and its ability to smother crops and reduce productivity is a concern for land holders. Conventional control methods such as hand-pulling and slashing is time-consuming and the plant can re-shoot from the broken fragments left behind (Waterhouse and Norris, 1987; Holm et al., 1991). Biological control therefore is seen as a viable strategy.

Following additional host specificity testing by CABI, *P. spegazzinii* was approved for release in both countries. Laboratory trials suggested that the rust has the ability to reduce the growth rate of *M. micrantha*, which should reduce its competitiveness and limit its ability to smother crops (Day et al., 2011). Field monitoring at two sites confirmed that plant density has decreased since the release of the rust.

The rust has been widely released in PNG and has established in most provinces, where it is beginning to disperse from the release sites. At sites where it is currently in low abundance due to being

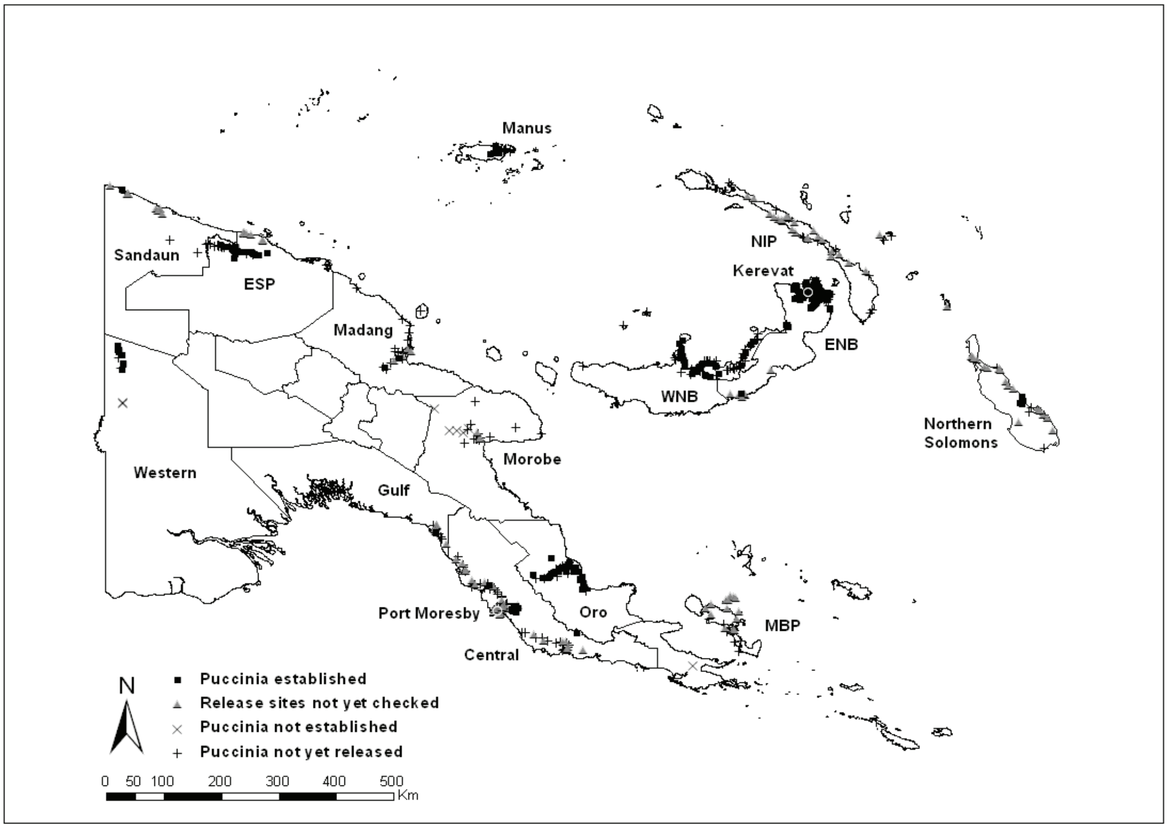


Figure 1. The distribution of *M. micrantha* in Papua New Guinea (all symbols); and the sites where *P. spegazzinii* is established, released but establishment unconfirmed, not established, and not yet released. ESP = East Sepik Province, ENB = East New Britain Province, MBP = Milne Bay Province, NIP = New Ireland Province and WNB = West New Britain.

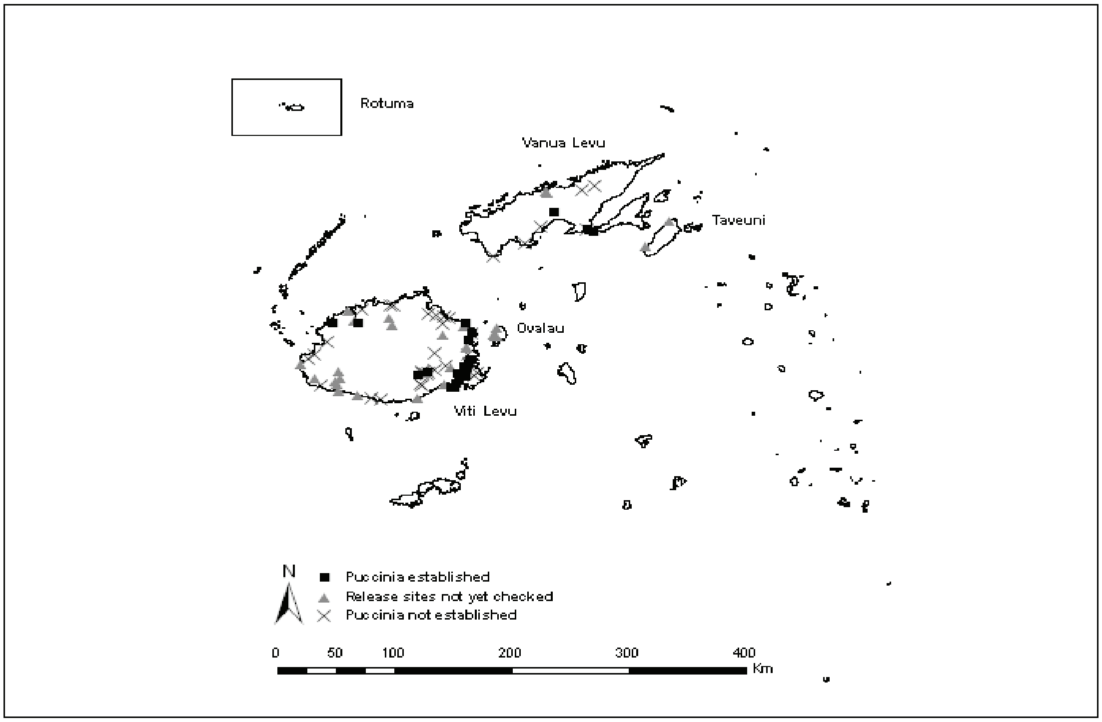


Figure 2. Sites in Fiji where *P. spegazzinii* is established, released but establishment unconfirmed, and not established.

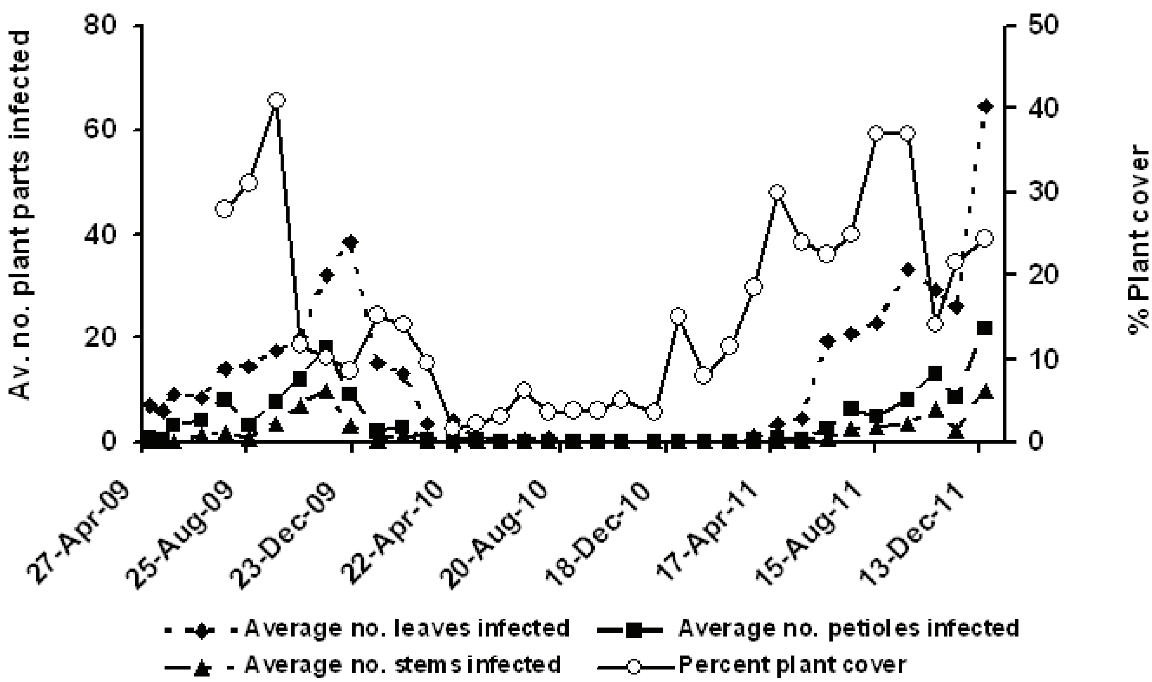


Figure 3. The mean number of leaves, petioles and stems of *M. micrantha* infected by *P. spegazzinii* per 1 m$^2$ and the percent plant cover of *M. micrantha* at site 1, Kerevat, East New Britain, PNG (release date: 10 January 2009).

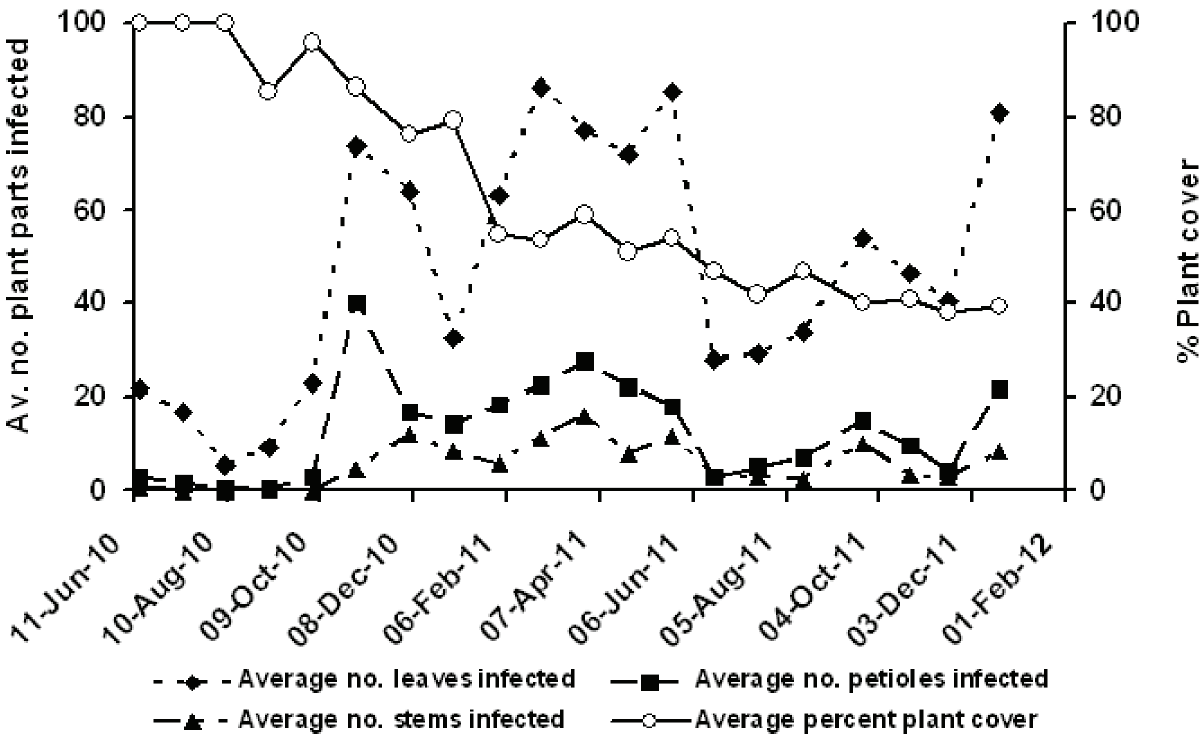


Figure 4. The mean number of leaves, petioles and stems of *M. micrantha* infected by *P. spegazzinii* per 1 m$^2$ and the percent plant cover of *M. micrantha* at site 2, near Kerevat, East New Britain, PNG (release date: 31 March 2010).

recently released, it is anticipated that populations will increase with time and it is expected that *P. spegazzinii* will have similar impacts on *M. micrantha* at these sites as at the monitoring sites. However, at some sites which are drier, such as in parts of Gulf and Morobe provinces and around Port Moresby, the impact of the rust may be less.

There are still many release sites that need to be checked and still a few sites where the rust has not yet been released, especially in more remote regions. The release and monitoring program will therefore continue in an effort to get the rust established in all parts of PNG where *M. micrantha* occurs.

In Fiji, *P. spegazzinii* has not been as widely released. There were lengthy delays in obtaining approval to release the rust; and many sites, particularly those away from the main islands of Viti Levu and Vanua Levu, are difficult and costly to reach. The rust has established well in the eastern areas of Viti Levu, which are much wetter than the western part of the island. It has also established at several sites on Vanua Levu. Field monitoring continues, with a slight decrease in plant density observed following the release of the rust.

In other countries where *P. spegazzinii* has been released, establishment has been patchy. The rust has appeared to have established in Taiwan but does not appear to have established in mainland China or India (Ellison and Day, 2011). Following the promising results seen in PNG, plans are underway to introduce *P. spegazzinii* into Vanuatu and Guam and re-introduce it into mainland China.

## Acknowledgements

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## References

Cock, M.J.W., Ellison, C.A., Evans, H.C. & Ooi, P.A.C. (2000) Can failure be turned into success for biological control of mile-a-minute weed (*Mikania micrantha*)? In Proceedings of the X International Symposium on Biological Control of Weeds (ed Spencer, N.R.), pp. 155–167. Bozeman, Montana, USA.

Day, M.D., Kawi, A., Tunabuna, A., Fidelis, J., Swamy, B., Ratutuni, J., Saul-Maora, J., Dewhurst, C.F. & Orapa, W. (2011) The distribution and socio-economic impacts of *Mikania micrantha* (Asteraceae) in Papua New Guinea and Fiji and prospects for its biocontrol. In Proceedings of the 23rd Asian-Pacific Weed Science Society Conference, pp 146–153. Asian-Pacific Weed Science Society.

Day, M.D., Kawi, A., Kurika, K., Dewhurst, C.F., Waisale, S., Saul Maora, J., Fidelis, J., Bokosou, J. Moxon, J., Orapa, W. and Senaratne, K.A.D. (in press) *Mikania micrantha* Kunth (Asteraceae) (mile-a-minute): Its distribution and physical and socio economic impacts in Papua New Guinea. Pacific Science.

Dovey, L., Orapa, W. & Randall, S. (2004) The need to build biological control capacity in the Pacific. In Proceedings of the XI International Symposium on Biological Control of Weeds (eds Cullen, J.M., Briese, D.T., Kriticos, D.J., Lonsdale, W.M., Morin, L. & Scott, J.K.), pp. 36–41. CSIRO Entomology Canberra, Australia.

Ellison, C. & Day, M. (2011) Current status of releases of *Puccinia spegazzinii* for *Mikania micrantha* control. Biocontrol News and Information **32,** 1N.

Ellison, C.A., Evans, H.C., Djeddour, D.H. & Thomas, S.E. (2008) Biology and host range of the rust fungus *Puccinia spegazzinii*: A new classical biological control agent for the invasive, alien weed *Mikania micrantha* in Asia. Biological Control **45,** 133–145.

Evans, H.C. & Ellison, C.A. (2005) The biology and taxonomy of rust fungi associated with the neotropical vine *Mikania micrantha*, a major invasive weed in Asia. Mycologia **97**, 935–947.

Holm L.G., Plucknett, D.L., Pancho, J.V. & Herberger, J.P. (1991) The World's Worst Weeds: Distribution and Biology. Kreiger Publishing Company, Malabar, Florida.

Julien, M.H. & Griffiths, M.W. (1998) Biological Control of Weeds. A World Catalogue of Agents and their Target Weeds. Fourth Edition. CABI Publishing, Wallingford, U.K. 223p.

Pene, S., Orapa, W. & Day, M. (2007) First fungal pathogen to be utilized for weed biocontrol in Fiji and Papua New Guinea. Biocontrol News and Information **28,** 55N–56N.

Waterhouse, D.F. (1994) Biological Control of Weeds: Southeast Asian Prospects. ACIAR, Canberra. 302 pp.

Waterhouse, D.F. & Norris, K.R. (1987) Biological Control: Pacific Propects. Inkata Press, Melbourne. 355–372 pp.

# The Invasive Alien Tree *Falcataria moluccana*: Its Impacts and Management

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## Abstract

*Falcataria moluccana* (Miq.) Barneby and Grimes is a large tree that has become invasive in forests and developed landscapes across many Pacific islands. A fast-growing nitrogen-fixing species, it transforms invaded ecosystems by dramatically increasing nutrient inputs, suppressing native species and facilitating invasion by other weeds. Individuals rapidly reach heights of 35 m, and their massive limbs break easily in storms or with age, creating significant hazards in residential areas and across infrastructure corridors such as roads and power lines. Their management is extremely costly for landowners, utilities, and local governments, since removal of hazardous trees can cost several thousand dollars apiece. Although efficient mechanical and chemical controls are being used with some success against incipient invasions of *F. moluccana*, biological control is needed to manage spread of populations and the massive seedling recruitment that occurs once mature individuals have been killed. The benefits of a biological control program for *F. moluccana* would likely extend to tropical islands throughout the Pacific, helping prevent further loss of native forest biodiversity and saving many millions of dollars in damage and maintenance associated with these trees growing near utilities, roads, homes and workplaces.

## Introduction

Alien species have caused untold damage to the ecology and economies of areas they have invaded (Elton, 1958). Where such species introduce new biological processes or disturbance regimes into ecosystems, they have the potential to profoundly alter both community characteristics and ecosystem functions, often to the extreme detriment of the native flora and fauna being invaded (Vitousek et al., 1987; D'Antonio and Vitousek, 1992). The invasive alien *Falcataria moluccana* (Miq.) Barneby and Grimes (synonyms: *Paraserianthes falcataria* (L.) I.C. Nielsen, *Albizia falcataria* (L.) Fosberg, *Albizia falcata* auct) is a very large, fast-growing, nitrogen-fixing tree in the legume family (Fabaceae) (Wagner et al., 1999). Recognized as the world's fastest growing tree species, it is capable of averaging 2.5 cm gain in height per day (Walters, 1971; Footman, 2001). Individuals reach reproductive maturity within four years and subsequently produce copious amounts of viable seed (Parrotta, 1990) contained within seed pods that can be wind-dispersed over substantial distances (i.e., > 200 m up- and down-slope during windy conditions). Mature trees can reach heights over 35 m, with the canopy of a single tree extending over a one-half hectare area. The broad umbrella-shaped canopies of multiple trees commonly coalesce to cover multiple hectares and even up to square kilometers (Hughes and Denslow, 2005). An important constraint to *F. moluccana* seedling recruitment is light availability; seedlings are very sensitive to shade and germinate in abundance only where the overstory canopy is open enough to allow sufficient light penetration (Soerianegara et al., 1994).

Although valued by some, *F. moluccana* has become invasive in forests and developed landscapes across many Pacific islands. Native to the Moluccas, New Guinea, New Britain, and Solomon Islands (Wagner et al., 1999), *F. moluccana* was exported widely across the Pacific, typically for the purpose of providing shade and nutrients (via litterfall) to crop species. It is currently considered invasive in the Republic of Palau, Pohnpei, Yap, New Caledonia, Fiji, Independent Samoa, American Samoa, the Cook Islands, the Society Islands, and the Hawaiian Islands, and it is present though not yet considered invasive on Guam, Wallis and Futuma, and Tonga (USDA Forest Service, 2012). Given the widespread presence of *F. moluccana* across the Pacific Islands, it poses a serious threat to the highly diverse biological hotspot that these islands collectively constitute (Myers et al., 2000). An archetypical early successional (i.e., pioneer) species, *F. moluccana* is generally found in mesic to wet forest and favors open, high-light environments such as disturbed areas; its capacity to readily acquire nitrogen via its symbiotic association with *Rhizobium* bacteria allows it to colonize even very young, nutrient-limited lava flows such as those found on Hawaii Island (Hughes and Denslow, 2005).

*Falcataria moluccana* was first introduced to the Hawaiian Islands from Borneo and Java in 1917 by the explorer botanist – and champion of native Hawaiian species – Joseph F. Rock (Rock, 1920). He noted the rapid growth rate of *F. moluccana*, stating that it is capable of reaching a height of over 35 m in 25 years time and that, "trees nine years old had reached a height of over a hundred feet, a rapidity of growth almost unbelievable." Ironically, Rock also commented on the life cycle of *F. moluccana* that "the only objection to the tree is its short-lived period, but as it is an abundant seeder, there should always be a good stand of this tree present" (Rock, 1920), yet individuals planted by Rock in 1917 remain living today, nearly 100 years later, on the grounds of the Lyon Arboretum on Oahu, Hawaii. Following its introduction, *F. moluccana* was one of the most commonly planted tree species in concerted, long-term, and wide-ranging non-native tree establishment efforts conducted by Hawaii Territorial and State foresters during the early to mid-1900s; approximately 140,000 individuals were planted throughout the Forest Reserve systems across the Hawaiian Islands, and populations have spread extensively from those intentional plantations (Skolmen and Nelson, 1980; Woodcock, 2003).

## Ecological Impacts

Previous research on the impacts of *F. moluccana* on native forests in Hawaii has demonstrated that this species profoundly transforms invaded forests by dramatically increasing inputs of nitrogen, facilitating invasion by other weeds while simultaneously suppressing native species. Hughes and Denslow (2005) described the impacts of *F. moluccana* invasion on some of the last intact remnants of native wet lowland forest ecosystems in Hawaii. They found that primary productivity in the form of litterfall was more than eight times greater in *F. moluccana*-dominated forest stands compared to stands dominated by native tree species. More importantly, nitrogen (N) and phosphorus (P) inputs via litterfall were up to 55 and 28 times greater in *F. moluccana* stands compared to native-dominated forests (Hughes and Denslow, 2005), and rates of litter decomposition – as well as rates of N and P release during decomposition – were substantially greater in *F. moluccana* invaded forests relative to native-dominated forests (Hughes and Uowolo, 2006). These inputs of up to 240 kg N $ha^{-1}$ $y^{-1}$ in *F. moluccana* stands exceed typical application rates of N fertilizer documented for industrial, high output corn cropping systems of the US Midwest (Jaynes et al., 2001). As a consequence, soil N availability was 120 times greater in *F. moluccana* forests relative to native-dominated forests on comparably-aged lava flow substrates. Simultaneously, *F. moluccana* invasion increased soil enzyme – particularly acid phosphatase – activities and converted the fungal-dominated soil communities of native stands to bacteria-dominated soil communities (Allison et al., 2006). These profound functional changes coincided with dramatic compositional and structural changes; *F. moluccana* facilitated an explosive increase in densities of understory alien plant species – particularly strawberry guava (*Psidium cattleianum* L.). Native species – particularly the overstory tree, ʻohiʻa lehua (*Metrosideros polymorpha* Gaud.) – suffered widespread mortality to the point of effective elimination from areas that they had formerly dominated. Based on these findings,

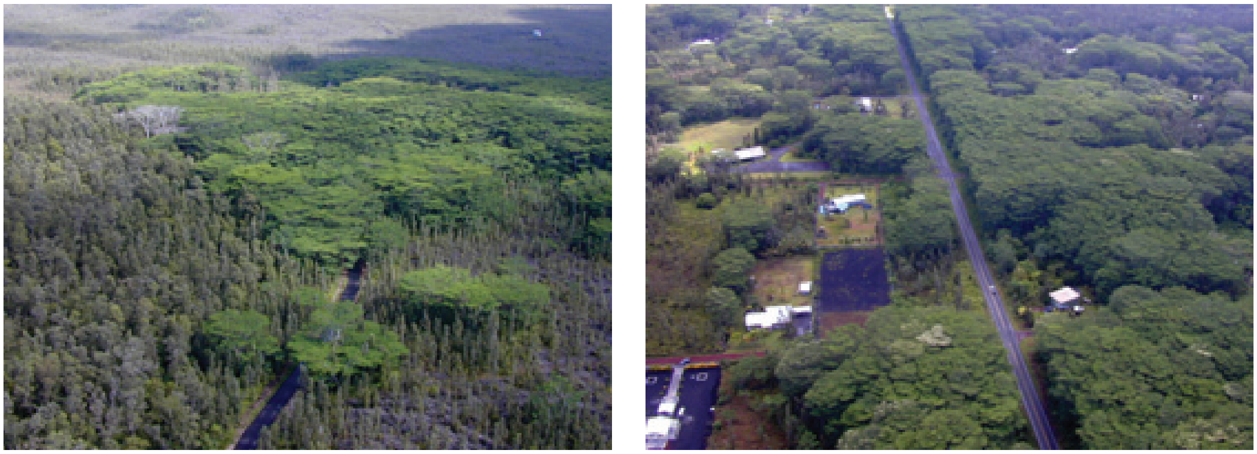

Figure 1. Invasion by *Falcataria moluccana* on Hawaii Island within Keauohana Forest Reserve (left) and in a residential area (right).

Hughes and Denslow (2005) concluded that the continued existence of native-dominated lowland wet forests in Hawaii largely will be determined by the future distribution of *F. moluccana* (Figure 1).

In American Samoa, where *F. moluccana* (locally known as tamaligi) was introduced in the very early 1900s and was present across 35% of the main island of Tutuila by 2000, an aggressive campaign has been undertaken by federal, state, and local groups to control and ideally eradicate this invasive species from the island (Hughes et al., 2012). Research addressing the role of *F. moluccana* in Samoan native forest communities supports the need for control as well the feasibility of eradication in these ecosystems. Results indicate that *F. moluccana* displaces native trees: although aboveground biomass of intact native forests did not differ from those invaded by *F. moluccana*, greater than 60% of the biomass of invaded forest plots was accounted for by *F. moluccana*, and biomass of native species was significantly greater in intact native forests. Following removal of *F. moluccana* (i.e., killing of mature individuals), the native Samoan tree species grew rapidly, particularly those which exhibit early successional, or pioneer species traits. The presence of such pioneer-type tree species appeared to be most important reason why *F. moluccana* removal is likely a successful management strategy; once *F. moluccana* is removed, native tree species grow rapidly, exploiting available sunlight and the legacy of increased available soil N from *F. moluccana* litter. Recruitment by shade intolerant *F. moluccana* seedlings was severely constrained to the point of being non-existent, likely a result of the shade cast by reestablishing native trees in management areas (Hughes et al., 2012). Thus, although *F. moluccana* is a daunting invasive species, its ecological characteristics and those of many of Samoa's native trees actually create conditions and opportunities for successful, long-term control of *F. moluccana* in lowland forests of American Samoa.

## Socio-Economic Impacts

*Falcataria moluccana* is also a roadside, urban forest and residential pest of major significance. Because individuals rapidly and routinely reach heights near 35 m and their weak wood breaks easily in storms or with age, catastrophic failure of massive limbs creates major hazards in residential areas and across infrastructure corridors such as roads and power lines. For example, on April 16, 2010, a 25-30 m tall *F. moluccana* tree fell across a residential street in the Puna District of Hawaii Island, destroying power lines and fences and landing in a backyard area where children often play (Hawaii Tribune Herald, May 6, 2010). Management of these large hazardous trees is extremely challenging for landowners, utilities, and local governments (Figure 1).

The potential economic burden posed by *F. moluccana* is staggering. In 2009 on the island of Kauai, the Hawaii Department of Transportation (HDOT) was compelled to act on two unconfirmed near fatalities involving large branches of *F. moluccana* dropping onto cars and a house located close to the road right-of-way. In response, the HDOT spent one million dollars to remove approximately 1,500 *F. moluccana* individuals growing along a single mile of roadway. Because *F. moluccana* has such soft wood and unstable branches, arborists were forced in this case to employ expensive cranes and lifts to remove these trees. As a consequence the larger trees cost in excess of $10,000 per individual to remove safely. Across the state of Hawaii, it has been estimated that over 40% of HDOT damage claims involving falling trees and branches are due to *F. moluccana* and between 50 and 100 miles of state roads have maturing *F. moluccana* populations (personal communication, Christopher A. Dacus, Landscape Architect and Certified Arborist, Hawaii State Department of Transportation). Even where *F. moluccana* grow at some distance from roads, they are considered problematic and hazardous because limbs can fall into waterways and accumulate against bridges, potentially causing flooding and physical damage to critical infrastructure. In addition, natural events such hurricanes or storms often cause extreme damage to *F. moluccana* stands which in turn contribute to road closures, electrical outages, and property damage, thus exacerbating post-storm and cyclone cleanup and repair work. With no natural predators to constrain them, *F. moluccana* populations are increasing in both stature and area, with concomitant maintenance costs increasing annually.

## Control Measures

Successful efforts to control *F. moluccana* populations within the National Park of American Samoa (NPAS) and adjacent lands employed a girdling method. Field crews of 2–6 people incised the bark of each mature individual at its base using bark spuds and manually peeled up the bark in large strips around the entirety of the trunk, resulting in a 1–3 m wide girdled section. Individual trees died gradually but inevitably, six months to a year following treatment. NPAS field crews have killed over 6,000 mature trees, thus restoring approximately 1,500 ha of native Samoan forest. This approach has been successful for three main reasons. First, significant funding was available to implement *F. moluccana* control across the targeted areas. Second, overwhelming public support for the *F. moluccana* control effort has been cultivated through outreach and informational meetings with local village leadership, employment of villagers from areas adjacent to infestations, and use of media outlets on a consistent basis. Third, *F. moluccana* exhibits characteristics that make it vulnerable to successful control: it is easily killed by girdling or herbicides, and its seeds and seedlings are exceedingly shade intolerant, while many of the common native Samoan tree species recover quickly from disturbance, and the shade they cast preempts subsequent *F. moluccana* seedling recruitment (Hughes et al., 2012).

Herbicides also have proven to be effective in controlling saplings and larger, mature *F. moluccana*. On the Hawaiian Island of Molokai, the Molokai-Maui Invasive Species Committee spearheaded a multi-agency effort in 2008 to eliminate a large stand of *F. moluccana* with extensive root systems threatening sensitive cultural sites (Wianecki, 2011). Field crews girdled the trees with chainsaws and applied Garlon 3A mixed with crop oil. Significant canopy defoliation was noted within weeks of treatment. Mortality of treated trees was 98% one year following application, and 100% with no subsequent seedling recruitment in the 3 years since treatment. As of this writing, all known populations of *F. moluccana* on Molokai have been killed, providing a compelling example of island-wide eradication of this highly invasive tree. As in American Samoa, the *F. moluccana* control project was successful in bringing together a diversity of community members, agency staff, and cultural practitioners. Participants are determined to use this project as a model for community involvement and creating a proper emphasis on Hawaiian cultural practices.

Encouraging recent advances in the development and use of another herbicide, Milestone® (EPA reg. no. 62719-519; active ingredient aminopyralid), have provided a highly effective means to quickly and efficiently kill mature *F. moluccana*. Milestone is administered by injection of very low volume, metered doses of the undiluted formulation. Trials indicate that very low dosage treatments resulted in near 100% mortality in less than one month. This new method – demonstrated to be safer and more effective than current conventional methods – appears to be a "game changer," allowing efficient control of *F. moluccana* populations across broad landscapes of Hawaii (personal communication, James Leary, Invasive Weed Management Specialist, University of Hawaii; http://www.ctahr.hawaii.edu/LearyJ/videos/albizia.html).

## Biological Control

While girdling and herbicide can provide effective means to kill *F. moluccana* saplings and mature trees, more challenging is control of the massive seedling recruitment that occurs once mature individuals have been killed. This is particularly true in Hawaii, where fast-growing pioneer-type tree species are not common in the native flora (Wagner et al., 1999). Identifying appropriate biological control agents is a logical and compelling solution to this challenge. Already at least one natural enemy of *F. moluccana* appears worth investigation: the gall rust *Uromycladium tepperianum* (Sacc.) McAlpine has been identified as a damaging pest of *F. moluccana* grown in plantations of Southeast Asia (Rahayu et al., 2010).

Recent biological control programs targeting alien *Acacia* species in South Africa have met with considerable success by focusing on agents that attack reproduction and reduce spread of trees from existing stands (Hoffmann et al., 2002; Post et al., 2010). In another successful effort in South Africa, seed feeders have been employed to control a close relative of *F. moluccana*, the Australian tree *Paraserianthes lophantha* (Willd.) I.C. Nielsen (Donnelly, 1992; Dennill et al., 1999). Seed predators make sense as a potential biological control agent for *F. moluccana* given that ongoing herbicide trials demonstrate the ease of killing mature trees: if post-control seedling recruitment could be minimized through seed predation, effective control of *F. moluccana* populations in Hawaii might be feasible. The benefits of a combined chemical and biological control program for *F. moluccana* would likely extend to tropical islands throughout the Pacific. Further loss of native forests and biodiversity, as well as extremely high costs in damage to private property and public infrastructure, can be expected from *F. moluccana* invasion if chemical and biological control work is not initiated.

## Conclusions

Previous research and recent experience demonstrate that unchecked invasion by *F. moluccana* poses significant threats to native ecosystems and human health and welfare across the Pacific Islands. Successful containment of *F. moluccana* by self-perpetuating biological control agents, along with improved chemical control measures, are needed to sustainably manage native ecosystems and to save many millions of dollars in damage and maintenance costs associated with these trees growing near utilities, roads, homes and workplaces.

## References

Allison S.D., Nielsen C., & Hughes R.F. (2006) Elevated enzyme activities in soils under the invasive nitrogen-fixing tree *Falcataria moluccana*. Soil Biology and Biochemistry **38**, 1537–1544.

D'Antonio, C.M., & Vitousek, P.M. (1992) Biological invasions by exotic grasses, the grass fire cycle, and global change. Annual Review of Ecology and Systematics **23**, 63–87.

Dennill, G.B., Donnelly, D., Stewart, K., & Impson, F.A.C. (1999) Insect agents used for the biological control of Australian *Acacia* species and *Paraserianthes lophantha* (Fabaceae) in South Africa. African Entomology Memoir No.1: 45–54.

Donnelly, D. (1992) The potential host range of three seed-feeding *Melanterius* spp. (Curculionidae), candidates for the biological control of Australian *Acacia* spp. and *Paraserianthes* (*Albizia*) *lophantha* in South Africa. Phytophylactica **24**, 163–167.

Elton, C.S. (1958) The Ecology of Invasions by Animals and Plants. University of Chicago Press. 196 pp.

Footman, T. (2001) Guinness World Records 2001. Little Brown & Co., New York. 288 pp.

Hoffmann, J.H., Impson, F.A.C., Moran, V.C. & Donnelly, D. (2002) Biological control of invasive golden wattle trees (*Acacia pycnantha*) by a gall wasp, *Trichilogaster* sp. (Hymenoptera: Pteromalidae), in South Africa. Biological Control **25**, 64–73.

Hughes, R.F., & Denslow, J.S. (2005) Invasion by an $N_2$-fixing tree, *Falcataria moluccana,* alters function, composition, and structure of wet lowland forests of Hawai'i. Ecological Applications **15**, 1615–1628.

Hughes, R.F., & Uowolo, A. (2006) Impacts of *Falcataria moluccana* invasion on decomposition in Hawaiian lowland wet forests: the importance of stand-level controls. Ecosystems **9**, 977–991.

Hughes, R.F., Uowolo, A.L., & Togia, T.P. (2012) Recovery of native forest after removal of an invasive tree, *Falcataria moluccana*, in American Samoa. Biological Invasions. DOI: 10.1007/s10530-011-0164-y.

Jaynes, D.B., Colvin, T.S., Karlen, D.L., Cambardella, C.A., & Meek, D.W. (2001) Nitrate loss in subsurface drainage as affected by nitrogen fertilizer rate. Journal of Environmental Quality **30**, 1305–1314.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B., & Kent, J. (2000) Biodiversity hotspots for conservation priorities. Nature **403**, 853–858.

Parrotta, J.A. (1990) *Paraserianthes falcataria* (L.) Nielsen, Batai, Moluccan sau. SO-ITF-SM-31. Institute of Tropical Forestry, Southern Forest Experiment Station, USDA Forest Service, Rio Piedras, Puerto Rico. 5 pp.

Post, J.A., Kleinjan, C.A., Hoffmann, J.H., & Impson, F.A.C. (2010) Biological control of *Acacia cyclops* in South Africa: the fundamental and realized host range of *Dasineura dielsi* (Diptera: Cecidomyiidae). Biological Control **53**, 68–76.

Rahayu, S., Lee, S.S., & Shukor, N.A.Ab. (2010) *Uromycladium tepperianum*, the gall rust fungus from *Falcataria moluccana* in Malaysia and Indonesia. Mycoscience **51**, 149–153.

Rock, J.F.C. (1920) The Leguminous Plants of Hawaii. Hawaiian Sugar Planters' Association, Experiment Station, Honolulu. 234 pp.

Skolmen, R.G., & Nelson, R.E. (1980) Plantings on the Forest Reserves of Hawaii, 1910-1960. Institute of Pacific Islands Forestry, Pacific Southwest Forest and Range Experiment Station, U.S. Forest Service, Honolulu. 481 pp.

Soerianegara, I., Lemmens, E.N., & Lemmens, R.H.M.J. (eds.) (1994) Plant resources of South East Asia No. 5 (1), Timber trees: major commercial timbers. PROSEA Foundation, Bogor.

USDA Forest Service (2012) Pacific Island Ecosystems at Risk (PIER). Online resource at http://www.hear.org/pier/species/falcataria_moluccana, accessed March 15, 2012.

Vitousek, P.M., Walker, L.R., Whitaker, L.D., Mueller-Dombois, D., & Matson, P.A. (1987) Biological invasion by *Myrica faya* alters ecosystem development in Hawaii. Science **238**, 802–804.

Wagner, W.L., Herbst, D.R., & Sohmer, S.H. (1999) Manual of the Flowering Plants of Hawai'i. University of Hawaii Press, Honolulu. 1919 pp.

Walters, G.A. (1971) A species that grew too fast – *Albizia falcataria*. Journal of Forestry **69**, 168.

Wianecki, S. (2011) Asking alibizia to go – Moloka'i style. Blog of the Maui Invasive Species Committee, December 2011. (http://mauiinvasive.org/2011/12/17/)

Woodcock, D. (2003) To restore the watersheds: early twentieth-century tree planting in Hawaii. Annals of the Association of American Geographers **93**, 624–635.

# Effective Biological Control Programs for Invasive Plants on Guam

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## Abstract

Several biological control agents were imported and released in Guam for the control of siamweed (*Chromolaena odorata* (L.) King & H.E. Robins), ivy gourd (*Coccinia grandis* (L.) Voigt), and the giant sensitive weed (*Mimosa diplotricha* C. Wright ex Sauvalle). Substantial control of *C. odorata* was achieved using the moth (*Pareuchaetes pseudoinsulata* Rego Barros ) (Lepidoptera: Arctiidae) and the gall fly (*Cecidochares connexa* Macquart) (Diptera: Tephritidae). There was a remarkable reduction of plant height caused by *C. connexa*. A biological control program on *C. grandis* has been effective, following the success achieved in Hawaii, through the introduction of the natural enemies *Melittia oedipus* Oberthür (Lepidoptera: Sesiidae) and *Acythopeus cocciniae* O'Brien and Pakaluk (Coleoptera: Curculionidae). At this moment, there are no infestations of *C. grandis* seen in Guam. Although *Heteropsylla spinulosa* Muddiman, Hodkinson & Hollis (Homoptera: Psyllidae) established successfully at release sites on Guam, it has yet to provide significant control of *M. diplotricha*. Presently, a biological control program has been initiated against *Mikania micrantha* (L.) Kunth. (Asterales: Asteraceae), using the rust fungus *Puccinia spegazzinii* De Toni (Basidiomycotina: Uredinales). Additionally, the biological control programs will be extended to neighboring Micronesian islands.

## Introduction

Invasive and exotic pest plant species have become an escalating problem in Guam and other Micronesian islands. Non-native plant invasions can be seen in agricultural and residential areas, roadsides, rangelands, pastures, forests, wetlands and parks (Reddy, 2011). Control of invasive, non-native plant species involves difficult and complex procedures. Reddy (2011) listed the top 20 invasive plant species which have impacted Guam greatly and a strategic plan with several possible control measures was suggested.

Siam weed, *Chromolaena odorata* (L.) King & H.E. Robins (Asterales: Asteraceae), is one of the most severe invasive weeds in Guam and other Micronesian Islands. It is a problem mostly apparent in plantations, pastures, vacant lots and disturbed forests (Cruz et al., 2006). It grows extremely rapidly, invading a wide range of vegetation types, forming dense monospecific stands and smothering other vegetation (Zachariades et al., 2009). Biological control using insects is considered an effective component of an Integrated Pest Management (IPM) program for this weed and has been incorporated into the IPM strategy in several countries where this weed is a problem. The moth *Pareuchaetes pseudoinsulata* Rego Barros (Lepidoptera: Arctiidae) was introduced from India and Trinidad and became established on

Guam in the 1980s (Zachariades et al., 2009). The gall fly *Cecidochares connexa* Macquart (Diptera: Tephritidae) was introduced from Indonesia in 1998 and established on Guam in 2002 and other Micronesian islands in succeeding years (Cruz et al., 2006; Zachariades et al., 2009).

Ivy gourd or scarlet gourd, *Coccinia grandis* (L.) Voigt (Violales: Cucurbitaceae), is an invasive and perennial vine which grows best under conditions of adequate rainfall and high humidity (Muniappan et al., 2009). Introduction of this vine in the 1980s resulted in invasion of over 100 hectares in different parts of Guam and almost one-third of Saipan (Bamba et al., 2009). It is also invading neighboring islands, Rota and Tinian (Muniappan et al., 2009). Based on the success of biological control in Hawaii, a program was initiated in the Mariana Islands using the natural enemies *Acythopeus cocciniae* O'Brien and Pakaluk (Coleoptera: Curculionidae), *Acythopeus burkhartorum* O'Brien and Pakaluk (Coleoptera: Curculionidae) and *Melittia oedipus* Oberthür (Lepidoptera: Sesiidae) (Reddy et al., 2009a, b). The two weevil species, A. *cocciniae* and *A. burkhartorum*, were field released in various locations on Guam in 2003 and 2004, respectively (Bamba et al., 2009 and Raman et al., 2007), and *M. oedipus* was released in 2007 (Reddy et al., 2009b).

The giant sensitive weed, *Mimosa diplotricha* C. Wright ex Sauvalle (Fabales: Fabaceae), also referred to in the literature as *M. invisa*, is a serious weed occurring mainly in vacant lots, roadsides, and crop lands (Kuniata, 2009). It has invaded most of the islands in Micronesia and the South Pacific (Esguerra et al., 1997). Recently, it has become established and spread to approximately two hectares in Guam, 120 hectares in Rota, 150 hectares in Tinian and 140 hectares in Saipan. After host specificity tests were conducted in Australia, *Heteropsylla spinulosa* Muddiman, Hodkinson & Hollis (Homoptera: Psyllidae) was released in Australia, Papua New Guinea, Samoa, Fiji, Cook Islands, Pohnpei, Yap and Palau (Esguerra et al., 1997; Wilson and Garcia, 1992), and it has effectively suppressed the weed in all the introduced countries. Because herbicidal control of *M. diplotricha* is expensive, labor intensive and requires frequent application, it is not a viable technique in the Marianas, and it was decided in 2005 to initiate biological control. Nymphs and adults of *H. spinulosa* were collected from Pohnpei and Palau and were field released on Guam in 2008.

The objective of this project is to assess the impact and interaction of the established natural enemies of *Chromolaena odorata*, *Coccinia grandis* and *Mimosa diplotricha* at various locations on Guam.

## Methods and Materials

Several sites with well-established stands of the three invasive plant species were selected for this study from villages in northern, central and southern Guam to represent the entire area of the island (Table 1). The sites were selected to include forested areas, suburban areas, waysides, and agricultural areas. A 12-channel global positioning system (GPS) (Garmin Corp., Taiwan) device was used to record longitude and latitude coordinates of each study site. Vegetation of each target weed was examined in randomly placed quadrats ($1m^2$) (Reddy, 2011), with 2-4 replicates per site (Brower et al., 1998). The number of stems, leaves, and plant height of *Chromolaena odorata* was measured, *C. connexa* galls in each quadrat were counted, and number of *P. pseudoinsulata* larvae and adults and their feeding damage in terms of larval holes and yellow leaves were counted. Similarly, holes in leaves and stems of *Coccinia grandis* caused by *A. cocciniae* and *M. oedipus*, respectively, and number of larvae or adults of *A. cocciniae*, *A. burkhartorum* and *M. oedipus* were counted. Damaged leaves and dead branches of *M. diplotricha* caused by *H. spinulosa* feeding were counted, and number of nymphs and adults of *H. spinulosa* were counted. Sites were visited monthly.

All data were analyzed using the GLIMMIX procedure in SAS v.9.2. For yield data (by site), a one-way ANOVA was performed, and if treatment effects were significant ($P < 0.05$), mean pairwise comparisons were performed by the least-squares difference method. If the treatment and/or month effects were significant, pairwise mean comparisons were performed with log-transformed LSMEANS.

## Results

### Effect of natural enemies on *C. odorata*

There has been a significant increase in mean number of *C. connexa* gall formations on *C. odorata* over the years and a corresponding significant decrease in growth of *C. odorata* (Figure 1). The average height of *C. odorata* was 65.2 cm in 2006 and decreased to 18.3 cm in 2010. Although larvae of *P. pseudoinsulata* were present in all five years we monitored, there was no significance in population build up (Table 2), except in the case of small larva holes, which were significantly higher in 2010 than in the previous years (P<0.05). However, the leaves of *C. odorata* turned yellow due to larval feeding by *P. pseudoinsulata* in all the years.

### Effect of natural enemies on *C. grandis*

The weevil *A. burkhartorum* has not become established, but population levels of *A. cocciniae* have increased significantly over the years (Table 3), and damage in terms of feeding holes on the leaves was observed to be significant in each year (P<0.05). Similarly, the damage to the stems caused by larvae of M. oedipus increased significantly over the years (P<0.05; Table 3), even though *M. oedipus* adults were not consistently observed.

### Effect of natural enemies on *M. diplotricha*

Populations of nymphs and adults of *H. spinulosa* and incidence of damaged branches of *M. diplotricha* increased consistently between years, significantly from 2009-2010 (Table 4). However, incidence of dead branches remained low.

## Discussion

Worldwide, biological weed control programs have had an overall success rate of 33 percent, with success rates considerably higher for programs in individual countries (Culliney, 2005). According to Reddy (2011), *C. odorata* has been rated the eighth most invasive weed on Guam. The two introduced natural enemies, *C. connexa* and *P. pseudoinsulata*, were well established on all parts of Guam. First and foremost, *C. connexa* has significantly affected the height of *C. odorata*. Our results agree with Zachariades et al. (2009), who suggested that *C. connexa* may provide good control of *C. odorata*. The impact of *C. connexa* on growth and reproduction, in addition to the defoliation by *P. pseudoinsulata*, should provide successful control of *C. odorata* in other parts of the world. Although *P. pseudoinsulata* was established on Guam in 1985 followed by *C. connexa* in 2005, *C. odorata* is still among the top invasive weeds in Guam. Therefore, it is advisable to mass rear *P. pseudoinsulata* and release them at various locations in Guam to suppress *C. odorata*.

*Coccinia grandis* agents *A. cocciniae* and *M. oedipus* established well and provided effective control. Currently, there are no infestations of *C. grandis* on Guam. Although *H. spinulosa* was established at release sites, it has not yet provided a significant control of *M. diplotricha*. Esguerra et al. (1997) reported that a few months after release, *H. spinulosa* became well established and assisted in the control of this weed in both Pohnpei and Yap. Similarly, it is expected that *H. spinulosa* will reduce *M. diplotricha* populations by affecting all aerial parts, causing damage that can lead to the death of the entire plant. A biological control program is underway for mile-a-minute weed, *Mikania micrantha* (L.) Kunth. (Asterales: Asteraceae), the ninth most invasive weed in Guam, using a rust fungus *Puccinia spegazzinii* De Toni (Basidiomycotina: Uredinales) (Reddy, 2011).

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**Table 1.** Monitoring sites on Guam

| Site | Invasive plant | Coordinates | No. of samples per site (n) |
|---|---|---|---|
| Yigo | *Chromolaena odorata* | 13°31.869' N, 144°52.291' E | 4 |
| Agat | | 13°21.789' N, 144°39.001' E | 4 |
| Dededo | | 13°30.700' N, 144°51.173' E | 4 |
| Hagatña | | 13°28.161' N, 144°44.817' E | 4 |
| Mangilao | | 13°26.978' N, 144°48.737' E | 4 |
| Talofofo | | 13°23.025' N, 144°46.342' E | 4 |
| Inarajan | | 13°15.259' N, 144°43.300' E | 4 |
| Merizo | | 13°15.058' N, 144°43.071' E | 4 |
| | | | |
| Marbo Cave | *Coccinia grandis* | 13°49.789' N, 144°87.001' E | 3 |
| Barrigada | | 13°28.385' N, 144°48.132' E | 3 |
| Inarajan Bay | | 13°28.395' N, 144°75.885' E | 3 |
| Yoña | | 13°24.359' N, 144°46.352' E | 2 |
| Merizo | | 13°15.063' N, 144°43.074' E | 3 |
| Mangilao | | 13°26.978' N, 144°48.737' E | 3 |
| Hagatña | | 13°28.598' N, 144°44.313' E | 3 |
| | | | |
| Tarja Falls | *Mimosa diplotricha* | 13°24.348' N, 144°46.363' E | 4 |
| AES, Yigo | | 13°31.872' N, 144°52.297' E | 2 |

**Table 2.** Effect of *Pareuchaetes pseudoinsulata* on *Chromolaena odorata*

| Year | Mean number ± SE (n=8) / one m² quadrat | | | | |
|---|---|---|---|---|---|
| | Larvae | Adults | Small larval holes | Large larval holes | Yellow leaves |
| 2006 | 2.4±0.8a | 0.0±0.0a | 8.0±0.4a | 3.2±0.8a | 3.0±0.1a |
| 2007 | 3.3±1.2a | 0.0±0.0a | 8.5±2.8a | 4.0±0.3a | 2.0±0.6a |
| 2008 | 1.6±1.4a | 0.0±0.0a | 7.0±0.9a | 3.0±0.5a | 1.4±0.3a |
| 2009 | 1.8±0.5a | 0.0±0.0a | 4.5±1.2a | 0.0±0.0a | 2.5±0.4a |
| 2010 | 4.5±0.6a | 3.5±0.7a | 12.4±0.3b | 8.5±0.6a | 4.5±0.8a |

Means within each column followed by different letters are significantly different at the $P<0.05$ level.

Table 3. Effect of *Acythopeus cocciniae, Acythopeus burkhartorum* and *Melittia oedipus* on *Coccinia grandis*

| Date | Mean number ± SE (n=6) / one m² quadrat | | | | | |
|---|---|---|---|---|---|---|
| | Acythopeus cocciniae | | Acythopeus burkhartorum | | Melittia oedipus | |
| | Feeding holes on leaves | Adults | No. of galls formed | Adults | Larval damage on stems | Adults |
| 2006 | 43.2±2.2a | 22.5±3.4a | 0.0±0.0a | 0.0±0.0a | not released | not released |
| 2007 | 120.9±4.1b | 34.2±1.8b | 0.0±0.0a | 0.0±0.0a | 2.4±2.7a | 0.0±0.0a |
| 2008 | 223.6±3.4c | 46.4±0.6c | 2.4 ±1.3a | 2.0±0.4a | 12.5±1.2b | 2.0±0.2a |
| 2009 | 436.2±1.8d | 48.6±4.2c | 4.0±0.6a | 0.0±0.0a | 22.6±3.1c | 0.0±0.0a |
| 2010 | all plants died | | | | | |

Means within each column followed by different letters are significantly different at the P<0.05 level.

Table 4. Effect of *Heteropsylla spinulosa* on *Mimosa diplotricha*

| Date | Mean number ± SE (n=4) / one m² quadrat | | |
|---|---|---|---|
| | Nymphs/Adults | Damaged branches | Dead branches |
| 2008 | 8.4±1.8a | 1.5±0.2a | 0.0±0.0a |
| 2009 | 11.6±2.4a | 6.4±0.1a | 0.5±0.2a |
| 2010 | 28.0±0.3b | 13.0±2.8b | 4.2±1.2a |

Means within each column followed by different letters are significantly different at the P<0.05 level.

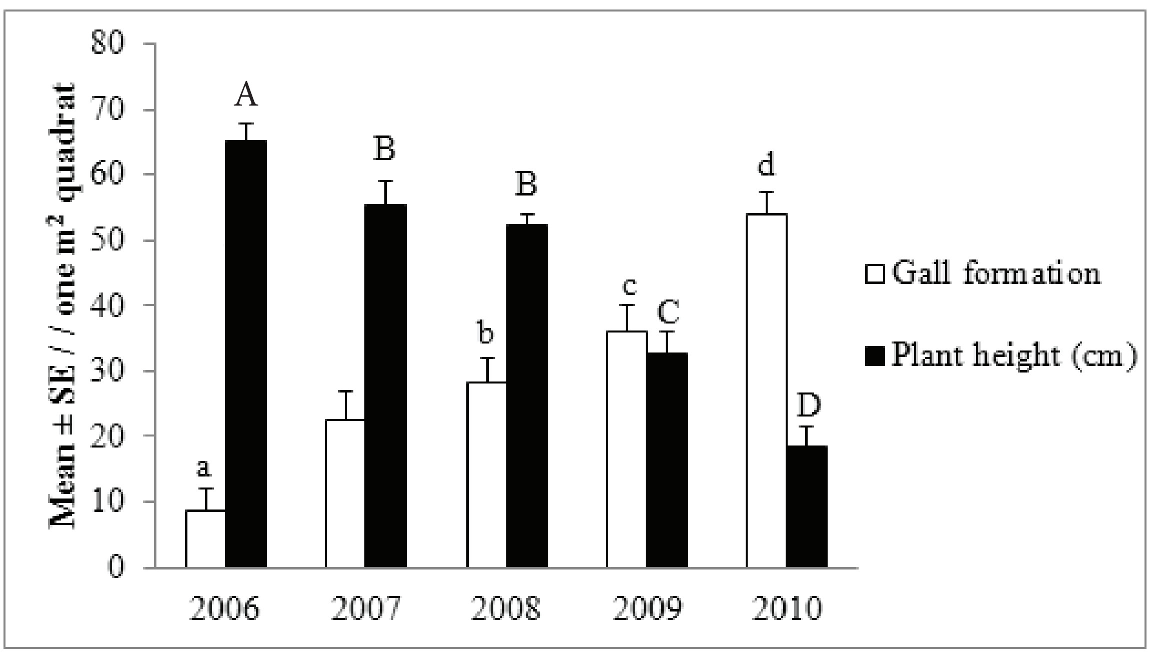


Figure 1. Effect of *Cecidochares connexa* on gall formation and plant height (n=8) of *Chromolaena odorata*
Means marked by different letters are significantly different at the P<0.05 level.

## References

Bamba, J.P., Miller, R.H., Reddy, G.V.P. & Muniappan, R. (2009) Studies on the biology, host specificity, and feeding behavior of *Acythopeius cocciniae* O'Brien and Pakaluk (Coleoptera: curculionidae) on *Coccinia grandis* (L.) Voigt (Cucurbitaceae) and *Zehneria guamensis* (Merrill) Fosberg (Cucurbitaceae). Micronesica 41, 70–82.

Brower J.E., Zar, J.H. & von Ende, C.N. (1998) Field and Laboratory Methods for General Ecology, Fourth Edition, MCB/McGraw-Hill Companies, Inc. 273p.

Cruz, Z. T., Muniappan, R. & Reddy, G.V.P. (2006) Establishment of *Cecidochares connexa* (Diptera: Tephritidae) in Guam and its effect on the growth of *Chromolaena odorata* (Asteraceae). Annals of the Entomological Society of America 99, 845–850.

Culliney, T.W. (2005) Benefits of classical biological control for managing invasive plants. Critical Reviews in Plant Sciences 24, 131–150.

Esguerra, N. M., William, J. D., Samuel, R. P. & Diopulos, K. J. (1997) Biological control of the weed, *Mimosa invisa* Von Martius on Pohnpei and Yap. Micronesica 30, 421–427.

Kuniata, L.S. (2009) *Mimosa diplotricha* C. Wright ex Sauvalle (Mimosaceae), ). In Biological Control of Tropical Weeds Using Arthropods (eds. Muniappan, R., Reddy, G.V.P. & Raman, A.), pp. 247-255, Cambridge University Press, Cambridge, UK.

Muniappan, R., Reddy, G.V.P. & Raman, A. (2009) Coccinia grandis (L.) Voigt (Cucurbitaceae). In Biological Control of Tropical Weeds Using Arthropods (eds Muniappan, R., Reddy, G.V.P. & Raman, A.), pp. 175–182, Cambridge University Press, Cambridge, UK.

Raman, A., Cruz, Z.T., Muniappan, R. & Reddy, G.V.P. (2007) Biology, host-specificity of gall-inducing *Acythopeus burkhartorum* (Coleoptera: Curculionidae), a biological-control agent for the invasive weed *Coccinia grandis* (Cucurbitaceae) in Guam and Saipan. Tijdschrift voor Entomologie 150, 181–191.

Reddy, G.V.P. (2011) Survey of invasive plants on Guam and identification of the 20 most widespread. Micronesica **41**, 263–274.

Reddy, G.V.P., Cruz, Z.T., Braganza, N. & Muniappan, R. (2009a) The response of *Melittia oedipus* (Lepidoptera: Sesiidae) to visual cues is increased by the presence of food source. Journal of Economic Entomology **102**, 127–132.

Reddy, G.V.P., Cruz, Z.T. & Muniappan, R. (2009b) Life-history, host preference and establishment status of *Melittia oedipus* (Lepidoptera: Sesiidae), a biological control agent for *Coccinia grandis* (Cucurbitaceae) in the Mariana Islands. Plant Protection Quarterly **24**, 27–31.

Wilson, B. W. & Garcia, C. A. (1992). Host specificity and biology of *Heteropsylla spinulosa* (Hom.: Psyllidae) introduced into Australia and Western Samoa for the biological control of *Mimosa invisa*. Entomophaga **37**, 293–299.

Zachariades, C., Day, M., Muniappan, R. & Reddy, G.V.P. (2009) *Chromolaena odorata* (L.) King and Robinson (Asteraceae). In Biological Control of Tropical Weeds Using Arthropods (eds. Muniappan, R., Reddy, G.V.P. & Raman, A.), pp. 130–162, Cambridge University Press, Cambridge, UK.

# Releases of Natural Enemies in Hawaii since 1980 for Classical Biological Control of Weeds

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## Abstract

A comprehensive review of biological control of weeds in Hawaii was last published in 1992, covering 74 natural enemy species released from 1902 through 1980. The present review summarizes releases of 21 natural enemies targeting seven invasive weeds from 1981 to 2010. These projects were carried out by Hawaii Department of Agriculture (HDOA), USDA Forest Service (USFS), University of Hawaii (UH), and US Geological Survey Biological Resources Discipline. An appendix summarizing the chronology and outcomes of releases is included (Appendix 1).

## Introduction

The practice of classical biological control of weeds began in Hawaii in 1902, with the release by the Territory of Hawaii of a tingid lacebug (*Teleonemia scrupulosa* Stål) for control of lantana (*Lantana camara* L.) (Swezey, 1924). Since that time, Hawaii has witnessed several spectacular successes in weed biological control, and today continues the science of managing weeds at the landscape level using natural enemies introduced from the target's native range after thorough testing and evaluation. The most recent comprehensive review of weed biological control in Hawaii (Markin et al., 1992) summarized 74 introductions of natural enemies between 1902 and 1980. Additional information for introductions through the mid-1990s was included in the worldwide compilation by Julien and Griffiths (1998). Hawaii's weed biological control projects from 1902 to1980 resulted in establishment of 42 insects and one fungal agent on 19 target weeds.

Our objective here is to provide an updated report of agents released for weed biological control in Hawaii. We briefly summarize results for each natural enemy released since 1981, and we include an appendix listing all weed biological control agents released in Hawaii from 1902 to 2010 (Appendix 1).

## Methods

Data on weed targets and weed biological control agents released since 1981 were compiled from published and unpublished sources, including records of the Hawaii Department of Agriculture and personal observations of biological control specialists and weed management partners.

## Results

### *Passiflora tarminiana* Coppens & V. E. Barney (Passifloraceae), banana poka

*Passiflora tarminiana* (formerly *P. mollissima*) is a vine native to the South American Andes, apparently introduced into Hawaii in the early 1900s (Wagner et al., 1990). It is invasive in native forests on the islands of Hawaii and Kauai, and is found in alien forest habitat in the Kula area of Maui (Hauff, 2006). Funding for the biological control program in Hawaii came primarily from the USFS and National Park Service. *P. tarminiana* also is invasive in New Zealand, where a biological control program is being implemented (Williams and Hayes, 2007).

**_Scea_ (= _Cyanotricha_) _necyria_ (Felder & Rogenhofer) (Notodontidae)**

*Scea necyria* was imported from Colombia and subsequently released on the islands of Hawaii, Kauai and Maui, but failed to establish. Despite repeated releases between 1988 and 1992 totaling over 15,000 individuals (including adult moths, defoliating larvae, and eggs), no evidence of establishment was ever observed. Larvae and pupae collected from the field exhibited 17% and 9% parasitism, respectively, while no parasites were recovered from field collected eggs (Campbell et al., 1995). It was suspected that *S. necyria* pupae may have been significantly preyed upon by birds. Research in Colombia has suggested that adult moths may be missing an obligate nectar source in the Hawaii environments where this species was released (Campbell et al., 1995).

**_Pyrausta perelegans_ Hampson (Crambidae)**

*Pyrausta perelegans* imported from Venezuela was released on Hawaii, Maui, and Kauai islands in 1991-1992, but established only on Hawaii and Maui. Larvae feed inside flower buds, consuming the ovary, anther, gynophore, inner flower tube, and petals (Ramadan et al., 2008). *P. perelegans* populations have remained at low levels, with vine infestation rates averaging 2-11% in post-release monitoring in 1992-1993 by Ramadan et al. (2008), and around 2% or less of flower buds infested a decade later (M.T. Johnson, unpublished data). While generalist lepidopteran parasitoids were known to be active in the study area and could utilize *P. perelegans* in lab tests, no field-collected larvae or pupae were found to be parasitized (Ramadan et al., 2008). *Trichogramma chilonis* (Trichogrammatidae) parasitism affected from 0 to 26% of field collected eggs (Ramadan et al., 2008), and may be a significant factor suppressing *P. perelegans* (Campbell et al., 1995). Several common predators of lepidopteran larvae were noted also, but definitive evidence of their impacts on *P. perelegans* was lacking (Campbell et al., 1995; Ramadan et al., 2008).

**_Septoria passiflorae_ Syd. (Mycosphaerellaceae)**

Septoria passiflorae, a fungus originally from Colombia, attacks P. tarminiana leaves, first forming distinct yellow spots which eventually spread to cover much of the leaf and cause premature abscission. It was released on Hawaii Island in 1996 (Trujillo et al., 2001), and quickly controlled a large infestation of banana poka, which had smothered native forest canopy at approximately 2,000 m elevation. S. passiflorae was much less effective in the drier habitat of Kula, Maui (G. Shishido, pers. comm.). In Kokee, Kauai, defoliation of vines was observed at inoculation sites, but the clumped distribution of the weed in the forest may have inhibited dispersal of the pathogen (G. Kawakami, pers. comm.). Furthermore, the climate in Kokee is somewhat drier than the windward inoculation sites on the island of Hawaii, where infection and control results were substantial (Trujillo, 2005).

### *Coccinia grandis* (L.) Voigt (Cucurbitaceae), ivy gourd

Ivy gourd is probably native to central East Africa, and was most likely moved to the Indo-Malayan region in centuries past. It may have come to Hawaii as a food or medicinal plant, via immigrants from that region. Ivy gourd was first reported on Oahu in 1968, and has since spread to Hawaii, Maui, Kauai and Lanai. This climbing vine blanketed large areas of alien wayside trees and shrubs on the island of Oahu, and less so in drier Kona (Hawaii). Three insects were released for biological control between 1996 and 1999 (Chun, 2002).

**_Melittia oedipus_ Oberthür (Sessiidae)**

*Melittia oedipus*, a clear-winged moth from

Kenya, was released from 1996 through 2002. Larvae feed in both roots and stems of the vine, forming galls. Galls can grow larger than 1.5 cm and cause breakage of the vine, so that the foliage above in the tree canopy dies. *M. oedipus* appears to be responsible for a widespread reduction in ivy gourd foliage density in tree and shrub canopies on Oahu. Development of land for housing also contributed to the decline of ivy gourd in the Kona area on Hawaii Island. Rat predation on *M. oedipus* larvae and pupae appeared to be significant, but the potential for biotic interference has not been studied further (Chun, 2002).

**_Acythopeus coccineae_ O'Brien and Pakaluk, _Acythopeus burkhartorum_ O'Brien and Pakaluk (Curculionidae)**

Two weevil species of the genus *Acythopeus* were first released in 1999. *A. burkhartorum*, a stem gall former, failed to establish, despite many releases in different habitats. *A. coccineae*, whose larvae are leaf miners, established on Oahu and in Kona, and appears capable of some impact. Ivy gourd has been a target of physical containment on Kauai, Lanai and Maui, and these efforts, on Maui in particular, likely contributed to lack of establishment of *A. coccineae* there. The parasitoid *Eupelmus* prob. *cushmani* (Eupelmidae) has been reared from *A. cocciniae* larvae and pupae, and may contribute to the low numbers of *A. cocciniae* in field populations (M. Ramadan, pers. comm.). Both *Acythopeus* species were also released for the biological control of ivy gourd in Guam, however, biotic interference by an unidentified hymenopteran parasitoid emerging from *A. coccineae* pupae was noted (Muniappan et al., 2009).

## *Miconia calvescens* DC. (Melastomataceae), miconia

Miconia was introduced to Hawaii as an ornamental tree around 1961 and planted on four of the major Hawaiian Islands before it was recognized as a serious invasive threat to native forests and watersheds (Conant et al., 1997). Miconia containment programs have been in effect since 1991 on Hawaii and Maui, and eradication programs continue on Oahu and Kauai. The containment effort on Maui has been very expensive, entailing aerial application of herbicide and chemical/mechanical control on the ground. On Hawaii, the task is even more daunting, given the large area invaded, and resources are presently not available to maintain extensive control. A single fungal pathogen has been released for miconia biological control, in both Hawaii and Tahiti. Additional agents are under development (Johnson, 2010).

**_Colletotrichum gloeosporioides_ (Penz.) f. sp. _miconiae_ Killgore et al. (Glomerellaceae)**

This anthracnose fungus, released in 1997, is currently the only natural enemy approved for miconia control in Hawaii (Killgore, 2002). Although laboratory tests by Meyer et al. (2008) found significant mortality of miconia seedlings infected with *C. g.* f. sp. *miconiae* in Tahiti, the effects of the fungus on flowering and fruiting remain unknown. Post-release evaluation studies found this agent causing premature leaf drop in wild sapling plants in Hawaii (Brenner, 2000). At higher elevations in Tahiti, partial defoliation of large monospecific stands have increased light levels penetrating the canopy so that some limited regeneration of native flora is occurring (Meyer et al., 2011).

## *Lantana camara* L. (Verbenaceae), lantana

Lantana has been a target of weed biological control work worldwide since 1902, when the first ever natural enemy was released here in Hawaii (Swezey, 1924). A total of 25 agents have been released to control this weed in Hawaii, with only one release made after 1980.

***Septoria* sp. (Mycosphaerellaceae)**

*Septoria* sp. collected from lantana in Ecuador was first released in 1997 by Dr. Eduardo E. Trujillo (UH) on the islands of Hawaii and Kauai (Trujillo, 2005). He reported excellent control of lantana at inoculated sites at Kokee on Kauai. There has been no further update published on the impact of the fungal pathogen on its host.

## *Clidemia hirta* (L.) D. Don (Melastomataceae), Koster's curse

*Clidemia hirta* was first collected in Hawaii in 1949, but was known to occur on Oahu since 1941 (Wagner et al., 1990). It is now highly invasive on all the islands except Niihau and Kahoolawe, which are probably too dry. It is a large shrub that dominates the subcanopy of both native and alien wet forests, and also can be a serious pest of windward pastures. Effectiveness of biological control agents released before 1981 is thought to be limited to open, sunny habitats (Reimer and Beardsley, 1986; Reimer and Beardsley, 1988). As a result of HDOA exploration and testing in the Republic of Trinidad and *Tobago*, four more insect agents were released between 1988 and 1995. Additional natural enemies are still needed for sufficient control.

***Lius poseidon* Napp (Buprestidae)**

Larvae of *Lius poseidon*, released in 1988, are leaf miners of *C. hirta*, while adult beetles are leaf feeders (Conant, 2002). Larvae are parasitized by at least one natural enemy, intentionally released for the control of agromyzid leaf miners (Conant, 2002). Combined foliar damage by adults and larvae to wild plants has been minimal.

***Antiblemma acclinalis* Hübner (Noctuidae)**

*Antiblemma acclinalis* was first released in 1995 (Conant, 2009). This leaf feeder is recorded as established on Oahu and Kauai, but appears to never have become common, perhaps due to parasitism.

***Carposina bullata* Meyrick (Carposinidae)**

*Carposina bullata*, first liberated in 1995 failed to establish, possibly due to the low number of pupae that survived shipment from Tobago (Conant, 2009). Poor survival resulted in only about 140 adults being released, primarily on Hawaii and very few on Oahu.

***Mompha trithalama* Meyrick (Coleophoridae)**

*Mompha trithalama* survived shipment from *Tobago* much better than *C. bullata*, resulting in a higher number of individuals released on Hawaii and Oahu in 1995 (Conant, 2009). *M. trithalama* was subsequently moved to Kauai and Maui. Larvae can now be found statewide, commonly feeding on the seeds of green fruit. It is possible that *M. trithalama* damage can result in premature fruit drop, but the overall impact of this agent on seed production has not yet been quantified. A pteromalid wasp parasitoid has been reared from the young fruit of Koster's curse, suggesting possible biotic interference (T. Johnson, unpublished data).

***Colletotrichum gloeosporioides* f. sp. *clidemiae* Trujillo (Glomerellaceae)**

This pathogen was imported by Trujillo (2005) from Panama and released in 1986. Repeated annual inoculations were observed to reduce *C. hirta* cover in one area, and similar mycoherbicidal application has been pursued elsewhere on a limited basis. More recently, natural defoliation events affecting as much as 90% of *C. hirta* cover were observed on the wet windward side of Kauai, but plants appeared to recover with time (N. Barca, pers. comm.). This phenomenon has been commonly observed on several islands at unpredictable intervals once the fungus became well established in the 1990s. Cool, rainy, windy weather conditions appear conducive to outbreaks.

## *Morella* (= *Myrica*) *faya* (Aiton) Wilbur (Myricaceae), firetree

*Morella faya* is thought to have been introduced by Portuguese plantation workers who emigrated from Atlantic islands in the 1800s. Firetree was used for reforestation in Hawaii in the 1920s, and now occurs on the islands of Hawaii, Maui, Lanai, Oahu and Kauai (Whiteaker and Gardner, 1992). *M. faya* is considered one of the worst invasive species in Hawaii Volcanoes National Park, since its ability to fix nitrogen allows it to thrive in low-nutrient lava soils (Whiteaker and Gardner, 1985). A tortricid moth released for biological control of *M. faya* by HDOA in 1956 is considered ineffective, because it only affected a minor population of *Morella cerifera* (L.) Small (Markin, 2001). The National Park Service provided most of the funding for *M. faya* biological control efforts in the 1980s and early 1990s. Two natural enemies were released since 1980, but neither appears to have any noticeable impact (G. Markin, pers. observation).

***Caloptilia coruscans* (Walsingham) [= *C.* sp. nr. *schinella* (Walsingham)] (Gracillariidae)**

*Caloptilia coruscans*, whose larvae are blotch miners and leaf edge rollers, was released in 1991 from collections made in the Azores and Madeira (Markin, 2001). Populations have remained low, and foliar damage has been minimal. Field collected larvae were infected by a fungal pathogen, hymenopteran parasitoids emerged from pupae, and lab tests found that local parasitoids attack its egg stage (Markin, 2001). Evidence of biotic interference also includes high levels of predation of *C.coruscans* larvae within leaf rolls (P. Yang and D. Foote, unpublished data).

### *Septoria hodgseii* Gardner (Mycosphaerellaceae)

*Septoria hodgseii*, a fungus collected from wax myrtle, *Morella cerifera*, in North Carolina, was tested for host specificity at the HDOA Plant Pathogen Containment Facility in Honolulu and was subsequently released and briefly monitored on Hawaii Island in 1997 (Culliney et al., 2003). *S. hodgsei* was found established, but was never abundant in the experimental area, and no follow up work has been done. Smith (2002) mentions a personal communication from Trujillo, which suggested that acid rain near the volcano could be inhibiting spore germination, and that the fungus should be released elsewhere.

## Ulex europaeus L. (Fabaceae), gorse

*Ulex europaeus* was introduced to Hawaii in the 1800s possibly as a cultivated hedge row plant from Europe, and may also have been used as a grazing plant for sheep. It now occupies over 2,000 ha on Mauna Kea (Hawaii) and over 2,000 ha in the Olinda area on Maui. The first biological control effort against gorse was launched by HDOA in 1927 and more recently has been a cooperative effort among HDOA, USFS and Landcare Research of New Zealand. In total, eight agents have been released, but only four became established (Markin and Conant, in these proceedings).

### *Agonopterix ulicetella* (Stainton) (Oecophoridae)

*Agonopterix ulicetella* was first released in 1988 and became established on both Hawaii and Maui (Markin et al., 1995). This species is univoltine and overwinters as adults. In the spring larvae feed on terminal shoots, sometimes causing considerable damage, which can reduce flowering (Markin, unpublished data). Three species of parasitoids attack *A. ulicetella* pupae, but no larval parasitoids had ever been found, even with intensive searching, and egg parasitism by *Trichogramma* sp. appeared low (Markin et al., 1996).

### *Stenopterapion scutellare* (Kirby) (Brentidae)

*Stenopterapion scutellare* was first liberated in 1961 (Markin and Yoshioka, 1989) on Maui (186 released), but failed to establish and so was re-released in 1989 on the island of Hawaii (788 released). None of the characteristic galls caused by the weevil were ever seen outside the field release cages in the 1990s, nor have they been seen since then.

### *Sericothrips staphylinus* Haliday (Thripidae), gorse thrips

Two biotypes of this thrips, both a winged and brachypterous form, were released in Hawaii between 1991 and 1994 (Markin et al., 1996). The thrips feed on the mesophyll of gorse foliage, producing pale stippled areas on leaves, spines, and stems (Hill et al., 2001). Both biotypes became established and widespread in the gorse infestation on Hawaii Island, but finding visible feeding damage in the field on mature plants is difficult. Seedlings may be more affected, given that *S. staphylinus* at high densities in lab experiments can damage and kill gorse seedlings (Fowler and Griffin, 1995). Populations of this agent may be limited by predators (Markin and Conant, in these proceedings).

### *Tetranychus lintearius* Dufour (Tetranychidae), gorse spider mite

First released in 1995 (Culliney and Nagamine, 2000), *Tetranychus lintearius* dispersed rapidly throughout the gorse infestation on Hawaii Island, and was subsequently released on Maui. *T. lintearius* populations increased tremendously during summer seasons, and resulted in considerable damage to gorse foliage in disjunct patches. *T. lintearius* feeding induces mottled chlorosis with stunting, and flowering may be aborted on damaged shoots in spring. Some shoots may even die from heavy feeding (Hill et al., 1991). However, after the year 2000, annual *T. lintearius* population explosions ceased, presumably caused by an accumulation of predacious mite populations.

### *Pempelia genistella* (Duponchel) (Pyralidae), gorse hard shoot moth

Releases of *Pempelia genistella* on Hawaii were conducted by USFS 1996-1997, but after initial establishment all populations apparently were eradicated as a result of a 2001-2002 control effort using herbicide and burning (Markin et al., 2002; Markin and Conant, in these proceedings). In its native habitat in Europe, larvae feed during fall and winter months, followed by pupation and adult emergence in early summer. Larvae often feed gregariously within webbing on older spines and may girdle the terminal shoots (Markin et al., 1996).

### *Uromyces pisi* (DC.) Otth f. sp. *europaei* Wilson and Henderson (Pucciniaceae)

This rust fungus was released on Hawaii Island in 2000, and was seen once soon after, but never recorded again during occasional searches over several years (Markin et al., 2002; Markin and Conant, in these proceedings).

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## References

Brenner, G. (2000) Analysis of miconia data. Hawaii Department of Agriculture, Hilo, Hawaii, USA. Available at: http://www.statpros.com/Publications/Miconia_Report.pdf_ (Accessed 19 October 2011).

Campbell, C.L., Markin, G.P. and Johnson, M.W. (1995) Fate of *Cyanotricha necyri* (Lepidoptera: Notodontidae) and *Pyrausta perelegans* (Lepidoptera: Crambidae) released for biological control of banana poka (*Passiflora mollissima*) on the island of Hawaii. Proceedings of the Hawaiian Entomological Society **32**, 123–130.

Chun, M.E. (2002) Biological control of ivy gourd, *Coccinia grandis* (Cucurbitaceae), in Hawaii. In Proceedings of Workshop on Biological Control of Native Ecosystems in Hawaii (eds Smith, C.W., Denslow, J. and Hight, S.), pp. 8–12. Pacific Cooperative Studies Unit, University of Hawaii at Manoa, Department of Botany, Technical Report 129, Honolulu, Hawaii USA. 122p.

Conant, P. (2002) Classical biological control of *Clidemia hirta* (Melastomataceae) in Hawaii using multiple strategies. In Proceedings of Workshop on Biological Control of Native Ecosystems in Hawaii (eds Smith, C.W., Denslow, J. and Hight, S.), pp. 13–20. Pacific Cooperative Studies Unit, University of Hawaii at Manoa, Department of Botany, Technical Report 129, Honolulu, Hawaii USA. 122p.

Conant, P. (2009) *Clidemia hirta* (L.) D. Don (Melastomataceae) In Biological Control of Tropical Weeds Using Arthropods (eds Muniappan R., Reddy, G.V.P. and Raman, A.). Cambridge University Press, Cambridge, UK. 508p.

Conant, P., Medeiros, A.C. and Loope, L.L. (1997) A multiagency containment program for miconia (*Miconia calvescens*) an invasive tree in Hawaiian rain forests. In Assessment and Management of Plant Invasions (eds Luken, J.O. and Thieret, J.W.), pp. 249–254. Springer, New York, USA. 324p.

Culliney, T.W. and Nagamine, W.T. (2000) Introductions for biological control in Hawaii,1987–1996. Proceedings of the Hawaiian Entomological Society **34**, 121–133.

Culliney, T.W., Nagamine, W.T. and Teramoto, K. (2003) Introductions for biological control in Hawaii 1997–2001. Proceedings of the Hawaiian Entomological Society **36**, 145–153.

Fowler, S.V. and Griffin, D. (1995) The effects of multi-species herbivory on shoot growth in gorse *Ulex europaeus*. Proceedings of the VIII International Symposium on Biological Control of Weeds (ed Delfosse, E.S.), pp 579–584. DSIR/CSIRO, Melbourne, Australia.

Hauff, R. (2006) Controlling banana poka on Maui. Na Leo O Ka Aina. Newsletter of the Hawaii Department of Land and Natural Resources Division of Forestry and Wildlife **2(1)**, p. 9.

Hill, R.L., Grindell, J.M., Winks, C.J., Sheat, J.J. and Hayes, L.M. (1991) Establishment of gorse spider mite as a control agent for gorse. In Proceedings of the 44th New Zealand Weed and Pest Control Conference (ed Popay, I.A.) pp. 31–34. Tauranga, New Zealand.

Hill, R.L., Markin, G.P., Gourlay, A.H., Fowler, S.V. and Yoshioka, E. (2001) Host range, release, and establishment of *Sericothrips staphylinus* Haliday (Thysanoptera: Thripidae) as a biological control agent for gorse, *Ulex europaeus* L. (Fabaceae), in New Zealand and Hawaii. Biological Control **21**, 63–74.

Johnson, M.T. (2010) Miconia biocontrol: Where are we going and when will we get there? In Proceedings of the International Miconia Conference, Keanae, Maui, Hawaii, May 4–7, 2009 (eds Loope, L.L., Meyer, J.-Y., Hardesty, B.D. and Smith, C.W.) Maui Invasive Species Committee and Pacific Cooperative Studies Unit, University of Hawaii at Manoa. Available at: http://www.hear.org/conferences/miconia2009/proceedings/2009 (Accessed 30 May 2012).

Julien, M.H. and Griffiths, M.W. (1998) Biological Control of Weeds. A World Catalogue of Agents and their Target Weeds. Fourth Edition. CABI Publishing, Wallingford, U.K. 223p

Killgore, E. (2002) Biological control potential of *Miconia calvescens* using three fungal pathogens. In Proceedings of Workshop on Biological Control of Native Ecosystems in Hawaii (eds Smith, C.W., Denslow, J. and Hight, S.), pp. 45–52. Pacific Cooperative Studies Unit, University of Hawaii at Manoa, Department of Botany, Technical Report 129, Honolulu, Hawaii USA. 122p.

Markin, G.P. (2001) Notes on the biology and release of *Caloptilia* sp. nr. *schinella* (Walsingham) (Lepidoptera: Gracillariidae), a biological control moth for the control of the weed firetree (*Myrica faya* Aiton) in Hawaii. Proceedings of the Hawaiian Entomological Society **35**, 67–76.

Markin, G.P. and Conant, P. (in these proceedings) Status of biological control of the shrub gorse (*Ulex europaeus*) on the island of Hawaii. In Proceedings of the XIII International Symposium on Biological Control of Weeds (Submitted October 2011).

Markin, G.P., Conant, P., Killgore, E. and Yoshioka, E. (2002) Biological control gorse in Hawaii: a program review. In Proceedings of Workshop on Biological Control of Native Ecosystems in Hawaii (eds Smith, C.W., Denslow, J. and Hight, S.), pp. 8–12. Pacific Cooperative Studies Unit, University of Hawaii at Manoa, Department of Botany, Technical Report 129, Honolulu, Hawaii USA. 122p.

Markin, G.P., Lai, P.Y. and Funasaki, G.Y. (1992) Status of biological control of weeds in Hawaii and implications for managing native ecosystems. In Alien Plant Invasions in Native Ecosystems of Hawaii. Management and Research (eds Stone, C.P., Smith, C.W. and Tunison, J.T.), pp. 466–482. Cooperative National Park Resources Studies Unit, University of Hawaii, Honolulu, Hawaii USA. 903p.

Markin, G.P., Yoshioka, E.Y. and Brown, R.E. (1995) Gorse. In Biological control in the western United States. Publication 3361 (eds Nechols, J. R., Andres, L. A., Beardsley, J. W., Goeden, R. D. and Jackson, C. G.), pp. 299–302. University of California, Division of Agriculture and Natural Resources, Oakland, California USA.

Markin, G.P., Yoshioka, E.Y. and Conant, P. (1996) Biological control of gorse in Hawaii. In Proceedings of the IX International Symposium on Biological Control of Weeds (eds Moran, V.C. and Hoffman, J.H.), pp.371–375. University of Cape Town, Stellenbosch, South Africa. 563p.

Markin, G.P. and Yoshioka, E.R. (1989) Present status of biological control of the weed gorse (*Ulex europaeus* L.) in Hawaii. In Proceedings of the VII Symposium on Biological Control of Weeds (ed Delfosse, E.S.), pp. 357–362. CSIRO (Australia); Ministero dell'agricoltura e delleforeste (Italy).

Meyer, J., Fourdrigniez, M. and Taputuarai, R. (2011) Restoring habitat for native and endemic plants through the introduction of a fungal pathogen to control the invasive tree *Miconia calvescens* in the island of Tahiti. Biocontrol, Available at: http://www.li-an.fr/jyves/Meyer_et_al_in_press_BioControl.pdf (Accessed 27 June 2011).

Meyer, J., Taputuarai, R. and Killgore, E. (2008) Dissemination and impacts of the fungal pathogen *Colletotrichum gloeosporioides* f. sp. *miconiae* on the alien tree *Miconia calvescens* in Tahiti (South Pacific). In Proceedings of the XII International Symposium on Biological Control of Weeds (eds Julien, M.H., Sforza, R., Bon, M.C., Evans, H.C., Hatcher, P.E., Hinz, H.L. and Rector, B.G.), pp. 594-599. CABI Publishing, Wallingford, UK.

Muniappan, R., Reddy, G.V.P. and Raman, A. (2009) *Coccinia grandis* (L.) Voight (Cucurbitaceae). In Biological control of tropical weeds using arthropods (eds Muniappan, R., Reddy, G.V.P. and Raman, A.), pp. 175-182. Cambridge University Press Cambridge, UK.

Ramadan, M., Markin, G.P. and Johnson, M.W. (2008) Field biology of *Pyrausta perelegans* (Lepidoptera: Crambidae) a flower bud feeder on *Passiflora mollissima* an invasive vine in Hawaiian forests. Tropical Lepidoptera Research **18**, 71-79.

Reimer, N.J. and Beardsley, J.W. (1988) Effectiveness of *Liothrips urichi* Karny (Thysanoptera: Phlaeothripidae) introduced for biological control of *Clidemia hirta* in Hawaii, U.S.A. Environmental Entomology **18**, 1141-1146.

Reimer, N.J. and Beardsley, J.W. (1986) Some notes on parasitization of *Blepharomastix ebulealis* (Guenee) (Lepidoptera: Pyralidae) in Oahu forests. Proceedings of the Hawaiian Entomological Society **27**, 91-93.

Smith, C.W. (2002) Forest pest biological control program in Hawaii. In Proceedings of Workshop on Biological Control of Native Ecosystems in Hawaii (eds. Smith, C.W., Denslow, J. and Hight, S.), pp. 91-102. Pacific Cooperative Studies Unit, University of Hawaii at Manoa, Department of Botany, Technical Report 129, Honolulu, Hawaii USA. 122p.

Swezey, O.H. (1924) Records of introduction of beneficial insects into the Hawaiian Islands. Proceedings of the Hawaiian Entomological Society **5**, 299-304.

Trujillo, E.E. (2005) History and success of plant pathogens for biological control of introduced weeds in Hawaii. Biological Control **33**, 113-122.

Trujillo, E.E., Kadooka, C., Tanimoto, V., Bergfeld, S., Shishido, G. and Kawakami, G. (2001) Effective biomass reduction of the invasive weed species banana poka by *Septoria* leaf spot. Plant Disease **85**, 357-361.

Wagner, W.L., Herbst, D.R. and Sohmer, S.H. (1990) Manual of the Flowering Plants of Hawaii. University of Hawaii Press, Honolulu, Hawaii USA. 988p.

Williams, P.A. and Hayes, L. (2007) Emerging weed issues for the West Coast Regional Council and their prospects for biocontrol. Landcare Research Contract Report: LC0607/109. Landcare Research, Auckland, New Zealand. 41p.

Whiteaker, L.D. and Gardner, D.E. (1985) The distribution of *Myrica faya* Ait. in the State of Hawaii. Cooperative National Park Resources Study Unit, Technical Report 55. Department of Botany, University of Hawaii, Honolulu, Hawaii, USA. 31p.

Whiteaker, L.D. and Gardner, D.E. (1992) Fire tree (*Myrica faya*) distribution in Hawaii. In Alien Plant Invasions in Native Ecosystems of Hawaii: Management and Research (eds Stone, C.P., Smith, C.W. and Tunison, J.T.), pp. 225-240. Cooperative National Park Resources Studies Unit, University of Hawaii, Honolulu, Hawaii USA. 903p.

Appendix 1. Agents introduced to Hawaii for biological control of weeds 1902-2010, compiled from Julien and Griffiths (1998), recent publications cited in this review, and unpublished records of the Hawaii Department of Agriculture.

| Target Weed | Agent Origin | First Release | Agent Family | Agent Species | Impact |
|---|---|---|---|---|---|
| Lantana<br>*Lantana camara* L.<br>(Verbenaceae) | Mexico | 1902 | Agromyzidae | *Ophiomyia lantanae* (Froggart) | Ineffective |
| | Mexico | 1902 | Brentidae | *Apion*, 2 spp. | Not established |
| | Mexico | 1902 | Cerambycidae | *Parevander xanthomelas* (Guérin-Méneville) | Not established |
| | Mexico | 1902; 1955 | Cerambycidae | *Aerenicopsis championi* Bates | Not established |
| | Mexico | 1902[1]; 1953 | Chrysomelidae | *Octotoma scabripennis* Guérin-Méneville | Partial |
| | Mexico | 1902 | Gracillariidae | *Cremastobombycia lantanella* Busck | Partial |
| | Mexico | 1902 | Hepialidae | *Hepialus* sp. | Not established |
| | Mexico | 1902 | Lycaenidae | *Strymon bazochii gundlachianus* (Bates) | Ineffective |
| | Mexico | 1902 | Lycaenidae | *Tmolus echion* (L.) | Ineffective |
| | Mexico | 1902 | Pterophoridae | *Lantanophagapusillidactyla* (Walker) | Ineffective |
| | Mexico | 1902 | Tephritidae | *Eutreta xanthochaeta* Aldrich | Ineffective |
| | Mexico; Cuba; Belize; Florida, USA; Trinidad; Brazil | 1902; 1952; 1953; 1954; 1954; 1954 | Tingidae | *Teleonemia scrupulosa* Stål | Partial |
| | Mexico | 1902 | Tortricidae | *Crocidosema lantana* Busck | Partial |
| | Cuba | 1953 | Chrysomelidae | *Octotoma gundlachi* Suffrain | Not established |
| | Mexico | 1953; 1965 | Crambidae | *Pseudopyrausta santatalis* (Barnes & McDunnough) | Not established |
| | Honduras | 1954 | Chrysomelidae | *Octotoma championi* Baly | Not established |
| | Panama; Mexico | 1954; 1962 | Noctuidae | *Diastema tigris* Guenée | Not established |
| | California | 1955 | Noctuidae | *Neogalia sunia* (Guenée) | Partial |
| | Florida, USA; Cuba | 1956 | Crambidae | *Salbia haemorrhoidalis* Guenée | Substantial |
| | Kenya/Zimbabwe; Philippines | 1957; 1965 | Noctuidae | *Hypena laceratalis* Walker | Substantial |
| | Mexico | 1960 | Cerambycidae | *Plagiohammus spinipennis* (Thomson) | Partial |
| | Brazil | 1961 | Chrysomelidae | *Uroplata girardi* Pic | Partial |
| | Colombia/Peru via Australia | 1970 | Tingidae | *Leptobyrsa decora* Drake | Ineffective |
| | Ecuador | 1997 | Mycosphaerellaceae | *Septoria* sp. | Uncertain[2] |

| Target Weed | Agent Origin | First Release | Agent Family | Agent Species | Impact |
|---|---|---|---|---|---|
| Purple nutsedge *Cyperus rotundus* L. (Cyperaceae) | Philippines | 1925 | Curculionidae | *Athesapeuta cyperi* Marshall | Ineffective |
| | Philippines | 1925 | Tortricidae | *Bactra venosana* (Zeller) | Ineffective |
| Gorse *Ulex europaeus* L. (Fabaceae) | England; England via New Zealand; France | 1927[1]; 1949[1]; 1955 | Brentidae | *Exapion ulicis* (Forster) | Partial |
| | Portugal | 1958 | Brentidae | *Apion* sp. | Not established |
| | Portugal; Spain; France | 1961; 1989; 1990; 1991 | Brentidae | *Stenopterapion scutellare* (Kirby) | Not established |
| | England; Portugal | 1988; 1991 | Oecophoridae | *Agonopterix ulicetella* (Stainton) | Partial |
| | England; Portugal; France | 1991; 1992; 1992 | Thripidae | *Sericothrips staphylinus* Haliday | Uncertain[2] |
| | England, Portugal, Spain via New Zealand via Oregon, USA | 1995 | Tetranychidae | *Tetranychus lintearius* Dufour | Partial |
| | Portugal | 1996 | Pyralidae | *Pempelia genistella* (Duponchel) | Not established |
| | England | 2000 | Pucciniaceae | *Uromyces pisi* (DC.) Otth f. sp. *europaei* Wilson and Henderson | Not established |
| Maui pamakani *Ageratina adenophora* (Spreng.) King & H. Rob. (Asteraceae) | Mexico | 1945 | Tephritidae | *Procecidochares utilis* Stone | Substantial |
| | Mexico | 1955 | Tephritidae | *Xanthaciura connexionis* Benjamin | Not established[3] |
| Prickly pear *Opuntia* spp. (Cactaceae) | Mexico via Australia | 1949 | Dactylopiidae | *Dactylopius opuntiae* (Cockerell) | Substantial |
| | Texas, USA | 1949 | Pyralidae | *Melitara dentata* (Grote) | Not established |
| | Texas, USA | 1949 | Pyralidae | *Melitara prodenialis* Walker | Not established |
| | Texas, USA | 1950 | Cerambycidae | *Moneilema armatum* LeConte | Not established |
| | Argentina via Australia | 1950 | Pyralidae | *Cactoblastis cactorum* (Berg) | Substantial |
| | Mexico via Australia | 1951 | Cerambycidae | *Lagocheirus funestus* Thomson | Partial |

| Target Weed | Agent Origin | First Release | Agent Family | Agent Species | Impact |
|---|---|---|---|---|---|
| Koster's curse *Clidemia hirta* (L.) D. Don (Melastomataceae) | Trinidad via Fiji | 1953 | Phlaeothripidae | *Liothrips urichi* Karny | Partial |
| | Trinidad; Puerto Rico | 1970 | Crambidae | *Ategumia matutinalis* Guenée | Ineffective |
| | Panama | 1986 | Glomerellaceae | *Colletotrichum gloeosporioides* f. sp. *clidemiae* Trujillo | Partial |
| | Trinidad | 1988 | Buprestidae | *Lius poseidon* Napp | Ineffective |
| | Tobago | 1995 | Carposinidae | *Carposina bullata* Meyrick | Not established |
| | Tobago | 1995 | Coleophoridae | *Mompha trithalama* Meyrick | Partial |
| | Tobago | 1995 | Noctuidae | *Antiblemma acclinalis* Hübner | Ineffective |
| Christmas berry *Schinus terebinthifolius* Raddi (Anacardiaceae) | Brazil | 1954 | Tortricidae | *Episimus unguiculus* Clarke | Ineffective |
| | Brazil | 1960 | Bruchidae | *Lithraeus atronotatus* (Pic) | Ineffective |
| | Brazil | 1961 | Gelechiidae | *Crasimorpha infuscata* Hodges | Not established |
| Firetree *Morella* (= *Myrica*) *faya* (Aiton) Wilbur (Myricaceae) | Florida/Georgia, USA | 1956 | Tortricidae | *Strepsicrates smithiana* Walsingham | Ineffective |
| | Azores/Madeira, Portugal | 1991 | Gracillariidae | *Caloptilia coruscans* (= *C.* sp. nr. *schinella*) (Walsingham) | Ineffective |
| | North Carolina, USA | 1997 | Mycosphaerellaceae | *Septoria hodgesii* D.E. Gardner | Uncertain[2] |
| Sourbush *Pluchea carolinensis* (Jacq.) G. Don (Asteraceae) | Mexico | 1957 | Gelechiidae | *Dichomeris aenigmatica* (Clarke) | Ineffective |
| | Guatemala | 1959 | Tephritidae | *Acinia picturata* (Snow) | Ineffective |
| Emex *Emex australis* Steinheil *Emex spinosa* (L.) Campd. (Polygonaceae) | South Africa | 1957 | Brentidae | *Perapion antiquum* (Gyllenhal) | Substantial |
| | Morocco | 1962 | Brentidae | *Perapion neofallax* (Warner) | Not established |
| | Portugal | 1962 | Brentidae | *Perapion violaceum* (Kirby) | Not established |

| Target Weed | Agent Origin | First Release | Agent Family | Agent Species | Impact |
|---|---|---|---|---|---|
| Asian melastome *Melastoma septemnervium* Lour. (Melastomataceae) | Philippines | 1958 | Crambidae | *Ategumia fatualis* (Lederer) | Ineffective |
| | Malaysia | 1965 | Crambidae | *Ategumia adipalis* (Lederer) | Ineffective |
| | Malaysia | 1965 | Noctuidae | *Rhynchopalpus brunellus* (Hampson) | Partial |
| Elephant's foot *Elephantopus mollis* Kunth (Asteraceae) | Trinidad via Fiji | 1961 | Tephritidae | *Tetraeuaresta obscuriventris* Loew | Ineffective |
| Puncture vine *Tribulus cistoides* L. *Tribulus terrestris* L. (Zygophyllaceae) | Italy via Calif./Arizona, USA | 1962 | Curculionidae | *Microlarinus lareynii* (Jacquelin du Val) | Substantial |
| | Italy via Calif./Arizona, USA | 1963 | Curculionidae | *Microlarinus lypriformis* (Wollaston) | Substantial |
| Florida blackberry *Rubus argutus* Link (Rosaceae) | California, USA | 1963 | Schreckensteiniidae | *Schreckensteinia festaliella* Hübner | Partial |
| | Oregon, USA | 1963 | Sesiidae | *Pennisetia marginata* (Harris) | Not established |
| | Mexico | 1964 | Tortricidae | *Croesia zimmermani* Clarke | Partial |
| | Oregon/California, USA | 1966 | Tenthridinidae | *Priophorus morio* (Lepeletier) | Ineffective |
| | Missouri, USA | 1969 | Chrysomelidae | *Chlamisus gibbosa* (Fabricius) | Not established |
| Klamath weed *Hypericum perforatum* (Hypericaceae) | France via California, USA via Australia/New Zealand | 1965 | Cecidomyiidae | *Zeuxidiplosis giardi* (Keiffer) | Substantial |
| | France via Australia via California, USA | 1965 | Chrysomelidae | *Chrysolina quadrigemina* (Suffrain) | Substantial |
| Hamakua pamakani *Ageratina riparia* (Regel) King & H. Rob. (Asteraceae) | Mexico | 1973 | Pterophoridae | *Oidaematophorus beneficus*Yano & Heppner | Partial |
| | Mexico | 1974 | Tephritidae | *Procecidochares alani* Steyskal | Partial |
| | Jamaica | 1975 | Entylomataceae | *Entyloma ageratinae* Barreto & Evans | Substantial |
| Russian thistle *Salsola tragus* L. (Chenopodiaceae) | Pakistan via California, USA | 1980 | Coleophoridae | *Coleophora klimeschiella* Toll | Not established |
| | Egypt/Pakistan via California, USA | 1980 | Coleophoridae | *Coleophora parthenica* Meyrick | Not established |

| Target Weed | Agent Origin | First Release | Agent Family | Agent Species | Impact |
|---|---|---|---|---|---|
| Banana poka *Passiflora tarminiana* Coppens & V.E. Barney (Passifloraceae) | Colombia/ Ecuador | 1988 | Notodontidae | *Scea* (= *Cyanotricha*) *necyria* (Felder & Rogenhofer) | Not established |
| | Venezuela | 1991 | Crambidae | *Pyrausta perelegans* Hampson | Ineffective |
| | Colombia | 1996 | Mycosphaerellaceae | *Septoria passiflorae* Syd. | Partial |
| Ivy gourd *Coccinia grandis* (L.) Voigt (Cucurbitaceae) | Kenya | 1996 | Sesiidae | *Melittia oedipus* Oberthür | Substantial |
| | Kenya | 1999 | Curculionidae | *Acythopeus burkhartorum* O'Brien and Pakaluk | Not established |
| | Kenya | 1999 | Curculionidae | *Acythopeus cocciniae* O'Brien and Pakaluk | Partial |
| Miconia *Miconia calvescens* DC. (Melastomataceae) | Brazil | 1997 | Glomerellaceae | *Colletotrichum gloeosporioides* (Penz.) f. sp. *miconiae* Killgore et al. | Partial |

[1] These early releases failed to establish.

[2] Established, but population and/or distribution limited, and evidence on impact lacking.

[3] Agent apparently was released on both Ageratina spp.

# Gall Nematode of Miconia: A Potential Classical Biological Control Agent for Weedy Melastomataceae

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## Abstract

Miconia (*Miconia calvescens* DC.) is a small tree or shrub from the neotropics that was introduced into Pacific Islands as an ornamental plant and, released from its natural enemies, became a devastating invader of native forests. Exploratory assessments of plant pathogens to be used for biological control have yielded a variety of possible agents, including two nematode species belonging to the genus *Dytilenchus*, namely: *D. drepanocercus* Goodey and a new species *Ditylenchus* sp. nov. The latter forms abundant galls and deformations on aerial tissues of several Melastomataceae, including *M. calvescens* and Koster's Curse (*Clidemia hirta* (L.) D. Don), which also is a noxious invader in Pacific islands. The disease caused by this nematode can be very severe and therefore it was intensively investigated to elucidate: aspects of its biology and ecology; gall ontogeny; host range; and impact on *M. calvescens*. Its host range is restricted to plants belonging to the Melastomataceae, with members of the genus *Miconia* appearing to be the most susceptible. *Ditylenchus* sp. nov. was pathogenic both to the Brazilian and the Hawaiian biotypes of *M. calvescens*. Population dynamics of this nematode species were studied in Viçosa, and it was found capable of surviving in a state of anhydrobiosis, in dehydrated plant materials, for up to six months. There was a decrease in the development of plants of *M. calvescens* with increased concentration of the inoculum, indicating the potential for significant impact by the nematode. Considering that there are no native members of the Melastomataceae in the Hawaiian flora and that other members of this family introduced into Hawaii are either weedy or economically insignificant, we conclude that *Ditylenchus* sp. nov. has clear potential for use as a classical biological control agent against *M. calvescens* and possibly also *C. hirta*.

See our recent publication: Oliveira, R. D. L., Santin, A. M., Seni, D. J. Dietrich, A., Salazar, L.A., Subbotin, S. A., Mundo-Ocampo, M., Goldenberg, R., Barreto, R. W. (2012) *Ditylenchus gallaeformans* sp. n. (Tylenchida: Anguinidae) - a neotropical nematode with biocontrol potential against weedy Melastomataceae. Nematology, DOI: 10.1163/15685411-00002670

# Lepidopterans as Potential Agents for the Biological Control of *Miconia calvescens*

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## Abstract

Miconia (*Miconia calvescens* DC.) (Melastomataceae) is a severe weed found in rainforest ecosystems on oceanic islands, including French Polynesia, Hawaii and New Caledonia, and Australia, where it was introduced as ornamental plant. This plant is native to Central and South America and is classified among the 100 worst invasive species around the world. To select agents for biological control of *M. calvescens*, surveys of the arthropods that attack this weed in Brazil have been carried out since 2001. Eight species of Lepidoptera were found attacking *M. calvescens*, including six defoliators: *Salbia lotanalis* Druce (Pyralidae), *Druentia inscita* Schaus (Mimallonidae), *Antiblemma leucocyma* Hampson (Noctuidae) and three unidentified Limacodidae species; a fruit borer: *Carposina cardinata* Meyrick (Carposinidae); and a flower feeder: *Pleuroprucha rudimentaria* Guenée (Geometridae). We evaluated the damage, host specificity and population dynamics of these Lepidoptera species and the field occurrences of their natural enemies. Based on host specificity and damage caused to plants, *S. lotanalis* and *D. inscita* are the most promising species for biological control of *M. calvescens*. If *C. cardinata* and *P. rudimentaria* prove host-specific in future tests, they may also be appropriate as biological control agents.

# Can Wild Gingers Ever be Tamed?
# The Search for Natural Enemies Hots up

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## Abstract

Kahili ginger, *Hedychium gardnerianum* Sheppard ex J. B. Ker Gawler, and yellow ginger, *H. flavescens* W. Carey ex W. Roscoe (Zingiberaceae), stunning and fragrant ornamental herbs native to the Eastern Himalayan foothills, have escaped cultivation to become aggressive colonizers of indigenous and intact forest habitats, smothering unique and delicate ecosystems and threatening specialized communities. In the worst affected countries such as the US (Hawaii) and New Zealand, Kahili ginger continues its range expansion through seed spread to new pristine sites, while large monotypic infestations are deemed lost causes, with management efforts largely restricted to outlier populations. In 2008, consortium funding allowed an exploratory survey to the states of Assam, Meghalaya and Sikkim in India, with reviews of the scientific and botanical literature, as well as historical herbarium records providing the geographical focus. Since then, repeated field trips across the season have been conducted in Sikkim, where the most natural populations of Kahili ginger were identified. Whilst literature studies highlighted a dearth of damaging species associated with wild gingers in the introduced range, the plant was always subject to significant natural enemy pressure in India, from a diverse entomofauna occupying a range of niches/guilds as well as from pathogenic fungi. Here we report the results of surveys with emphasis on those agents which have shown the most promise as biological control agents based on identifications, field observations and preliminary specificity studies. Future prospects and opportunities are discussed in the light of the access and benefit sharing challenges faced thus far.

# Determining the Origin of African Tulip Tree, *Spathodea campanulata* (Bignoniaceae), Populations in the Pacific Region Using Genetic Techniques

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## Abstract

African tulip tree, *Spathodea campanulata* Beauv. (Bignoniaceae), is a problematic invasive weed in the Pacific region for which a biological control program has been initiated. The species is native in western and central Africa where three distinct subspecies are recognized. The polymorphic nature of the species increases the likelihood that natural enemies collected for biological control will have local adaptation to different variants of the plant. One of the potential biological control agents for *S. campanulata* is a gall forming eriophyid mite that is likely to complete multiple generations on a single host plant individual, and is therefore likely to develop local adaptations to certain plant variants. The African region where the Pacific *S. campanulata* population originated is expected to be the most appropriate region in which to collect biological control agents because natural enemies will be adapted to the same variant of *S. campanulata* that is present in the Pacific region. Morphological characteristics are unreliable for identification to the subspecies level, making it difficult to determine the origin of the Pacific population. DNA sequencing of five non-coding regions and Inter-Simple Sequence Repeats were used to determine the origin of the introduced *S. campanulata* population in Fiji. The closest relatives to the Fijian *S. campanulata* were plants from Ghana indicating that the *S. campanulata* population in Fiji originated from the West African subspecies, *S. campanulata* subsp. *campanulata* Beauv. West Africa is therefore the most appropriate region to survey for potential biological control agents for the management of *S. campanulata* in the Pacific.

# Managing *Miconia calvescens* in Hawaii: Biology and Host Specificity of *Cryptorhynchus melastomae,* a Potential Biological Control Agent

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## Abstract

*Cryptorhynchus melastomae* Champion (Coleoptera: Curculionidae) is a stem boring weevil from Costa Rica under evaluation as a potential biological control agent for the invasive tree miconia, *Miconia calvescens* DC. (Melastomataceae). Adult *C. melastomae* feed externally on miconia foliage and stems, and larvae bore stems. Under lab rearing the life cycle of *C. melastomae* averages 218 days from egg deposition until death. Eggs hatch within two weeks; larvae undergo rapid growth for the first 70 days and pupate around day 111. Adult eclosion occurs at day 140, and the mean adult lifespan is 75 days, although it is not unusual for adults to survive 4-6 months. Adults reach sexual maturity at one month, and females lay large eggs at a rate of 3-6 per week up until death. Larval feeding can result in death of the distal portion of stem, and adult feeding can severely impact growing tips and leaf veins. Thirty two plant species, including a variety of natives and non-natives within the order Myrtales, were tested to assess potential non-target impacts of this weevil. No-choice and multi-choice tests with adult *C. melastomae* revealed a host range restricted to melastomes (family Melastomataceae), all of which are invasive weeds in Hawaii. In addition to miconia, adults fed mainly on arthrostemma (*Arthrostemma ciliatum* Pav. ex D. Don), Koster's curse (*Clidemia hirta* (L.) D. Don), false meadowbeauty (*Pterolepis glomerata* (Rottb.) Miq.), princess flower (*Tibouchina urvilleana* (DC.) Cogn.), Asian melastome (*Melastoma septemnervium* Lour.), pearlflower (*Heterocentron subtriplinervium* (Link & Otto) A. Braun & Bouché), and cane tibouchina (*Tibouchina herbacea* (DC.) Cogn.). Egg laying was largely restricted to a subset of these species. Ideally, *C. melastomae* might contribute to management of several species of weedy melastomes, but the actual consequences of such interactions with multiple hosts are difficult to predict.

# Biological Control for Management of Cane Tibouchina and Other Weedy Melastome Species in Hawaii

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## Abstract

*Syphraea uberabensis* Bechyné (Coleoptera: Chrysomelidae) is a South American flea beetle whose adults and larvae feed externally on foliage and soft stems of *Tibouchina* spp., causing enough damage to kill small plants. Under quarantine evaluation as a potential biological control agent for cane tibouchina, *Tibouchina herbacea* (DC.) Cogn. (Melastomataceae), *S. uberabensis* has been tested on a variety of native and non-native species within the order Myrtales to identify its expected host range in Hawaii. Multi-choice behavioral tests with adult beetles and no-choice tests with adults and larvae indicated a host range restricted to several species within the tribe Melastomeae, all of which are invasive weeds in Hawaii. Preferences were found for feeding and egg laying on cane tibouchina, longleaf glorytree (*Tibouchina longifolia* (Vahl) Baill. ex Cogn.), false meadowbeauty (*Pterolepis glomerata* (Rottb.) Miq.) and Asian melastome (*Melastoma septemnervium* Lour.), and all four of these species were suitable hosts for the complete life cycle of *S. uberabensis*. Beetles appeared unlikely to impact other seriously invasive melastomes including princess flower (*Tibouchina urvilleana* (DC.) Cogn.), miconia (*Miconia calvescens* DC.) and Koster's curse (*Clidemia hirta* (L.) D. Don). We consider the potential for using this biological control agent in management of multiple weedy melastomes.

# Biological Control of *Solanum mauritianum*: South African Experiences and Prospects for the Pacific Islands

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## Abstract

*Solanum mauritianum* Scop. (Solanaceae), a fast-growing tree with a high seed output, threatens commercial activities and natural habitats in several tropical, subtropical and warm temperate regions worldwide. The plant's high reproductive output, long-distance seed dispersal by birds and short-lived seed banks, suggest that it is an appropriate target for biological control using agents that can reduce its rapid growth rates and high levels of fruiting. South Africa was the first country to explore this possibility and has pursued it for 26 years. The program was recently extended to New Zealand, and several other countries (e.g., Pacific Islands) also may be able to benefit from South African experiences. Although surveys in South America have revealed several promising candidate agents, there have been major difficulties in securing their release because of the conservative nature of host-specificity testing and several cultivated and native plant species in the genus *Solanum*. Despite these hurdles, two agents have been released and established in South Africa and are now pending release in New Zealand. Guidelines for countries wishing to target *S. mauritianum* for biological control include: (i) conducting pre-introduction surveys of the plant and any native or cultivated *Solanum* species to record any host-range extensions of native insect herbivores and natural enemies that could affect introduced agents; (ii) selecting host-range testing methodologies that are less likely to yield ambiguous results; (iii) determining the economic or conservation status of all cultivated and native congeneric plants; (iv) quantifying the economic and environmental damage already caused by the weed in relation to any potential risks; and (v) conducting quantitative prerelease studies on the impact of promising agents. Although *S. mauritianum* is a difficult target for biological control, there is potential for success.

# Future Prospects for Biological Control of Weeds in Fiji Islands

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## Abstract

Fiji has been a strong supporter of biological control of weeds and insect pests. Biological control has been found to be a sustainable and environmentally friendly method, and a viable alternative to the steadily growing use of pesticides. In the past, the use of biological control has achieved great success in control of many weeds in Fiji. Taking this into account, biological control will be needed in the future for many introduced weeds, including African tuliptree (*Spathodea campanulata* P. Beauv.), fire plant (*Clerodendrum quadriloculare* (Blanc.) Merr.), noogora burr (*Xanthium pungens* Wallr.), merremia (*Merremia peltata* (L.) Merr.) , wedelia (*Sphagneticola trilobata* (L.) Pruski) and water lettuce (*Pistia stratiotes* L.). These weeds are major problems for crop cultivation, and are difficult to control using herbicides in some cases. Water lettuce, recently introduced through floriculture, is becoming a problem for waterways.

# Defoliation and Leaf-Rolling by *Salbia lotanalis* (Lepidoptera: Pyralidae) Attacking *Miconia calvescens* (Melastomataceae)

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## Abstract

*Salbia lotanalis* Druce (Lepidoptera: Pyralidae) is a leaf-roller that attacks miconia (*Miconia calvescens* DC., Melastomataceae) in Costa Rica and Brazil (Morais et al., 2010). We monitored population dynamics of *S. lotanalis* and quantified defoliation and leaf-rolling in *M. calvescens* leaves at a field site in central Costa Rica. Larval populations peaked during the transition from rainy season to dry season and were lowest at the end of the dry season. Leaf rolling and defoliation both greatly reduced leaf area exposed to sunlight, likely reducing photosynthetic capacity. Damage by *S. lotanalis* was very high compared to other leaf feeders attacking *M. calvescens* elsewhere in the native range, including larvae of the sawfly *Atomacera petroa* Smith (Hymenoptera: Argidae) and the moth *Antiblemma leucocyma* Hampson (Lepidoptera: Noctuidae) (Badenes-Pérez and Johnson, 2007; Badenes-Pérez and Johnson, 2008).

## References

Badenes-Pérez, F.R. & Johnson, M.T. (2007) Ecology and impact of *Atomacera petroa* Smith (Hymenoptera: Argidae) on *Miconia calvescens* DC. (Melastomataceae). Biological Control **43**, 95–101.

Badenes-Pérez, F.R. & Johnson, M.T. (2008) Biology, herbivory, and host specificity of *Antiblemma leucocyma* (Lepidoptera: Noctuidae) on *Miconia calvescens* DC. (Melastomataceae) in Brazil. Biocontrol Science and Technology **18**, 183–192.

Morais, E.G.F., Picanço, M.C., Barreto, R.W., Silva, G.A., Moreno, S.C. & Queiroz, R.B. (2010) Biology of the leaf roller *Salbia lotanalis* and its impact on the invasive tree *Miconia calvescens*. BioControl **55**, 685–694.

# Survey for Natural Enemies of *Bocconia frutescens* in Costa Rica

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## Abstract

Bocconia (*Bocconia frutescens* L.) (Papaveraceae) are small trees up to 6 m tall native to the Neotropics. Bocconia has established populations on the islands of Maui and Hawaii, spreading from dense groves in disturbed sites to invade native dryland and mesic forests, where it is considered a threat to rare endemic organisms. Bocconia is recognized as a noxious weed by the State of Hawaii, making it a target for eradication on islands where it is not already established. Mechanical and chemical controls have been pursued in some areas, but are prohibitively expensive over its present wide distribution. Bocconia is found in a variety of habitats in biodiversity-protected land of Costa Rica, typically colonizing disturbed areas such as tree falls and landslides but without displaying invasiveness. Plants in this native range were explored for insects and other natural enemies between December 2008 and September 2009. On monthly survey trips habitat and plant conditions were noted, and its natural enemies were photographed and collected for rearing and identification. A total of 38 species of natural enemies have been documented (35 insects, one mite, one phytoplasma and one fungus). Thus far only three potential control agents are recognized: a gregarious leafminer (*Liriomyza* sp.) (Agromyzidae), a treehopper (*Ennya pacifica* Fairmaire) (Membracidae) which deposits egg masses in leaf veins and inflorescence stems, and an unidentified leaf tier moth (Tortricidae) whose larvae damage young leaves. These insects appear to merit further study, but there may be serious constraints (for example, low impact and possible biotic interference) on their efficacy as biological control agents. Additional exploratory field work, perhaps in other areas of Bocconia's native range, might discover more promising biological agents.