Expanding classical biological control of weeds with pathogens in India: the way forward

P. Sreerama Kumar,[1] R.J. Rabindra[1] and C.A. Ellison[2]

Summary

Invasive alien weeds are a major constraint in agriculture, forestry and the environment in India. Classical biological control (CBC) of these exotic weeds through deliberate introduction of arthropods is almost a century-old practice. History has recently been made with the successful introduction of the first plant pathogen, *Puccinia spegazzinii* de Toni, against mikania weed (*Mikania micrantha* H.B.K.) in India. With the mechanism in place for the importation, quarantining and release of pathogens, it is envisaged that more introductions will be made in the future. The agent under immediate consideration is *Puccinia abrupta* Diet. and Holw. var. *partheniicola* (Jackson) Parmelee against parthenium weed (*Parthenium hysterophorus* L.), generally considered as the worst terrestrial social weed in India. Down the line, other terrestrial weeds such as *Chromolaena odorata* (L.) R. King and H. Robinson and *Lantana camara* L. and aquatic species like *Eichhornia crassipes* (Martius) Solms-Laubach could be targeted for pathogens. This article, besides presenting an overview of the research that has gone into selection of candidate fungi for CBC of *M. micrantha* and *P. hysterophorus*, also analyses the infrastructure and expertise requirements for further expanding the target list.

Keywords: *Mikania micrantha*, *Parthenium hysterophorus*, invasive alien weeds, Indian infrastructure for biological control, rust pathogens.

Introduction

The impact of invasive alien weeds on agriculture, horticulture, forestry and the environment has been felt for centuries in India. History is replete with examples of reports and records of 'new' and 'emerging' or 'invading' weeds. In India, traditionally an aggressive trading nation, movement of unwanted plants into and out of the country was probably widespread before the government-run quarantine system came into existence with the promulgation of the Destructive Insects and Pests Act in 1914.

Classical biological control (CBC) of these exotic weeds through deliberate introduction of natural enemies, principally arthropods, has been in practice for almost a century in India. Surprisingly, however, pathogens have not received much attention in India though the approach of manipulating plant pathogens for suppressing troublesome weeds has been known to science for more than a century (Wilson, 1969).

Nevertheless, India has now caught up with the rest of the pioneers in the field by recently introducing a host-specific plant pathogen, *Puccinia spegazzinii* de Toni, against mikania weed (*Mikania micrantha* H.B.K.), and thereby became the eighth country in the world to practise CBC of weeds with plant pathogens (Kumar *et al.*, 2005; Ellison *et al.*, 2006). It took more than three decades for India to adopt this strategy since the first successful use of an introduced pathogen elsewhere in the world, i.e. control of the skeleton weed, *Chondrilla juncea* L., in south-east Australia with the rust fungus, *Puccinia chondrillina* Bubak and Sydenham, was successfully implemented in the early 1970s (Cullen *et al.*, 1973).

A brief history of CBC of weeds in India

India has traditionally been one of the early-adopters of CBC of insect pests and weeds alike (see Table 1).

[1] Project Directorate of Biological Control, PB 2491, H.A. Farm Post, Hebbal, Bellary Road, Bangalore 560 024, India.
[2] CABI Europe-UK, Bakeham Lane, Egham, Surrey TW20 9TY, UK.
Corresponding author: P. Sreerama Kumar <psreeramakumar@yahoo.co.in>.

Table 1. Exotic natural enemies field-released for CBC of weeds in India.

Weed (purported year of introduction)	Agents released (year)[a]	Establishment in the field and impact
Terrestrial weeds		
Ageratina adenophora (Sprengel) R. King and H. Robinson (1900)	*Procecidochares utilis* Stone (1963)	Established - minimal control due to parasitoids
Chromolaena odorata (L.) King and H. Robinson (1914)	*Apion brunneonigrum* Béguin Billecocq (1972)	Not established
	Pareuchaetes pseudoinsulata Rego Barros (1973 and 1984)	Recently reappeared
	Cecidochares connexa (Macquart) (2005)	Established - too early to assess
Lantana camara L.(1809)	*Ophiomyia lantanae* (Froggatt) (1921)	Established - not effective
	Teleonemia scrupulosa Stål (1941)	Established - provides minimal control
	Diastema tigris Guenée (1971)	Not established
	Salbia haemorrhoidalis Guenée (1971)	Not established
	Octotoma scabripennis Guérin-Méneville (1972)	Established - not effective
	Uroplata girardi Pic (1972)	Established - not effective
Mikania micrantha H.B.K (1914)	*Puccinia spegazzinii* de Toni (rust pathogen, 2005 Assam and 2006 Kerala)	Established in Kerala - too early
Opuntia spp. (unknown)	*Dactylopius ceylonicus* (Green) against *Opuntia vulgaris* Miller (1795)	Established and provided excellent control
	Dactylopius confusus (Cockerell) against *O. vulgaris* (1836)	Not established
	Dactylopius opuntiae (Cockerell) against *Opuntia elatior* Miller and *Opuntia stricta* (Haworth) Haworth var. *dillenii* (Ker Gawler) L. Benson (1926)	Established and provided complete control of both species
Parthenium hysterophorus L. (1955)	*Zygogramma bicolorata* Pallister (1984)	Excellent control in some areas
Aquatic weeds		
Eichhornia crassipes (Martius) Solms-Laubach (1900)	*Neochetina eichhorniae* Warner (1983)	Established - provides good to variable control
	Neochetina bruchi Hustache (1984)	Established - provides good to variable control
	Orthogalumna terebrantis Wallwork (1986)	Established - alone not very effective
Salvinia molesta Mitchell (1955)	*Paulinia acuminata* (Degeer) (1974)	Established - uncertain control
	Cyrtobagous salviniae Calder and Sands (1983)	Established - spectacular control

[a]All agents are arthropods except where indicated otherwise.

Although the first exceptional success in CBC of a weed was in fact achieved with an erroneous introduction in 1795, that laid the foundation for further imports of specific natural enemies as a result of the realization of the potential of the approach. The agent in question was the mealybug *Dactylopius ceylonicus* (Green) introduced from Brazil in place of *Dactylopius coccus* Costa, the species intended for commercial production of cochineal dye. *D. ceylonicus* dramatically brought down the population of the prickly pear cactus, *Opuntia vulgaris* Miller, within 5 to 6 years in central and north India (Singh, 1989).

The same episode gave a lesson on the significance of host specificity as well. *D. ceylonicus*, when tried against *Opuntia stricta* (Haworth) Haworth var. *dillenii* (Ker Gawler) L. Benson [=*Opuntia dillenii* (Ker Gawler) Haworth], could not suppress the weed in south India. Subsequently, the intentional introduction of a North American species, *Dactylopius opuntiae* (Cockerell), from Sri Lanka in 1926 into India resulted in impressive control of *O. stricta* and the related *Opuntia elatior* Miller. This was the first successful intentional use of an insect to control a weed in India, and more than 40,000 ha area was thus cleared (Singh, 1989; Julien and Griffths, 1998).

The opuntia experience resulted in a series of introductions of phytophagous insects such as *Ophiomyia lantanae* (Froggatt) (ex Mexico, via Hawaii in 1921) against lantana weed (*Lantana camara* L.) *Procecidochares utilis* Stone (ex Mexico, via New Zealand in 1963) against crofton weed [*Ageratina adenophora* (Sprengel) R. King and H. Robinson] and *Pareuchaetes pseudoinsulata* Rego Barros (ex Trinidad in 1973) against Siam weed [*Chromolaena odorata* (L.) King and H. Robinson] (Julien and Griffiths, 1998).

In the post-independence era, CBC became more systematic and scientific with specific programmes managed by the erstwhile Indian Station of the Commonwealth Institute of Biological Control (CIBC) based in Bangalore. Later, country-specific programmes came under the purview of the All-India Coordinated Research Project (AICRP) on Biological Control of Crop Pests and Weeds, which was launched in 1977. This programme eventually came under the auspices of the Project Directorate of Biological Control (PDBC), which was formed in October 1993 under the Indian Council of Agricultural Research (ICAR). For weed control, only an insect and a plant pathogen have been introduced since the formation of PDBC. Table 1 provides the list of natural enemies other than fish imported for biological control of weeds in India and the current status of their impact.

An overview of two pathogen-based weed CBC projects in India

Target weed 1: *Parthenium hysterophorus*

The worst terrestrial social weed in India, *Parthenium hysterophorus* L., in general referred to as parthenium weed or 'congress grass', has been the primary target for possible biological control using both insects and pathogens.

Under the UK Department for International Development (DFID)-sponsored collaborative project between CABI Europe-UK (formerly CABI Bioscience) and the ICAR, between 1996 and 2000, development of both classical and the bioherbicide approaches were given prominence. Research in India culminated in the identification of a range of fungal pathogens of parthenium weed in Karnataka and Tamil Nadu in the south, Madhya Pradesh, Haryana, Punjab, Himachal Pradesh, Delhi and Uttar Pradesh in the north (Evans *et al.*, 2000). A few of these pathogens, despite possessing some potential as mycoherbicides, did not warrant the significant costs involved in further product development (Kumar and Evans, 2005).

In parallel research, two rust species were considered as options to be CBC agents, *Puccinia melampodii* Diet. and Holw. and *Puccinia abrupta* Diet. and Holw. var. *partheniicola* (Jackson) Parmelee. Both of these damaging rusts originate from Mexico and have already been fully screened and released in Australia for the control of parthenium weed. A comparison between these two rust species is given in Table 2.

P. abrupta var. *partheniicola* was found to severely reduce both the vegetative growth of young plants and the seed production of older plants under glasshouses conditions (Evans, 1987a, b). This rust is also known to be present in its exotic range, including India, though the strains do not appear to be widespread or aggressive as they are in their native range (Kumar and Evans, 2005). In India, the rust was first reported from an elevated site (930 m) (Evans and Ellison, 1987, cited by Parker *et al.*, 1994).

Unconfirmed reports suggest that *P. abrupta* var. *partheniicola* also occurs at lower elevations in India, but it is not a common pathogen of the weed (Kumar and Evans, 2005). A Mexican isolate (CABI no. W1905) of this rust was, however, found to be virulent and damaging to 12 *P. hysterophorus* collections from across India (Evans *et al.*, 2000).

Mexican isolates of *P. melampodii* (CABI nos. W1496 and W1500) were also found to be highly virulent towards the 12 Indian collections of *P. hysterophorus* producing high infection level and sporulation (Evans *et al.*, 2000). This rust was considered for introduction in India under the DFID project. However, the ability of the rust to infect calendula (*Calendula officinalis* L.) under glasshouse conditions could not be tolerated in India (as it was in Australia). Thus, field-based host-range testing was undertaken in Australia to see if Indian varieties of calendula could be infected under 'natural' conditions. Unfortunately, they were susceptible, and consequently the rust was not released in India.

Target weed 2: *Mikania micrantha*

The neotropical vine mikania weed is an increasing threat to natural and man-made forests as well as to several agricultural and horticultural ecosystems in India. Although in its native range *M. micrantha* is rarely weedy, in its exotic range, especially in south and south-east Asian countries, it has become an intractable weed over the past several decades. Because of its rapid growth habit, the plant, which can smother even such hardy trees as teak, eucalyptus, rubber, oil palm

Table 2. A comparison between two rust species used for the control of parthenium weed.

Puccinia melampodii	*Puccinia abrupta* var. *partheniicola*
Microcyclic, autoecious rust-producing telia and basidiospores	Macrocyclic, autoecious rust-producing uredinia and telia in the field. Pycnia and aecia have been induced in glasshouse conditions (Evans, 1987b)
'Summer rust' - found in the humid and warmer lowland plains of the Caribbean coast of Mexico (Evans, 1997)	'Winter rust' - found predominantly in the semi-arid, uplands of northern Mexico
Not present in India	Strain found in India (Evans and Ellison, 1987, cited in Parker *et al.*, 1994)
Infects calendula	Highly host-specific

and cocoa, has acquired one of its common names, mile-a-minute weed. Whereas in north-east India it is a great problem particularly in tea, it is an equally big problem in plantation crops in south-west India. The common control measures that are prevalent in tea gardens and plantations are either cultural or chemical means. These methods are expensive and impracticable. Moreover, chemical herbicides can be very harmful to the non-target plants, people and the environment.

Between 1996 and 1999, surveys were conducted throughout the tropical and sub-tropical American native range of *M. micrantha* for pathogens having potential for CBC in India. Three microcyclic rust species, *P. spegazzinii*, *Dietelia portoricensis* (Whetzel and Olive) Buriticá and J.F. Hennen and *Dietelia mesoamericana* H.C. Evans and C.A. Ellison, were found to occur in association with the plant (Evans and Ellison, 2005). However, *P. spegazzinii* was selected for use as a CBC agent in India after an extensive host-range screening and studies on the environmental requirements for the fungus (Ellison, 2001). This rust is a microcyclic, autoecious species that infects all aerial parts of the plant causing necrosis and cankering, leading to plant death. These studies were carried out in the CABI Europe-UK quarantine in Ascot with funding from DFID, under a collaborative project between CABI and research institutions in India between 1996 and 2000.

P. spegazzinii was imported into the National Containment-cum-Quarantine Facility (CQF) for Transgenic Planting Material of the National Bureau of Plant Genetic Resources (NBPGR) in New Delhi during 2003 and 2004. After establishing the fungus at NBPGR, an additional host-specificity screening was undertaken during 2004 and 2005. This involved 74 plant species, including 18 species that were earlier tested in the UK, and reconfirmed the results from the UK: the rust is totally specific to *M. micrantha*. At NBPGR, the rust was found to be pathogenic to populations of mikania weed from several locations within Kerala and Assam, which indicated that *P. spegazzinii* has considerable potential as a CBC agent for mikania weed in India.

A Supplementary Dossier on the additional host-specificity tests provided the basis for obta ining the permit for release of *P. spegazzinii* from the Plant Protection Advisor to the Government of India, Ministry of Agriculture, in June 2005 (Kumar *et al.,* 2005). 'Limited' field releases of the rust have been made since 2005 in both Assam and Kerala (Ellison *et al.*, 2006; Sankaran *et al.*, in this volume). India has thus become the eighth country in the world to have released a plant pathogen for the CBC of a weed. This is also the first time that a fungal pathogen is being used as a CBC for mikania weed. An estimate made in 2004 indicates that more than 26 species of fungi originating from 15 different countries have been used as CBC agents against more than 26 weed species in seven countries (Barton, 2004).

The mikania weed CBC project in India has become a 'flag-ship' project. Other Asian countries, including China, are following the Indian example for future management of *M. micrantha* using *P. spegazzinii*.

The contrasts between the parthenium and mikania weeds fungal-CBC projects are presented in Table 3.

Future strategies

Parthenium weed

India is continuing work on both 'off-the-shelf' pathogens and arthropod natural enemies to increase the suppression of parthenium weed, already achieved by *Zygogramma bicolorata* Pallister. The seed-feeding weevil, *Smicronyx lutulentus* Dietz, is planned to be imported for the second time once the new quarantine facility being constructed at PDBC is functional. In addition, project funding will be sought to undertake strain selection studies of both rusts. For *P. abrupta* var. *partheniicola*, the aim is to identify a virulent strain that will be efficacious under Indian conditions and for *P. melampodii*, other strains need to be tested to see if there exists a strain that does not infect calendula.

There is also the option to investigate the potential of new agents, for example the white smut fungus, *Entyloma compositarum* de Bary. This fungus, capable of provoking severe leaf necrosis through the coalescing of grey, senescing lesions, was found in upland, humid, subtropical areas in Mexico and in semi-arid rangelands in Argentina by Evans (1997). Though this pathogen has not been evaluated as a CBC agent, it seems to have considerable potential (Kumar and Evans, 2005), especially in the light of the spectacular success of the closely related species, *Entyloma ageratinae* Barreto and Evans, against the highly invasive upland and cloud forest ecosystems weed mist flower [*Ageratina riparia* (Regal) R. King and H. Robinson] in Hawaii (Barreto and Evans, 1988), and more recently in both

Table 3. Contrasts between the parthenium and mikania weeds fungal-CBC projects.

Parthenium weed project	Mikania weed project
Off-the-shelf agents available (previously released in Australia)	New agent identified and screened
Arthropod CBC agent already released in India	No previous CBC attempt in India
Puccinia abrupta var. *partheniicola* already present in India	No coevolved agents present in India
Non-target risk with *P. melampodii*	No non-target risk identified
Importation of rusts put on hold	Project led to release of rust in India

South Africa and New Zealand (Evans *et al.,* 2001; Barton, 2004).

Overall, it is considered that an integrated approach is required for this weed, depending on the habitat it is invading and the level of control needed. For example, in peri-urban areas, a high level of control is necessary due to its toxicity to humans. Kumar and Evans (2005) stated: '…it is our considered opinion that management of parthenium weed in India will only be achieved through an integrated strategy based on biological control, specifically the classical approach with the introduction of host-specific or coevolved natural enemies from the plant's centre of origin/diversity in the Neotropics'.

Mikania weed

The CBC project for mikania weed using *P. spegazzinii* is still in its early days since the release of the rust. However, there is a clear need to improve the rust release strategy to elicit an epidemic of the rust so it is in high enough concentrations to survive the dry season. CABI has seven strains of the rust under quarantine in the UK, and strains other than the one released in India may prove to be more aggressive under field conditions. In the future, it may be worth considering previously untried rust pathogens such as *D. portoricensis* and *D. mesoamericana* in new areas such as the Andaman and Nicobar Islands, or even in Assam and Kerala, if *P. spegazzinii* does not give substantial control of the weed. Finally, it should not be forgotten that substantial work has been undertaken on the arthropod natural enemies of mikania weed; the CBC potential of many were not fully investigated (Cock *et al.*, 2000).

The way forward in India

Infrastructure

A brand-new quarantine facility of international standards is being constructed on the PDBC campus in Bangalore, funded by ICAR. This two-storey containment facility will allow for an increase in entomological work on introduced natural enemies at PDBC. It will also have a pathogen-safe unit of level-4 containment (CL-4), to allow for the importation and screening of pathogens for the control of weeds and other pests. The upper floor or the 'Pathology' quarantine cell has two dedicated laboratories and a large greenhouse with three individual bays complete with cement platforms for plant propagation and handling. The entry to these is routed through a shower room sandwiched between two changing rooms to safeguard from entry of unwanted organisms and exit of organisms under quarantine. International standard air and water handling systems for quarantine facilities and equipment for waste disposal, viz. a double-ended autoclave and an incinerator, are integrated into the overall configuration. This facility is due to be finished and operational by early 2008.

Although the original aim was to undertake the mikania weed work in the PDBC facility, the CL-4 CQF on the NBPGR campus in New Delhi had to be used as an interim facility by PDBC for both the quarantining and host-specificity screening of *P. spegazzinii*. This facility also includes features such as outer and inner decontamination rooms provision for safe effluent treatment, a large incinerator and a dedicated generator as a stand-by for uninterrupted power supply are available.

With funds from the DFID mikania weed project, rust propagation units were constructed at the Assam Agricultural University (AAU, Jorhat) and the Kerala Forest Research Institute (KFRI, Peechi). These facilities have an area for plant propagation, an inoculation chamber and an area for rust infected plants to develop symptoms, prior to being placed in the field.

Expertise

One of the major outcomes of the DFID-funded collaborative projects on *P. hysterophorus* and *M. micrantha* has been the development of local expertise in handing and quarantining exotic weed pathogens for biological control. The involvement of a host of institutes across the country in these projects has resulted in invaluable know-how and do-how expertise in India.

Funding

Both the CBC projects on parthenium and mikania weeds were funded by DFID. Similarly, Indian government agencies, including ICAR and the Department of Biotechnology (DBT), have supported several research projects on biological control of weeds with pathogens, principally the mycoherbicide approach. Other international aid agencies operating in the Indian region may provide funding in future, e.g. the Australian Centre for International Agricultural Research (ACIAR). However, India is likely to have to look inward to national and regional funding in the future, as its economy continues to grow and the country becomes less dependent on external donor support.

Process

Although India has a long history of importing CBC agents for the control of invasive alien weeds, until the mikania weed project, all the natural enemies had been arthropods or fish. The mikania weed project is considered a flagship project in India through which policy and procedures for the import and release of fungal CBC agents have been developed. This should enable easy passage of future agents through the regulatory system and into the field (Ellison *et al.,* 2005).

Selection of future target weeds

Environmental weeds, both terrestrial and aquatic, should be the main targets of control through the classical strategy (Kumar, 2005), although it is important to note that most environmental weeds also impact on agro-ecosystems and/or agroforestry.

The use of fungal pathogens in weed CBC is a relatively young technology compared to employing arthropods. Thus, it is not surprising that most weed targets for CBC, using fungal pathogens, are those where arthropods have not been effective, and this holds true for the major invasive alien plants in India.

Ageratina adenophora

Crofton weed is not under control in India a gall fly has been released, but a suite of native parasitoids have prevented it from being effective. Other arthropods and pathogens have been identified, in the native range of the plant (Mexico), with good biocontrol potential, e.g., a lepidopterous and a curculionid stem borer and a rust fungus *Baeodromus eupatorii* (Arthur) Arthur. These agents have yet to be even established in the laboratory and thus are unlikely to be considered in the near future by India.

Chromolaena odorata

A suite of fungal natural enemies have been documented from *C. odorata* in its native range (Evans, 1987a; Barreto and Evans, 1994), some of which have been partially assessed in the glasshouse (Elango *et al.*, 1993). However, the recent release of the stem gall fly, *Cecidochares connexa* (Macquart), against this weed in India (Bhumannavar *et al.*, 2007) means that no further agents will be considered in the short term.

Cyperus rotundus

The grassy weed, purple nutsedge or nutgrass, *C. rotundus* L., which is broadly considered to be the world's worst weed (Holm *et al.*, 1977), hinders vegetable cultivation and is a huge problem in crops such as maize and sugarcane across India. It has an Old World centre of origin, possibly India, but the natural enemies do not seem to exert sufficient pressure to keep it under check in India, suggesting that its true centre of origin may be elsewhere.

Currently, a specific sub-project within the ICAR-funded network programme on 'Application of Micro-organisms in Agriculture and Allied Sectors' is being undertaken to develop a mycoherbicide-based strategy for its control. *Puccinia canaliculata* (Schwein) Lagerh (reported as *Puccinia romagnoliana* Maire and Sacc.), which is widely prevalent across India during winter, has been evaluated for augmentative use (Bedi and Sokhi, 1994). *Puccinia cyperi* Arthur and *Puccinia cyperi-tegetiformis* (Henn.) F. Kern, recorded in the Neotropics, and the *Uredo* spp., reported from the Old World (Barreto and Evans, 1995), are the pathogens that need to be explored for within India or considered for importation and evaluation.

Eichhornia crassipes

Water hyacinth [*Eichhornia crassipes* (Martius) Solms-Laubach] was successfully controlled in many areas in India in the 1980s, but there have been some resurgence problems due in part to eutrophication of water bodies. There is a wealth of unexploited pathogens in its native range (Upper Amazon) (Evans, 1987a). Charudattan (1996) advocated research on the lifecycle, host-range and biocontrol efficacy of the rust *Uredo eichhorniae* Gonz. Frag. and Cif., which is found only in South America, as a high-priority area. This will of course necessitate significant investment, since a full (5 years +) project will be required.

Invasive grasses

There are a number of grassy weeds of growing importance in India, for example littleseed canarygrass (*Phalaris minor* Retz.), originating from the Mediterranean, is a serious weed in wheat, and is developing resistance to certain herbicides. In addition, two species of *Echinochloa*, barnyard grass [*Echinochloa crus-galli* (L.) Beauv.] and jungle rice [*Echinochloa colona* (L.) Link.], are problematic in rice. Grasses are notoriously difficult targets for CBC because of their close relationship to staple crop species. However, some biotrophic pathogens are known to be species specific, within the Poaceae, and could be investigated for these two genera. For example, smuts and/or rusts have been recorded to infect species from both genera.

Lantana camara

Lantana weed has had a wide range of natural enemies released to control it throughout its invasive range. Some have been more successful than others at suppressing the weed (Broughton, 2000; Day *et al.*, 2003). India is yet to invest significantly in studying the most successful agents and considering them for introduction. This included a leaf rust, *Prospodium tuberculatum* (Speg.) Arthur (ex Brazil) that was released in Australia in 2001 (Ellison *et al.*, 2006; Thomas *et al.*, 2006) and *Puccinia lantanae* Farl. (ex Peru) that attacks leaves, petioles and stems, which has been partially screened and would seem to have potential for control of lantana weed in India (Renteria and Ellison, 2004).

Mimosa diplotricha

The giant sensitive plant, *Mimosa diplotricha* C. Wright, native to South America, has been selected by India for CBC using an off-the-shelf agent *Heteropsylla spinulosa* Muddiman, Hodkinson and Hollis. This psyllid is having a high impact on populations of this weed in Papua New Guinea and Australia and is soon to be imported into India (Kuniata and Korowi, 2001). Pathogens, such as the rust *Uredo mimosae-invisae* Viégas, may be worth future assessment.

Phanerogamic parasitic weeds

Both hemi-parasitic and holo-parasitic weeds continue to cause enormous losses in several crops in India. *Striga* spp. interfere with cereals and legumes, whereas *Orobanche* spp. parasitise roots of solanaceous (particularly, tobacco) and asteraceous (e.g. sunflower) crops. *Cuscuta* spp. are equally problematic to ornamentals and trees. The dipteran, *Phytomyza orobanchia* Kaltenbach, imported into India from the former Yugoslavia, could not be field-released against *Orobanche* spp. because of problems in rearing of the fly. Both soil-borne and air-borne fungal pathogens described on *Striga* and *Orobanche* species are broad-range pathogens, excepting a few varieties or *formae speciales* of *Fusarium* species (Kroschel and Müller-Stöver, 2003). Highly host-specific pathogens still need to be collected in the centres of origin of these phanerogamic parasitic weeds.

Conclusions

India has a fast-developing CBC of weeds programme that has now branched out and embraced pathogens as natural enemies. This strategy, therefore, finds an important place in the Perspective Plan ('Vision 2025') document of PDBC. The expertise, infrastructure and now the precedent set by importing and releasing the *M. micrantha* rust means that future projects are set to roll, with the process fully in place. There is a wealth of off-the-shelf arthropod and pathogen agents that could be fast-tracked for release over the next decade, targeting the most noxious weed species in India. In addition, many more pathogen agents have been identified that could be considered in the longer-term that require full assessment. However, significant financial support must be invested into this proven technology if the true potential is to be realized.

Acknowledgements

The authors are grateful to Dr. Harry C. Evans, for reviewing the manuscript. This publication is an output from the research projects funded by the United Kingdom Department for International Development (DFID) for the benefit of developing countries (R6695, R6735 and R8228 Crop Protection Programme). The views expressed are not necessarily those of DFID.

References

Barreto, R.W. and Evans, H.C. (1988) Taxonomy of a fungus introduced into Hawaii for biological control of *Ageratina riparia* (Eupatorieae: Compositae), with observations on related weed pathogens. *Transactions of the British Mycological Society* 91, 81–97.

Barreto, R.W. and Evans, H.C. (1994) The mycobiota of the weed *Chromolaena odorata* in southern Brazil, with particular reference to fungal pathogens for biological control. *Mycological Research* 98, 1107–1116.

Barreto, R.W. and Evans, H.C. (1995) Mycobiota of the weed *Cyperus rotundus* in the state of Rio de Janeiro, with an elucidation of its associated *Puccinia* complex. *Mycological Research* 99, 407–419.

Barton, J. (2004) How good are we at predicting the field host-range of fungal pathogens used for classical biological control of weeds? *Biological Control* 31, 99–122.

Bedi, J.S. and Sokhi, S.S. (1994) *Puccinia romagnoliana* rust - a possible biological control agent for purple nutsedge, *Cyperus rotundus*. *Indian Journal of Plant Protection* 22, 217–218.

Bhumannavar, B.S., Ramani, S. and Rajeshwari, S.K. (2007) Field release and impact of *Cecidochares connexa* (Macquart) (Diptera: Tephritidae) on *Chromolaena odorata* (L.) King and Robinson. *Journal of Biological Control* 21, 59–64.

Broughton, S. (2000) Review and evaluation of lantana biocontrol programs. *Biological Control* 17, 272–286.

Charudattan, R. (1996) Pathogens for biological control of water hyacinth. In: *Strategies for Water Hyacinth Control - Report of a Panel of Experts Meeting*, 11–14 September 1995, Florida, USA. Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 189–196.

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

Cullen, J.M., Kable, P.F. and Catt, M. (1973) Epidemic spread of a rust imported for biological control. *Nature* 244, 462–464.

Day, M.D., Wiley, C.J., Playford, J. and Zalucki, M.P. (2003) *Lantana: Current Management Status and Future Prospects*. ACIAR, Canberra, Australia. 128 p.

Elango, D.E., Holden, A.N.G. and Prior, C. (1993) The potential of plant pathogens collected in Trinidad for biological control of *Chromolaena odorata* (L.) King and Robinson. *International Journal of Pest Management* 39, 393–396.

Ellison, C.A. (2001) Classical biological control of *Mikania micrantha*. In: Sankaran, K.V., Murphy, S.T. and Evans, H.C. (eds) *Alien Weeds in Moist Tropical Zones, Banes and Benefits, Workshop Proceedings,* 2–4 November 1999. Kerala Forest Research Institute, Peechi, India and CABI Bioscience, UK Centre (Ascot), Berkshire, UK, pp. 131–138.

Ellison, C.A., Murphy, S.T. and Rabindra, R.J. (2005) Facilitating access for developing countries to invasive alien plant classical biocontrol technologies: the Indian experience. In: Harris, D., Richards, J.I., Silverside, P., Ward, A.F. and Witcombe, J.R. (eds) *Aspects of Applied Biology 75, Pathways Out of Poverty*. Association of Applied Biologists, c/o Warwick HRI, Wellesbourne, Warwick, UK, pp. 71–80.

Ellison, C.A., Puzari, K.C., Kumar, P.S., Usha Dev, Sankaran, K.V., Rabindra, R.J. and Murphy, S.T. (2006) Sustainable control of *Mikania micrantha* - implementing a classical biological control strategy in India using the rust fungus *Puccinia spegazzinii*. In: *Program and Abstracts, Seventh International Workshop on Biological Control and*

Management of Chromolaena odorata *and* Mikania micrantha, 12–15 September 2006. National Pingtung University of Science and Technology, Pingtung, Taiwan, Republic of China, pp. 3–4.

Evans, H.C. (1987a) Fungal pathogens of some subtropical and tropical weeds and the possibilities for biological control. *Biocontrol News and Information* 8, 7–30.

Evans, H.C. (1987b) Life-cycle of *Puccinia abrupta* var. *partheniicola*, a potential biological control agent of *Parthenium hysterophorus*. *Transactions of the British Mycological Society* 88, 105–111.

Evans, H.C. (1997) The potential of neotropical fungal pathogens as classical biological control agents for management of *Parthenium hysterophorus* L. In: Mahadevappa, M. and Patil V.C. (eds) *Proceedings of the First International Conference on Parthenium Management*, 6–8 October 1997, vol. 1. University of Agricultural Sciences, Dharwad, India, pp. 55–62.

Evans, H.C. and 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.

Evans, H.C., Greaves, M.P. and Watson, A.K. (2001) Fungal biocontrol agents of weeds. In: Butt, T.M., Jackson, C.W. and Magan, N. (eds) *Fungi as Biocontrol Agents*. CABI Publishing, Wallingford, UK, pp.169–192.

Evans, H.C., Seier, M., Harvey, J., Djeddour, D., Aneja, K.R., Doraiswamy, S., Kauraw, L.P., Singh, S.P. and Kumar, P.S. (2000) *Final technical report: Developing strategies for the control of parthenium weed in India using fungal pathogens*. Unpublished report submitted to the Department for International Development, UK. 191 p.

Holm, L.G., Plucknett, D.L., Pancho, J.V. and Herberger, J.P. (1977) *The World's Worst Weeds, Distribution and Biology*. University Press of Hawaii, Manoa, Honolulu, HI. 609 p.

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, UK. 223 p.

Kroschel, J. and Müller-Stöver, D. (2003) Biological control of root parasitic weeds with plant pathogens. In: Inderjit (ed.) *Weed Biology and Management*. Kluwer Academic Publishers, Amsterdam, The Netherlands, pp. 423–438.

Kumar, P.S. (2005) Scope of fungal pathogens in weed control in India. In: Rabindra, R.J., Hussaini, S.S. and Ramanujam, B. (eds) *Microbial Biopesticide Formulations and Application - Proceedings of the ICAR-CABI Workshop on Microbial Biopesticide Formulations and Application*, 9–13 December 2002. Technical Document No. 55, Project Directorate of Biological Control, Bangalore, India, pp. 203–211.

Kumar, P.S. and Evans, H.C. (2005) The mycobiota of *Parthenium hysterophorus* in its native and exotic ranges: opportunities for biological control in India. In: Prasad, T.V.R., Nanjappa, H.V., Devendra, R., Manjunath, A., Subramanya, Chandrashekar, S.C., Kiran Kumar, V.K., Jayaram, K.A. and Prabhakara Setty, T.K. (eds) *Proceedings of the Second International Conference on Parthenium Management*, 5–7 December 2005. University of Agricultural Sciences, Bangalore, India, pp. 107–113.

Kumar, P.S., Rabindra, R.J., Usha Dev, Puzari, K.C., Sankaran, K.V., Khetarpal, R.K., Ellison, C.A. and Murphy, S.T. (2005) India to release the first fungal pathogen for the classical biological control of a weed. *Biocontrol News and Information* 26, 71N–72N.

Kuniata, L.S. and Korowi, K.T. (2001) Biological control of the giant sensitive plant with *Heteropsylla spinulosa* (Hom.: Psyllidae) in Papua New Guinea. In: *Proceedings of the VI Workshop for Tropical Agricultural Entomology, Darwin, Australia*. Technical Bulletin Department of Primary Industry and Fisheries, Northern Territory of Australia No. 288, pp.145–151.

Parker, A., Holden, A.N.G. and Tomley, A.J. (1994) Host specificity testing and assessment of the pathogenicity of the rust, *Puccinia abrupta* var. *partheniicola*, as a biological control agent of parthenium weed (*Parthenium hysterophorus*). *Plant Pathology* 43, 1–16.

Renteria B., J.L. and Ellison, C.A. (2004) Potential biological control of *Lantana camara* in the Galapagos using the rust *Puccinia lantanae*. *SIDA* 21, 1009–1017.

Singh, S.P. (1989) *Biological Suppression of Weeds*. Technical Bulletin No. 1, Biological Control Centre, National Centre for Integrated Pest Management, Bangalore, India, 27 p.

Thomas, S.E., Ellison, C.A. and Tomley, A.J. (2006) Studies on the rust *Prospodium tuberculatum*, a new classical biological control agent released against the invasive alien weed *Lantana camara* in Australia, II: host range. *Australasian Plant Pathology* 35, 321–328.

Wilson, C.L. (1969) Use of plant pathogens in weed control. *Annual Review of Phytopathology* 7, 411–434.