PERSPECTIVE

Weed Biological Control Status and Options for Sri Lanka

Day, M. D. and Senaratne, K. A. D. W.

Department of Agriculture and Fisheries, GPO 267, Brisbane, Qld 4001, AUSTRALIA

* Corresponding author: michael.day@daf.qld.gov.au

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Abstract

Invasive alien plants can cause significant losses in production and biodiversity, and due to the high costs of conventional control, biological control is often the only feasible long-term option for their management. Weed biological control was first attempted in Sri Lanka in 1865, with the introduction of *Dactylopius ceylonicus* to control prickly pear (*Opuntia monacantha*). Since then, 10 more biological control agents have been introduced into Sri Lanka to control an additional six weed species. Field surveys were conducted to record invasive weeds in Sri Lanka that had been targets for biological control in other countries to identify possible biological control options for Sri Lanka.

Over 70 sites were surveyed, covering eight of the nine provinces. Nineteen weed species that are considered invasive and the target of biological control elsewhere were sighted. Biological control attempts have been initiated in Sri Lanka against six of these species: Chromolaena (*Chromolaena odorata*), water hyacinth (*Pontederia crassipes*), two types of prickly pear (*Opuntia monacantha*, and *Opuntia stricta*), parthenium weed (*Parthenium hysterophorus*) and salvinia (*Salvinia molesta*), with mixed success. Introduced biological control agents were not found in all areas where their target weed species were sighted. Therefore, the re-distribution of some of these agents, as well as the introduction of additional biological control agents for chromolaena, lantana (*Lantana camara*) and parthenium weed, could be reconsidered, given the priorities attached to these species.

During the surveys, four biological control agents that had not been deliberately introduced into Sri Lanka were found on lantana, and one agent was found on Noogoora burr (*Xanthium strumarium*), presumably having spread from India. However, as lantana is not considered under adequate control, the importation of several other biological control agents that have been released worldwide could be investigated. There are good biological control prospects for numerous other weed species also, including alligatorweed (*Alternanthera philoxeroides*), Madeira vine (*Anredera cordifolia*), air yam (*Dioscorea bulbifera*), mile-a-minute (*Mikania micrantha*), two types of giant sensitive plants (*Mimosa diplotricha* and *Mimosa pigra*), parrot's feather (*Myriophyllum aquaticum*) and water lettuce (*Pistia stratiotes*).

Keywords: *Chromolaena odorata*, *Lantana camara*, *Mikania micrantha*, *Parthenium hysterophorus*

Introduction

Invasive alien plants in Sri Lanka can cause significant losses in terms of production (up to 50%) and biodiversity, as well as affecting fishing, water quality and supply, and human health (Gunasekera, 2009; Rajapakse *et al.*., 2012; Amarasinghe and Labrada, 2013; Ministry of Health, 2017). Controlling such weeds can be problematic.

Herbicides can be expensive and require repeated use if infestations are to be controlled effectively (Doeleman, 1989; Culliney, 2005). For instance, in coconut plantations, 20% of production costs are due to weed management (Senarathne *et al.*., 2003). Herbicides can also affect other species as well as have negative impacts on human health and the environment (Day *et al.*., 2012; Elledge *et al.*, 2014). Mechanical or manual control by physical removal can be labour-intensive. In addition, not all plant parts necessarily are killed, and due to the rapid regeneration of some weeds, populations can quickly return to high levels (Day *et al.*., 2012; Amarasinghe and Labrada, 2013).

Biological control is seen as an environmentally friendly, cost-effective and self-sustaining method to control many weeds (McFadyen, 1998; Culliney, 2005; van Wilgen and De Lange, 2011; Schwarzländer et al., 2018; Winston et al., 2021). It has been practised in 91 countries, involving the deliberate release of over 500 species against over 200 weed species, of which over 100 weed species have been severely impacted by at least one biological control agent in at least one country (Winston et al., 2021). The degree of host specificity testing and the large number of countries in which some biological control agents have been released, with no unpredicted off-target impacts, reinforces the low risk that biological control offers many countries in the management of their weeds (McFadyen, 1998; Julien et al., 2007; Day and Winston, 2016; Schwarzländer et al., 2018; Hinz et al., 2019).

Biological control can be used in many agricultural areas and cropping systems, as well as in natural ecosystems where weeds are not always actively controlled (McFadyen, 1998; Culliney, 2005; Winston et al., 2021). The cost of introducing known, tried, and proven biological control agents can be less than the cost of one treatment of herbicide in an average plantation. In the United States, costs of non-biological control range from about US$90 per ha to US$21,000 per ha, depending on the weed and habitat (Thayer and Ramey, 1986).

Biological control of weeds in Sri Lanka began in 1865, with the introduction of *Dactylopius ceylonicus* (Green) (Hemiptera: Dactylopiidae) to control prickly pear [*Opuntia monacantha* (Willd.) Haw.] (Cactaceae). Since then, 10 more biological control agents have been deliberately introduced to control six weed species, with variable success (Winston et al., 2021). Black sage [*Cordia curassavica* (Jacq.) Roem. & Schult.] (Boraginaceae), two types of prickly pear (*O. monacantha*, *O. stricta* (Haw.) Haw.) and salvinia (*Salvinia molesta* D. S. Mitch.) (Salviniaceae) are all deemed under successful biological control in most parts of Sri Lanka. However, chromolaena [*Chromolaena odorata* (L.) R.M.King & H.Rob.] (Asteraceae) and water hyacinth (*Pontederia crassipes* Mart.) (Pontederiaceae) are not under adequate control, despite biological control agents being deliberately released and having established (Winston *et al..*, 2021).

In addition to those biological control agents deliberately released in Sri Lanka, three other biological control agents have been reported in Sri Lanka. These are *Lantanophaga pusillidactyla* (Walker) (Lepidoptera: Pterophoridae), *Ophiomyia lantanae* (Froggatt) (Diptera: Agromyzidae) and *Insignorthezia insignis* (Browne) (Hemiptera: Ortheziidae). These have all been used as biological control agents against lantana (*Lantana camara* L. *sens. lat.*) (Verbenaceae) elsewhere and spread naturally into Sri Lanka, possibly from India (Winston et al., 2021).

Despite the successes of weed biological control, both in Sri Lanka and elsewhere in the world, no biological control agent has been deliberately released in Sri Lanka since 2005 (Winston et al., 2021). However, numerous weed species that have been listed as major weeds in Sri Lanka, including several weed species that are included in a national priority list, e.g., Madeira vine [*Anredera cordifolia* (Ten.) Steenis] (Basellaceae), chromolaena, lantana and mile-a-minute (*Mikania micrantha* Kunth) (Asteraceae), (Gunasekera, 2009; Rajapakse *et al.*., 2012; Ranwala *et al.*., 2012; CABI, 2024), have been targeted for biological control in at least one other country (Winston et al., 2021). Effective biological control agents for these weed species could be introduced into Sri Lanka to help with the management of these weeds if appropriate.

Following discussions with several weed researchers in Sri Lanka, a field survey was conducted to determine the presence and distribution of weeds in the country, particularly those that are targets of biological control elsewhere and to determine if any biological control agents are present. This paper documents weeds present in Sri Lanka that have been targeted for biological control in other countries and lists possible host-specific and effective biological control agents used elsewhere, which could be introduced into Sri Lanka to help manage these species. There has been no attempt to determine weed impacts in Sri Lanka as these have been covered in other publications (e.g. Rajapakse et al., 2012; Ranwala et al., 2012) or to prioritise weed species, as this should be left to the appropriate authorities.

Materials and Methods

Literature searches and personal correspondence

Prior to undertaking the 2013 field survey in Sri Lanka, a literature search was conducted to determine what weed species known to be targets for biological control, either in Sri Lanka or in other countries, have already been recorded in Sri Lanka. Records of all known weed biological control attempts or biological control agents present in Sri Lanka were extracted from Julien and Griffiths (1998). Discussions through direct contact or via email with researchers in Sri Lanka were held to determine if additional biological control attempts have been conducted since Julien and Griffiths (1998). These preliminary investigations provided a basis for which weed species and their biological control agents were likely to be seen during the field surveys.

Field survey

A three-week field survey was conducted throughout much of Sri Lanka in June-July 2013. Sites were chosen based on the presence of visible infestations of weeds encountered in each district or region visited or when weed species, previously unrecorded during the survey, were sighted.

At each site, only weed species known to be targets for biological control in Sri Lanka or in other countries were recorded. For all target species encountered, any biological control agent that was present was also recorded. The location and altitude of each site were recorded using a hand-held global positioning system (GPS) unit.

Analysis

Weed species that have been targeted for biological control in other countries and sighted during the field surveys were added to the list of weed species recorded for Sri Lanka in the literature. New biological control agents not previously recorded in Sri Lanka were added to those listed in Julien and Griffiths (1998). Due to the time passed since the initial survey, the list was later updated using Winston et al. (2021). This gave a comprehensive list of weed species in Sri Lanka that have also been the target for weed biological control in other countries.

The list of known biological control agents deliberately introduced into Sri Lanka and their status and the list of known biological control agents that have been recorded present in Sri Lanka but not deliberately introduced, were updated with new information acquired.

From the known weeds present in Sri Lanka and biological control attempted elsewhere, a list outlining biological control agents that could be introduced into Sri Lanka if deemed appropriate was compiled. There was no attempt to prioritise which weed species should be studied, as this should be left to the appropriate organisations within Sri Lanka.

Results

A total of 71 sites, covering eight of the nine provinces in Sri Lanka, were sampled during the survey in 2013 (Figure 1). The Western Province was sampled the most times, with 17 sites sampled, while only one site in each of Sabaragamuwa and North Western Provinces was sampled. Only the Northern Province was not covered in the survey due to time constraints.

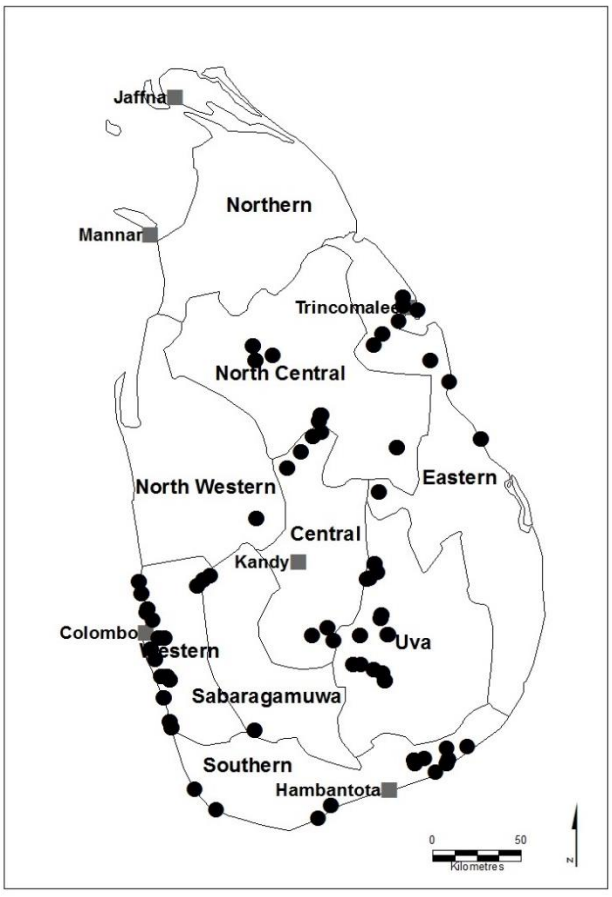


Figure 1 Sites in Sri Lanka that were surveyed in June-July 2013

Sites sampled ranged from 3 m above sea level (asl) in Eastern Province to 1902 m asl in Central Province and included sites in high rainfall areas around Nuwara Eliya Lake (average 1904 mm p.a.) in Central Province to drier regions around Hambantota (av. 1045 mm p.a.), Southern Province. Nineteen weed species that are known to be targets for biological control, either in Sri Lanka or in other countries (Winston et al., 2021), were seen during the survey (Table 1).

These included the three most important aquatic weeds in Sri Lanka, namely, water hyacinth, water lettuce and salvinia, which are also major weeds in many other Asian countries. Other major weed species that are biological control targets elsewhere and were found during the survey include chromolaena, lantana, mile-a-minute, two species of giant sensitive plants (*Mimosa* spp*.)* and parthenium weed. All are also widespread and problematic elsewhere in Asia.

Table 1 A list of weed species which have been targeted for biological control globally and were seen in Sri Lanka during the 2013 survey

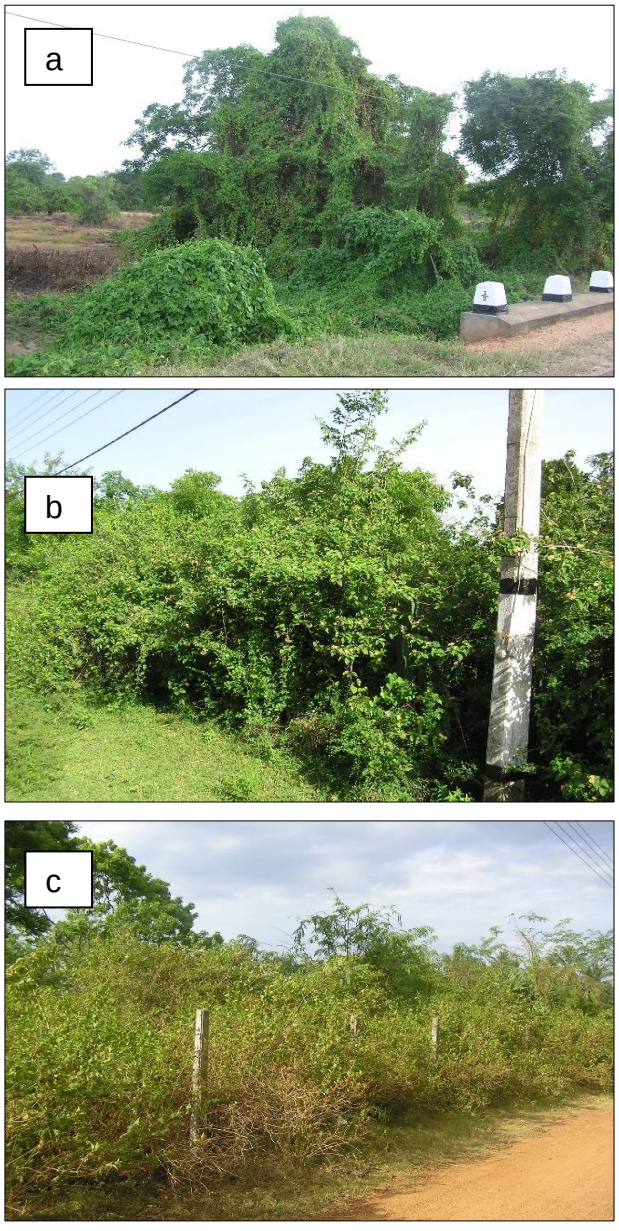
Family	Weed species	Common name	Habitat	Altitude where found (asl)
Amaranthaceae	*Alternanthera philoxeroides* (Mart.) Griseb.	alligator weed	aquatic	5-1900 m
Araceae	*Pistia stratiotes* L.	water lettuce	aquatic	5-175 m
Asteraceae	*Ageratina riparia* (Regel) R.M.King & H.Rob.	mistflower	riparian, cool, wet	600-1000 m
	**Chromolaena odorata* (L.) R.M.King & H.Rob.	chromolaena	grazing, roadsides	0-1000 m
	**Mikania micrantha* Kunth	mile-a-minute	farms, roadsides	0-1400 m
	**Parthenium hysterophorus* L.	parthenium weed	roadsides, fields	lowlands
	Xanthium strumarium L.	Noogoora burr	grazing, roadsides	600-700 m
Basellaceae	**Anredera cordifolia* (Ten.) Steenis	Madeira vine	riparian	~1300 m
Cactaceae	*Opuntia monacantha* (Willd.) Haw.	prickly pear	wastelands	5-277 m
	Opuntia stricta (Haw.) Haw.	prickly pear	wastelands	lowlands
Euphorbiaceae	*Jatropha gossypiifolia* L.	bellyache bush	wastelands	lowlands
Fabaceae	*Mimosa diplotricha* C. Wright	giant sensitive plant	grazing, roadsides	0-500 m
	**Mimosa pigra* L.	giant sensitive plant	grazing, roadsides	11-130 m
Haloragaceae	*Myriophyllum aquaticum* (Vell.) Verdc.	parrot's feather	aquatic	600-1900 m
Malvaceae	*Sida acuta* Burm.f.	spinyhead sida	grazing, roadsides	0-400 m
Melastomataceae	*Miconia crenata* (Vahl) Michelang.	Koster's curse	roadsides, higher altitudes	600-800 m
Pontederiaceae	**Pontederia crassipes* Mart.	water hyacinth	aquatic	5-1900 m
Salviniaceae	**Salvinia molesta* D.S.Mitch.	salvinia	aquatic	0-100 m
Verbenaceae	**Lantana camara* L.	lantana	grazing, natural forests	0-1800 m

* Weeds of National Significance in Sri Lanka (Rajapakse *et al.*., 2012)

The most widespread and most frequently found weed was mile-a-minute, which was found in all eight provinces covered in the survey and 63% of all sites sampled. Lantana was also found at 63% of all sites sampled but was only found in seven of the eight provinces surveyed. Chromolaena (52% of sites surveyed, seven provinces), spinyhead sida, *Sida acuta* Burm.f. (Malvaceae) (31%, six provinces) and water hyacinth (30%, six provinces) were also commonly found and widespread in Sri Lanka. Over

50% of the weed species found during the surveys were found at fewer than 10 sites each.

Of the weed species seen in the survey, six species have had biological control agents deliberately released against them in Sri Lanka. However, only three biological control agents that had been deliberately released, out of the eight that have reportedly been established, were found during the survey. These were *Cyrtobagous salviniae* Calder & Sands (Coleoptera: Curculionidae) on *S. molesta*, *D. ceylonicus* on *O. monacantha* and *Neochetina eichhorniae* Warner (Coleoptera: Curculionidae) on *P. crassipes*.



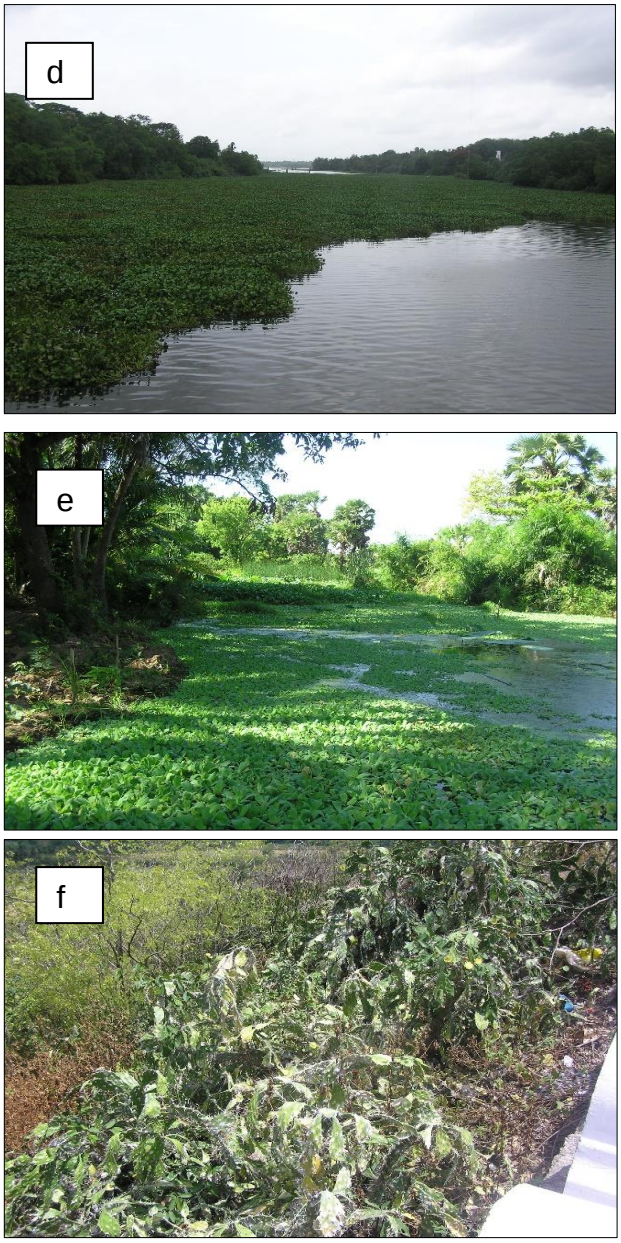


Figure 2. Various weed infestations in Sri Lanka: *M. micrantha* (a), *L. camara* (b), *C. odorata* (c), *P. crassipes* (d), *P. stratiotes* (e), *O. monacantha* damaged by *D. ceylonicus* (f).

A further eight biological control agents, which were not intentionally released into Sri Lanka, were found during the survey, possibly having spread from India or brought in on imported plants. Five of these agents were new records for Sri Lanka: *Calycomyza lantanae* (Frick) (Diptera: Agromyzidae), *Crocidosema lantana* Busck (Lepidoptera: Tortricidae), *Passalora lantanae* (Chupp) U. Braun & Crous var. *lantanae* (Capnodiales: Mycosphaerellaceae) and *Teleonemia scrupulosa* Stål (Hemiptera: Tingidae) on *L. camara*, and *Puccinia xanthii* Schweinitz on Noogoora burr *Xanthium strumarium* L. (Asteraceae).

In total, 17 biological control agents attacking nine weed species are now reported to be present in Sri Lanka (Tables 2 and 3). These agents are reported to have minimal to high impact on their respective target weeds and provide control of some of their target weed species in some areas (Winston *et al.*., 2021).

Table 2. Weed biological control agents (and their status) that have been deliberately introduced into Sri Lanka[a] (Winston et al., 2021)

Family	Weed species	Biological control agent introduced	Year introduced	Status[a]	Impact[a]
Asteraceae	**Chromolaena odorata* (L.) R.M.King & H.Rob.	*Apion brunneonigrum* Béguin-Billecocq	1975	Not established	
		Pareuchaetes pseudoinsulata Rego Barros	1973	Established	Variable
	**Parthenium hysterophorus* L.	*Zygogramma bicolorata* Pallister	2004	Not established	
Boraginaceae	*Cordia curassavica* (Jacq.) Roem. & Schult.	*Eurytoma attiva* Burks	1978	Established	High
		Metrogaleruca obscura (Degeer)	1978	Established	High
Cactaceae	*Opuntia monacantha* (Willd.) Haw.	*Dactylopius ceylonicus* (Green)	1865	Established[b]	High
Cactaceae	*Opuntia stricta* (Haw.) Haw.	*Dactylopius opuntiae* (Cockerell)	1925	Established	High
Pontederiaceae	**Pontederia crassipes* Mart.	*Neochetina eichhorniae* Warner	1988	Established[b]	Slight-variable
		N. bruchi Hustache	2005	Established	Slight-variable
Salviniaceae	**Salvinia molesta* D.S.Mitch.	*Cyrtobagous salviniae* Calder & Sands	1986	Established[b]	Variable-high
		Paulinia acuminata (De Greer)	1973	Not established	

* Weeds of National Significance in Sri Lanka; [a] From Winston *et al.*. (2021); [b] Seen during the survey

A total of 40 weed species reported as being present in Sri Lanka have been targeted for biological control in at least one country (Gunasekera, 2009; Rajapakse et al., 2012; Ranwala et al., 2012; CABI, 2024; Winston et al., 2021). Nine of these species are listed as weeds of national significance for Sri Lanka (Rajapakse *et al.*., 2012).

Of the 40 weed species that are present in Sri Lanka and have been targeted for biological control elsewhere, 19 species have highly effective biological control agents that are helping manage their respective weeds in other countries (Table 4). A further 21 weed species have biological control agents that cause only slight damage to their respective weed, or the impacts of the agent have not yet been assessed (Table 5).

Discussion

Eleven biological control agents targeting seven weed species have been deliberately introduced into Sri Lanka. Eight biological control agents have established from these introductions, with *Z. bicolorata* later establishing, following its natural spread from India, some 15 years later. In addition to *Z. bicolorata*, another eight biological control agents have spread naturally into Sri Lanka.

Thus, 17 biological control agents are now established in Sri Lanka, attacking nine weed species (Winston et al., 2021). Of the nine weeds that have biological control agents established in Sri Lanka, four weeds, namely black sage, two types of prickly pear and salvinia, are deemed under successful biological control in most parts of the country where their respective agents have established (Winston et al., 2021).

Table 3 Biological control agents that had naturally spread into Sri Lanka (Winston *et al.*., 2021)

Family	Weed species	Biological control agent	Guild	Impact
Asteraceae	*Parthenium hysterophorus* L.	*Zygogramma bicolorata* Pallister	leaf-feeding beetle	Unknown
Asteraceae	*Xanthium strumarium* L.	*Puccinia xanthii*[a] Schweinitz	rust pathogen	Slight
Verbenaceae	**Lantana camara* L.	*Calycomyza lantanae*[a] (Frick)	leaf-mining fly	Slight
		Crocidosema lantana[a] Busck	peduncle-boring moth	None
		Lantanophaga pusillidactyla (Walker)	flower-feeding moth	Moderate
		Ophiomyia lantanae (Froggatt)	fruit-feeding fly	Unknown
		Insignorthezia insignis (Browne)	stem sap-sucking bug	High
		Passalora lantanae (Chupp) U. Braun & Crous var. *lantanae*[a]	leaf pathogen	Slight
		Teleonemia scrupulosa[a] Stål	leaf sap-sucking bug	Slight

* Weeds of National Significance in Sri Lanka; [a] observed and reported in Sri Lanka for the first time in 2013

Table 4 Host-specific and effective biological control agents established elsewhere that could be introduced into Sri Lanka to help control their target weed species (Winston *et al.*., 2021).

Family	Weed species	Common name	Proposed biological control agent	No. of countries established	Overall impact elsewhere[a]
Amaranthaceae	*Alternanthera philoxeroides* (Mart.) Griseb.	alligator weed	*Agasicles hygrophila* Selman & Vogt	4	High
Araceae	*Pistia stratiotes* L.	water lettuce	*Neohydronomus affinis* Hustache	17	High
Asteraceae	*Ageratina adenophora* (Spreng.) R.M.King & H.Rob.	Crofton weed	*Passalora ageratinae* Crous & A.R.Wood	8	Variable
	Ageratina riparia (Regel) R.M.King & H.Rob.	mistflower	*Entyloma ageratinae* Barreto & Evans	4	High
			Procecidochares alani Steyskal	3	Variable
	**Chromolaena odorata* (L.) R.M.King & H.Rob.	chromolaena	*Cecidochares connexa* Macquart	11	Mainly high
	**Mikania micrantha* Kunth	mile-a-minute	*Puccinia spegazzinii* De Toni	5	Too early to assess
	**Parthenium hysterophorus* L.	parthenium weed	*Carmenta ithacae* (Beutenmüller)	1	High
			Epiblema strenuana (Walker)	4	High
			Listronotus setosipennis (Hustache)	1	Variable
			Puccinia xanthii var. *parthii-hysterophorae*	2	Variable
	Xanthium strumarium L.	Noogoora burr	*Epiblema strenuana*	4	Slight
Basellaceae	**Anredera cordifolia* (Ten.) Steenis	Madeira vine	*Plectonycha correntina* Lacordaire	1	Too early to assess

Family	Weed species	Common name	Proposed biological control agent	No. of countries established	Overall impact elsewherea
Bignoniaceae	*Dolichandra unguis-cati* (L.) L. G. Lohmann	cat's claw creeper	*Carvalhotingis visenda* Drake & Hambleton	2	Medium
			Hedwigiella jureceki (Obenberger)	1	Too early to assess
Cactaceae	*Opuntia monacantha* (Willd.) Haw.	prickly pear	*Cactoblastis cactorum* (Berg)	19	High
Cactaceae	*Opuntia stricta* (Haw.) Haw.	prickly pear	*Cactoblastis cactorum*	19	High
Dioscoreaceae	*Dioscorea bulbifera* L.	air potato	*Lilioceris cheni* Gressitt & Kimoto	1	High
Fabaceae	*Mimosa diplotricha* C. Wright	giant sensitive plant	*Heteropsylla spinulosa* Muddiman, Hodkinson & Hollis	15	High
Fabaceae	**Mimosa pigra* L.	giant sensitive plant	*Carmenta mimosa* Eichlin & Passoa	3	High
			Macaria pallidata (Warren)	1	Variable
			Malacorhinus irregularis Jacoby	1	Variable
			Neurostrota gunniella (Busck)	1	High
Haloragaceae	*Myriophyllum aquaticum* (Vell.) Verdc.	parrot's feather	*Lyathia* sp.	2	High
Malvaceae	*Sida acuta* Burm.f.	spinyhead sida	*Calligrapha pantherina* Stål	5	High
Melastomataceae	*Miconia crenata* (Vahl) Michelang.	Koster's curse	*Liothrips urichi* Stål	4	Mainly high
Verbenaceae	**Lantana camara* L.	lantana	*Aceria lantanae* (Cook)	2	Variable
			Falconia intermedia (Distant)	2	Medium
			Octotoma scabripennis Stål	7	Medium
			Ophiomyia camarae Spencer	11	Medium
			Uroplata girardi Pic	24	Mainly high

* Weeds of National Significance (Rajapakse *et al.*., 2012); [a] Winston *et al.*. (2021)

For the remaining weeds, namely, chromolaena, lantana, water hyacinth, parthenium weed and Noogoora burr, that have biological control agents established, adequate control has not yet been achieved (Winston et al., 2021). Black sage and its two biological control agents were not seen during the survey, presumably as the weed is reported to be under control (Winston et al., 2021) and, therefore, in very low densities. *Dactylopius opuntiae* (Cockerell) (Hemiptera: Dactylopiidae) was not seen on prickly pear (*O stricta*) at the only site where its target was found. This species is also deemed under control by its agent (Winston *et al.*., 2021). *Dactylopius ceylonicus* was particularly damaging to its host, the second prickly pear species (*O. monacantha*), at all the sites where it was observed. Both these control agents could be easily moved to new areas where their respective hosts are present without the agents.

Two of the aquatic weed species, e.g. water hyacinth and salvinia, that were widespread also did not always contain their respective biological control agents. As the agents, *Neochetina bruchi* Hustache and *N. eichhorniae,* both introduced to control water hyacinth and *Cyrtobagous salviniae* introduced to control salvinia, are highly effective (Winston et al., 2021), efforts could be made to re-distribute-them to areas in Sri Lanka where they are not already present.

Table 5 Host-specific biological control agents that are causing slight damage to the target weed elsewhere and that could be introduced into Sri Lanka to help control their target weed species (Winston et al., 2021)

Family	Weed species	Common name	Proposed biological control agent	No. of countries established	Overall impact elsewhere[a]
Bignoniaceae	*Spathodea campanulata* P.Beauv.	African tulip tree	*Colomerus spathodeae* (Carmona)	2	Too early
Cabombaceae	*Cabomba caroliniana* A.Gray	cabomba	*Hydrotimetes natans* Kolbe	1	Too early
Cyperaceae	**Cyperus rotundus* L.	nut grass	*Antonina australis* Froggatt	1	Slight
			Athesapeuta cyperi Marshall	3	Slight
			Bactra venosana (Zeller)	4	Slight
			Bactra verutana Zeller	1	High
Euphorbiaceae	*Jatropha gossypiifolia* L.	bellyache bush	*Stomphastis thraustica* Meyrick	1	Too early
Fabaceae	*Acacia dealbata* Link	silver wattle	*Melanterius maculatus* Lea	1	Medium
	Acacia decurrens Willd.	green wattle	*Melanterius maculatus* Lea	1	Medium
	Acacia longifolia (Andrews) Willd.	Sydney golden wattle	*Melanterius ventralis* Lea	1	Medium
			Trichilogaster acaciaelongifoliae (Froggatt)	2	Medium
	Acacia mearnsii De Wild.	black wattle	*Melanterius maculatus* Lea	1	Medium
	Acacia melanoxylon R.Br.	Australian blackwood	*Melanterius acaciae* Lea	1	Medium
	Caesalpinia decapetala (Roth) Alston	Mauritius thorn	*Sulcobruchus subsuturalis* (Pic)	1	Slight
	Leucaena leucocephala (Lam.) de Wit	leucaena	*Acanthoscelides macrophthalmus* (Schaeffer)	23	Slight
	Parkinsonia aculeata L.	parkinsonia	*Eueupithecia* spp.	1	Slight
			Penthobruchus germaini (Pic)	1	Slight
	Prosopis juliflora (Sw.) DC.	mesquite	*Algarobius prosopis* (Le Conte)	10	Slight
			Evippe sp. #1	1	Variable
			Neltumius arizonensis (Schaeffer)	4	Slight
	Ulex europaeus L.	gorse	*Agonopterix umbellana* (Fabricius)	3	Slight
			Exapion ulicis (Forster)	4	Slight

Family	Weed species	Common name	Proposed biological control agent	No. of countries established	Overall impact elsewherea
Fabaceae	*Ulex europaeus* L.	gorse	*Sericothrips staphylinus* Haliday	3	Slight
			Tetranychus lintearius Dufour	5	Slight-medium
	Vachellia nilotica subsp. *indica* (Benth.) Kyal. & Boatwr.	prickly acacia	*Acaciothrips ebneri* (Karny)	1	Too early
			Bruchidius sahlbergi Schilsky	1	Slight
			Chiasmia assimilis (Warren)	1	Variable
Hydrocharitaceae	*Egeria densa* Planch.	Brazilian waterweed	*Hydrellia egeriae* Rodrigues-Junior	1	Too early
	Hydrilla verticillata (L.f.) Royle	hydrilla	*Hydrellia pakistanae* Deonier	1	Variable
Melastomataceae	*Miconia calvescens* DC.	miconia	*Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc. f. sp. *miconiae* Killgore & L.Sugiyama	3	Slight-variable
Passifloraceae	*Passiflora tarminiana* Coppens & V.E.Barney	banana poka	*Septoria passiflorae* Sydenham	1	Variable
Poaceae	*Arundo donax* L.	giant reed	*Rhizaspidiotus donacis* (Leonardi)	2	Medium
			Tetramesa romana (Walker)	3	Medium
Pontederiaceae	**Pontederia crassipes* Mart.	water hyacinth	*Eccritotarsus catarinensis* (Carvalho)	1	Variable
			Megamelus scutellaris Berg	2	Medium-variable
			Niphograpta albiguttalis (Warren)	7	Mainly slight
			Orthogalumna terebrantis Wallwork	5	Slight-medium

* Weeds of National Significance (Rajapakse *et al.*., 2012); Winston *et al.*. (2021)

For other weed species, e.g., chromolaena, lantana and parthenium weed, only some of their respective biological control agents are present in Sri Lanka. *Pareuchaetes pseudoinsulata* Rego Barros (Lepidoptera: Erebidae), a biological control agent for chromolaena, is often only seasonally abundant (Day et al., 2013a) and populations may have been low during the time of these surveys. This may be why it was not detected.

The gall fly *Cecidochares connexa* Macquart (Diptera: Tephritidae) is proving very effective at controlling chromolaena in many countries in the Pacific, Asia and Africa (Day *et al.*., 2013b; Day and Winston, 2016; Winston *et al.*., 2021). Several additional and effective biological control agents for lantana and parthenium weed could also potentially be introduced into Sri Lanka to help improve the control of these weeds (Day *et al.*., 2003; Dhileepan and McFadyen, 2012; Winston *et al.*., 2021).

Literature searches show that there are at least 140 invasive weed species reported in Sri Lanka, of which 40 have been targeted for biological control in

at least one other country. Numerous biological control agents, considered to be host-specific and highly effective, i.e. having a moderate to high impact on their target weed elsewhere, have not been confirmed to be present in Sri Lanka. While some of the weeds in Sri Lanka that are not targets for biological control may be causing significant impacts on agriculture and the environment, there is merit in considering tried and proven biological control agents that have already been successfully utilised in other countries, even if the weed may not necessarily be the highest priority.

This is because all the native range surveys and host specificity testing have already been conducted elsewhere. Thus, it becomes a very cheap and effective way to help manage many weed species (Julien et al., 2007). However, prior to importing any biological control agent, it is worth conducting more detailed field surveys to determine the presence of some biological control agents, especially those that have been established in the region, such as in India.

A total of eight biological control agents, which were not deliberately introduced, have now been found in Sri Lanka (Winston et al., 2021). So, it is possible that other biological control agents established in India such as the chromolaena gall fly, may also be present but in low numbers and not detected in this study or by others.

Biological control of weeds offers a viable and cost-effective solution to managing many of Sri Lanka's worst weeds (Doeleman, 1989; Room and Fernando, 1992; McFadyen, 2008). Conventional control methods such as the use of herbicides, slashing or fire are not feasible in all areas where the weeds occur. Nor are these methods sustainable due to large areas affected or the large and prolonged seed banks (Culliney, 2005).

Fire cannot be used around plantations and crops due to possible damage to existing trees. The use of herbicides around crops is also risky due to the possible damage to crops and fruit and the health risks to farmers. Herbicides are also expensive and require multiple treatments to be effective (Doeleman, 1989; Culliney, 2005). In general, herbicides cannot feasibly be used in large areas. Slashing and manual control are time-consuming, and weeds can easily re-shoot from broken fragments and rootstocks (McFadyen, 1998; Day et al., 2012; Amarasinghe and Labrada, 2013).

The results of one of the few weed biological control projects undertaken by Sri Lanka, i.e. the introduction of *Cyrtobagous salviniae* from Australia for the management of salvinia during the 1980s, is testimony to how Sri Lanka has already benefitted from this transfer of technology (Room and Fernando, 1992). The cost of this transfer of technology is minimal in comparison to the huge costs that have been incurred by other countries for testing agents for their specificity or on-going conventional control.

The return on investment in the biological control of salvinia in Sri Lanka was estimated at 53:1 in cash and over 1600:1 in terms of labour costs (Doeleman, 1989). Apart from the high financial benefits, Doeleman (1989) also highlights how successful biological control of salvinia opens up new prospects for other weeds where chemical control is not feasible.

When considering the introduction of new biological control agents into Sri Lanka, it might be prudent to check what plant species were included in previous host specificity testing conducted elsewhere. This is because host specificity testing conducted in one country may not include particular species important to other countries. For example, *Neochetina bruchi* has been tested against over 250 plant species in 10 different countries, with each country testing plant species of particular economic or cultural importance to their own country (Julien *et al.*., 1999).

In another example, the rust *Puccinia spegazzinii* De Toni (Pucciniaceae) was tested against 130 plant species prior to its release against mile-a-minute in India (Ellison *et al.*., 2008; Kumar *et al.*., 2016). It was then tested against another 58 species prior to its introduction into China (Fu *et al.*., 2006), 104 species in Taiwan (S. S. Tzean, unpublished data) and another 11 species prior to its introduction into Papua New Guinea and Fiji (Day *et al.*., 2013c), as the original testing did not include plants important to those countries.

Including the studies conducted in Australia, where numerous other species were tested, 287 plant species have now been tested for susceptibility to the rust (Day and Riding, 2019), and the agent has been deliberately released into nine countries and has established in six of those (Winston et al., 2021).

Overall, there are many opportunities to improve the management of weeds in Sri Lanka using biological control (Tables 4 and 5). This paper lists some of the host-specific and most damaging biological control agents that have been utilised elsewhere, and that could be used in Sri Lanka if considered appropriate. A wealth of information is already available on biological control agents that have been tested for their specificity by countries

such as Australia (Julien *et al.*., 2012) and South Africa (Moran *et al.*., 2011) and released worldwide (Winston *et al.*., 2021). Due to the costs involved in host specificity testing, as these have to be conducted in appropriate quarantine facilities (Julien *et al.*., 2007), it is recommended that more emphasis is placed on the use of known, tested and effective biological control agents for the management of some of Sri Lanka's worst weeds. This paper deliberately has not prioritised weeds, as this is a decision that is best made by the relevant authorities in Sri Lanka.

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