Weed biological control in the Greater Mekong Subregion: status and opportunities for the future

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Abstract

The status of weed biological control in the six Greater Mekong Subregion (GMS) countries was assessed, and opportunities to develop biological control in the region are proposed. Twenty biological control agents targeting nine weed species have been introduced into GMS countries, with 13 agents establishing on seven weed species. Another nine biological control agents have spread unintentionally into the region. These agents are having a slight to high impact on their target weeds. However, the number of weeds in the region that have been targeted for biological control is only a fraction of the number of weeds (45) in the region that have been targeted for biological control elsewhere. This presents a tremendous opportunity to expand weed biological control in the region and reduce the dependency on herbicides while increasing productivity. There are numerous highly effective biological control agents present elsewhere that could be introduced to assist with the management of the region's most important weeds, such as *Pistia stratiotes*, *Salvinia molesta*, *Chromolaena odorata* and *Mikania micrantha*. Along with the introduction of biological control agents, there is also a scope to increase the capacity and training in biological control within GMS countries to develop effective weed control and management.

Keywords: Host specific, *Chromolaena odorata*, *Mikania micrantha*, *Salvinia molesta*

Review Methodology: Information on the status of weed biological was obtained from the on-line catalogue. Information on the list of alien invasive weeds which are present in each of the six GMS countries was obtained from various web-based databases (key words: country, invasive plant) and publications. We supplemented this with local knowledge in each country not present in any database or publication. We then applied various criteria (biological control targets, non-target impacts, medium to high impacts) to finalise a list of weeds that were targets for biological control in at least one country and that had biological control agents that were low-risk and causing medium to high impacts against the target weed.

Introduction

The Greater Mekong Subregion (GMS) is a natural economic area bound by the Mekong River Basin, covering 2.6 million square kilometres with a combined population of approximately 326 million people [1, 2]. The GMS countries are Cambodia, the People's Republic of China (specifically Yunnan Province and Guangxi Zhuang Autonomous Region), Lao People's Democratic Republic (Lao PDR), Myanmar, Thailand and Vietnam. Originating in China's Qinghai Province, the Mekong River (known in China as Lancang Jiang and Thailand as Mae Nam Khong), flows through Yunnan Province, China and forms the border between Myanmar and Lao PDR and most of the border between Lao PDR and Thailand. It then flows through Cambodia and southern Vietnam into a rich delta, before emptying into the South China Sea. The total length of the river is 4880 km, including 2161 km in China (1237 km in Yunnan Province) [2, 3].

The GMS is one of the most abundant areas of global biodiversity. The region is rich in water resources and fertile arable land. It is the main production and export area

for rice worldwide; Thailand and Vietnam's rice exports have been the largest and the second largest in the world, respectively, for many years [4], and the rubber production base of GMS is the largest in the world. In addition, the production of tropical fruit and aquatic products is also of significant economic importance in the region [5].

The six GMS countries belong to the developing countries of the world, and agriculture is the main economic pillar, accounting for a high proportion of their GDP, especially Myanmar, Lao PDR and Cambodia [4]. Most poor and malnourished people that live in rural areas of the region are dependent on subsistence and small-scale agriculture. Thus, sustainable agricultural production is highly important to food security in GMS countries.

Due to complex geographical and ecological conditions, the GMS is seriously afflicted with pests and invasive alien species, and the risk is increasing through cross-border trade and travel [6–8]. The threats posed by pests and invasive alien species are far beyond the management ability of any one country in the GMS and require effective regional cooperation. Currently, a great number of agricultural pests and invasive alien species, especially the rice planthopper, rice blast and noxious weeds, have become severe, resulting in huge economic losses and even threatening sustainable development of agriculture and livelihoods. In China alone, economic losses due to invasive alien species exceeds US$14 billion per year [9]. Therefore, there is an urgent need to cope with this situation through GMS plant protection workers taking joint action immediately [8].

In order to improve sustainable agricultural development and strengthen prevention and control of agricultural pests in GMS, the Plant Protection Working Group in GMS (PPWG-GMS) was established in August 2011 (under approval of the Third Steering Committee Meeting of the Exchange and Cooperation Consortium for Agricultural Science and Technology in GMS). The delegates represented the Cambodian Agricultural Research and Development Institute, Yunnan Academy of Agricultural Sciences, National Agriculture and Forestry Research Institute of Lao PDR, Myanmar Academy of Agricultural, Forestry, Livestock, and Fishery Sciences, Department of Agriculture, Ministry of Agriculture and Cooperatives of Thailand and Vietnam Academy of Agricultural Sciences. Much has been accomplished by membership institutions and experts of the PPWG-GMS since its founding, including multilateral cooperation and technology exchange, joint field surveys, technology training and green control demonstrations for rice and vegetable pests [10].

The costs of managing agricultural pests in the GMS, particularly invasive alien plants, can be extremely high. In China, the manual removal of *Eichhornia crassipes* (Mart.) Solms (Pontederiaceae) (water hyacinth) between 1991 and 2001 cost over US$12 million per year, but it was not effective [11]. Unfortunately, figures to control weeds in most countries in Asia are unavailable. However, elsewhere, the cost of weed control also runs into the millions of dollars. The cost to control *E. crassipes* on Lake Victoria in East Central Africa is over US$8.3 million per annum (p.a.), while Egypt spends approximately US$7 million p.a. to control aquatic weeds [12].

Considering that thousands of hectares have been invaded by these and other weeds in Asia, it is unlikely that these and many other plant species will be effectively controlled by mechanical and chemical means alone. Consequently, there is an urgent need to find economically sustainable solutions to existing and emerging weed problems in GMS countries. Biological control is a low-risk, self-sustainable alternative used to manage many weeds in many countries [13–15]. Indeed, China, Myanmar, Thailand and Vietnam have already deliberately introduced biological control agents to control some of their worst weeds. Numerous other weed biological control agents have also spread unintentionally into the region [15].

Training workshops and field surveys of invasive alien plants have recently been conducted in some GMS countries through cooperation between Yunnan Academy of Agricultural Science, China, the Centre for Agriculture and Bioscience International and the Queensland Department of Agriculture and Fisheries, Australia [16]. However, the biological control programme of invasive alien plants in GMS countries could be strengthened further due to the lack of specialist researchers in weed biological control in the region. This paper reviews the current status of classical biological control efforts against introduced weeds in the six GMS countries and identifies low-risk and effective biological control agents that could be introduced into GMS to help manage some of the worst weeds in the region.

Materials and Methods

The status of weed biological control in the six GMS countries was determined by extracting information from Winston *et al*. [15]. To this dataset, we added information from reports and communications acquired since its publication, resulting in the most current status of weed biological control activities in the region [16, 17].

A list of weeds present in each of the six GMS countries that are biological control targets elsewhere was obtained by first extracting from various databases and lists of alien plant species in each GMS country [18–20]. We supplemented this with local knowledge in each country, adding alien plant species present in a country but not present in any database.

From this compilation, we extracted all plant species that have been the target for weed biological control in at least one country worldwide (using [15]). We then removed all plant species that are considered native to Southeast Asia, leaving a list of plant species exotic to the region and that are targeted for weed biological control in at least one other country.

The plant list was reduced further by removing species for which there were only biological control agents under list 2 in Winston *et al.* [15]. These are biological control agents considered native to a country, yet employed to help manage weed populations within that country. We also removed plant species for which the biological control agents were only under list 3 of Winston *et al.* [15]. These are biological control agents that have been unintentionally introduced or have spread naturally into a country. Biological control agents in both these groups have never been subjected to host specificity testing, so they have not been proven suitable for release into a new country and should not be recommended for additional introductions. Biological control agents found in these two lists but also in list 1 (classical biological control agents intentionally released elsewhere in the world) were not removed.

We next removed plant species for which the only biological control agents available had reports of significant impacts against non-target species. We defined significant impacts as the biological control agents could cause damage and maintain populations on a desirable non-target species. Plant species with biological control agents that were reported to cause only occasional minor damage due to spillover effects were not removed [15].

Finally, the list was further reduced by removing plant species for which the only biological control agents available are ineffective. This resulted in a list of weed species for which there was at least one biological control agent that was considered low risk (i.e. host specificity testing had been conducted and specificity confirmed) and that was causing medium to high impacts on their target weed in at least one country elsewhere.

Tables of biological control agents that could be introduced into the six GMS countries (if target weeds were deemed sufficiently problematic) were prepared based on whether the biological agents were already present in Asia, present in other countries outside Asia and that have been recently released but impacts on their target weeds have not yet been determined.

There was no attempt to prioritize which weed species in each country should be targeted, as weed lists were based on their occurrence in a particular country and not whether they were causing impacts. The prioritization of weeds is, therefore, best left to the relevant authorities in each country. However, we have identified the most effective biological control agents available for each plant species, should biological control be considered for a particular weed.

Results

At least two weed biological control agents have established in each of the six GMS countries (Table 1). However, only four of the six countries have deliberately introduced weed biological control agents. Thailand has been the country most active in weed biological control, deliberately introducing 14 biological control agents against six weed species. China has also been very active, deliberately introducing nine biological control agents against five weed species.

Twenty biological control agents have now been deliberately introduced into the GMS region to control nine weed species. Of these, 13 biological control agents have established in at least one country. Nine biological control agents have been either unintentionally introduced or have spread naturally into the region from neighbouring countries (Table 2). A tenth species, *Orthezia insignis* Browne (Hemiptera: Ortheziidae), which is often found on *Lantana camara* L. (Verbenaceae), is also present in the region. However, this species attacks several non-target plants and is not considered a bona fide biological control agent; it is not recommended for introduction or re-distribution.

Of the biological control agents that have established in the region, the flea beetle *Agasicles hygrophila* Selman & Vogt (Coleoptera: Chrysomelidae) for the control of *Alternanthera philoxeroides* (Mart.) Griseb. (Amaranthaceae) and *Ophraella communa* LeSage (Coleoptera: Chrysomelidae) for the control of *Ambrosia artemisiifolia* L. (Asteraceae) are probably the most successful agents. Two beetles, *Neochetina bruchi* Hustache (Coleoptera: Erirhinidae) and *N. eichhorniae* Warner, introduced to control *E. crassipes*, cause variable degrees of control, depending on the location and types of infestations [15] (Table 2).

Most of the biological control agents established in the GMS region that are causing medium to high impacts against their target weeds are not present in all the countries with the weed. GMS countries where these biological control agents could be introduced are listed in Table 2.

Some biological control agents present in the region cause no or only slight damage to their target weeds, while others have not been assessed for their weed control efficacy. Biological control agents that are ineffective or have not been assessed have not been recommended for introduction to other countries (Table 2). However, those agents not assessed could be considered for introduction into other countries if their impacts were ever shown to be moderate to high.

There are 45 alien weed species present in the GMS region that are targets for biological control in at least one country worldwide (Table 3). Many of these weed species are quite widespread and are found in most GMS countries; nine species occur in all six countries. However, 14 species are reported to occur in only one of the GMS countries.

Ten biological control agents found elsewhere in Asia, and causing medium to high impacts on their target weeds, could be introduced into the GMS region where their respective target weed occurs (Table 4). Some of the more widely established and effective agents include *Cyrtobagous salviniae* Calder & Sands (Coleoptera: Erirhinidae) for the control of *Salvinia molesta* D.S. Mitch. (Salviniaceae) and *Cecidochares connexa* Macquart (Diptera: Tephritidae) for

Table 1 The number of weed species targeted for biocontrol and the number of biocontrol agents that have been deliberately introduced (intentional) and biocontrol agents that were not deliberately introduced but have been reported (unintentional) in the Greater Mekong Subregion countries

	Intentional introductions			Unintentional introductions		Total introductions	
Country	No. of weed species	No. of agents released	No. of agents established	No. of weed species	No. of agents established	No. of weed species	No. of agents established
Cambodia	0	0	0	2	2	2	2
China	5	9	6	7	10	9	16
Laos	0	0	0	2	3	2	3
Myanmar	2	3	3	3	5	4	6[1]
Thailand	6	14	9	3	6	8	15
Vietnam	3	7	4	3	4	5	8

[1]Two *Acanthoscelides* spp. had spread from Thailand and were later deliberately released to supplement field populations.

the control of *Chromolaena odorata*. Both of these agents are already present in four other countries in Asia.

Over 40 biological control agents causing medium to high impacts on 32 weed species are present outside of Asia (Table 5). These agents could be introduced into GMS countries if target weed infestations warrant it. Of these agents, *Neohydronomus affinis* Hustache (Coleoptera: Curculionidae) for the control of *Pistia stratiotes* L. (Araceae) is the most effective and widespread agent, being utilized in 19 countries. *Cactoblastis cactorum* Berg (Lepidoptera: Pyralidae) for the control of *Opuntia* spp. (Cactaceae) is also effective and widespread, and is also utilized in 19 countries.

Numerous biological control agents have only recently been released and/or their impacts have not yet been assessed (Table 6). These biological control agents have been thoroughly tested and deemed suitable for release, although releases have been made in only a few countries to date. These agents could be considered for introduction into the GMS, subject to field evaluations in countries where they have been released.

Discussion

Biological control of weeds has a long history in Asia, commencing in 1836 when the cochineal *Dactylopius confusus* Cockerell (Hemiptera: Dactylopiidae) was intentionally distributed within India to control *Opuntia monacantha* (Willd.) Haw. (Cactaceae). Since then, 42 biological control agents have been introduced into 15 countries in Asia to control 19 weed species [15]. Within the GMS, biological control agents have been deliberately released into only four countries. However, biological control agents can move, and all six GMS countries now contain at least two biological control agents. These agents are causing slight to high impacts on their target weeds.

Despite some success in weed biological control in the GMS, only one biological control agent has been deliberately released in the region in the last 20 years. The reasons for this lack of recent activity are many [21–23]. For some countries, there is no clear process or regulatory pathway to facilitate the introduction of biological control agents [23]. Such is the case in Cambodia and Lao PDR where biological agents have never been deliberately introduced. Other countries have processes in place, but they are reluctant to approve the release of a biological control agent. There is a lingering perception that either the biological control agent would not control the weed in all regions and therefore it is not useful [23], or that biological control is risky and that biological control agents could evolve or mutate to attack economically important or other desirable plant species [21].

There remains a lack of understanding of insect–plant interactions and host specificity testing, and what is involved when assessing potential biological control agents. Weed biological control has been practised since 1902, resulting in nearly 500 biological control agents being deliberately released on nearly 200 weed species in over 90 countries [15]. The vast majority of biological control agents were thoroughly tested against many plant species (sometimes against up to 100 plant species) prior to their release, and they have been established in the field for many years, even decades, without any reports of non-target impacts.

The two beetles *N. bruchi* and *N. eichhorniae* to control *E. crassipes* have been deliberately introduced into over 35 countries, while *Teleonemia scrupulosa* Stål (Hemiptera: Tingidae) and *Uroplata girardi* Pic (Coleoptera: Chrysomelidae), both biological control agents for *L. camara*, have each been introduced deliberately into over 25 countries; no non-target impacts have been reported for all four agents [15]. Yet, the introduction of these and other biological control agents is met with resistance due to perceived risks to the environment and agriculture.

A major hurdle is that for some countries, the impact of weeds on agriculture, the environment and human health has not been fully documented. The lack of understanding in the importance of weeds results in a reduced need to implement biological control or other management strategies. Where the importance of weeds has been documented, there is often a lack of capacity for weed biological control programmes, in terms of infrastructure

Table 2 Status of weed biocontrol agents deliberately released (intentional) and/or spread of their own accord (unintentional) into the Greater Mekong Subregion countries and the potential GMS countries in which they could be introduced

Weed family	Weed species	Biocontrol agent family	Biocontrol agent species	Guild	KHM	CHN	LAO	MMR	THA	VNM
Amaranthaceae	*Alternanthera philoxeroides* (Mart.) Griseb.	Chrysomelidae	*Agasicles hygrophila* Selman & Vogt	Leaf-feeding		I E H	*	*	I E H	*
Asteraceae	*Ageratina adenophora* (Spreng.) R. M. King & H. Rob.	Mycosphaerellaceae	*Passalora ageratinae* Crous & A.R. Wood	Pathogen		U E ?	~		~	~
		Tephritidae	*Procecidochares utilis* Stone	Stem-galling		I E S	*		I E S	*
	Ambrosia artemisiifolia L.	Chrysomelidae	*Ophraella communa* LeSage	Leaf-feeding		U E H				
			Zygogramma suturalis Fabricius	Leaf-feeding		I F				
		Tortricidae	*Epiblema strenuana* Walker	Stem-boring		I E M				
	Chromolaena odorata (L.) R. M. King & H. Rob.	Erebidae	*Pareuchaetes pseudoinsulata* Rego Barros	Leaf-feeding	~	~	~	~	I F	I F
		Eriophyidae	*Acalitus adoratus* Keifer	Leaf-galling	~	U E S	U E S	U E S	U E S	U E S
		Tephritidae	*Cecidochares connexa* Macquart	Stem-galling					I F	
	Mikania micrantha Kunth	Pucciniaceae	*Puccinia spegazzinii* De Toni	Pathogen		I F				
	Parthenium hysterophorus L.	Pucciniaceae	*Puccinia abrupta* Dietel & Holw. var. partheniicola (H.S. Jacks.) Parmelee	Pathogen		U E ?		*	*	*
		Tortricidae	*Epiblema strenuana* Walker[1]	Stem-boring		*		*	*	*
Fabaceae	*Leucaena leucocephala* (Lam.) de Wit	Chrysomelidae	*Acanthoscelides macrophthalmus* Schaeffer	Seed-feeding	*	U E S	*	*	U E ?	U E ?
	Mimosa pigra L.	Brentidae	*Coelocephalapion aculeatum* Fall	Flower-feeding					I F	
		Chrysomelidae	*Acanthoscelides puniceus* Johnson	Seed-feeding	~	~	U E ?	I E ?	I E S	I E N
			Acanthoscelides quadridentatus Schaeffer	Seed-feeding	~	~	U E ?	I E ?	I E S	I E N
			Chlamisus mimosae Karren	Leaf-feeding	~	~	~	~	I ?	I ?
		Sesiidae	*Carmenta mimosa* Eichlin & Passoa	Stem-boring	*	*	*	*	I F	I E M
Lamiaceae	*Clerodendrum chinense* (Osbeck) Mabb.	Chrysomelidae	*Phyllocharis undulata* (L.)	Leaf-feeding					I E ?	
Pontederiaceae	*Eichhornia crassipes* (Mart.) Solms	Crambidae	*Niphograpta albiguttalis* Warren	Petiole-boring	*	*	*	*	I E ?	*
			Xubida infusella Walker	Crown-boring	~	~	~	~	I E ?	~
		Erirhinidae	*Neochetina bruchi* Hustache	Crown-boring	*	I E V	*	*	I E H	I E ?
			Neochetina eichhorniae Warner	Crown-boring	U E ?	I E V	*	I E ?	I E H	I ?
		Miridae	Eccritotarsus catarinensis Carvalho	Leaf-feeding		I F				
Verbenaceae	*Lantana camara* L. (sens. lat.)	Agromyzidae	*Calycomyza lantanae* Frick	Leaf-mining	U E ?	U E S	~	~	U E S	U E S
			Ophiomyia lantanae Froggatt	Seed-mining	~	I E S	~	U E S	U E S	U E S
		Erebidae	*Hypena laceratalis* Walker	Leaf-feeding	~	U E S	~	~	~	~
		Pterophoridae	*Lantanophaga pusillidactyla* Walker	Flower-feeding	~	I E S	~	U E S	U E S	~
		Tingidae	*Teleonemia scrupulosa* Stål	Sap-sucking	*	*	*	*	U E S	*
		Tortricidae	*Crocidosema lantana* Busck	Flower-feeding	~	U E S	~	~	~	~

Countries: KHM, Cambodia; CHN, China; LAO, Laos; MMR, Myanmar; THA, Thailand; VNM, Vietnam. Status: I, intentionally introduced, U, unintentionally introduced; E, established; F, failed to establish; ?, unknown. Impact: H, high; M, moderate; N, none, S, slight; V, variable; ?, unknown.

*Potential countries where low-risk and effective biocontrol agents could be introduced (based on weed occurrence in each country, not weed density); ~weed is present in the country but the biocontrol agent is not recommended for introduction due to only causing minimal impacts.

[1]*Epiblema strenuana* has established on *Ambrosia artemisiifolia* but can be released on *Parthenium hysterophorus*.

Table 3 List of alien invasive weeds present in the Greater Mekong Subregion countries that have been deliberately targeted for biocontrol in at least one country worldwide and for which there are low-risk and effective biocontrol agents causing moderate to high impacts to their target weed elsewhere

Family	Species	Common name	Weed origin	KHM	CHN	LAO	MMR	THA	VNM
Amaranthaceae	*Alternanthera philoxeroides*	Alligator weed	South America		*	*	*	*	*
Apocynaceae	*Cryptostegia grandiflora* R. Br.	Rubber vine	Madagascar					*	
Araceae	*Pistia stratiotes* L.	Water lettuce	tropical America	*	*	*	*	*	*
Asteraceae	*Ageratina adenophora*	Crofton weed	Mexico		*	*		*	*
	Ambrosia artemisiifolia	Common ragweed	North America		*				
	Chromolaena odorata	Chromolaena	Tropical and subtropical America	*	*	*	*	*	*
	Elephantopus mollis Kunth	Tobacco weed	Central America						*
	Mikania micrantha	Mile-a-minute	Central and South America	*	*	*	*	*	*
	Parthenium hysterophorus	Parthenium weed	North, Central, South America		*		*	*	*
	Xanthium strumarium L.	Noogoora burr	North, Central, South America		*			*	*
Azollaceae	*Azolla filiculoides* Lam.	Water fern	North, Central, South America	*	*		*		
Basellaceae	*Anredera cordifolia* (Ten.) Steenis	Madeira vine	South America		*				
Bignoniaceae	*Dolichandra unguis-cati* (L.) L. G. Lohmann	Cat's claw creeper	Tropical America		*				
	Spathodea campanulata Beauv.	African tulip tree	Africa		*	*		*	
	Tecoma stans (L.) Juss. ex Kunth var. stans	Yellow bells	Tropical America					*	
Cactaceae	*Cereus jamacaru* DC.	Queen of the night	South America						*
	Opuntia elatior Mill.	Prickly pear	Caribbean, Central America					*	
	Opuntia ficus-indica (L.) Mill.	Indian fig	Mexico	*	*				*
	Opuntia monacantha (Willd.) Haw.	Drooping prickly pear	Argentina, Brazil, Paraguay, Uruguay		*			*	*
	Opuntia stricta (Haw.) Haw.	Common prickly pear	North and South America, Caribbean		*				*
Cucurbitaceae	*Coccinia grandis* (L.) Voigt	Ivy gourd	East Africa	*	*			*	*
Fabaceae	*Acacia cyclops* A. Cunn. ex G. Don	Red eye	Australia					*	
	Acacia dealbata Link	Silver wattle	Australia		*				
	Acacia decurrens (Wendl.) Willd.	Green wattle	Australia						*
	Acacia longifolia (Andrews) Willd.	Sydney golden wattle	Australia				*		*
	Acacia mearnsii De Wild.	Black wattle	Australia		*				*
	Acacia melanoxylon R. Br.	Australian blackwood	Australia					*	
	Acacia saligna (Labill.) H. L. Wendl.	Port Jackson willow	Australia						*
	Leucaena leucocephala	Leucaena	Mexico, Central America	*	*	*	*	*	*
	Mimosa diplotricha C. Wright	Sensitive plant	Tropical America	*	*	*	*	*	*
	Mimosa pigra	Giant sensitive plant	Tropical America	*	*	*	*	*	*
	Parkinsonia aculeata L.	Parkinsonia	Tropical and subtropical America	*		*		*	*
	Prosopis juliflora (Sw.) DC.	Mexican thorn	Colombia, Ecuador, Mexico, Peru, Venezuela	*			*	*	*
	Vachellia nilotica (L.) P.J.H.Hurter & Mabb.	Prickly acacia	Indian subcontinent				*		*
Haloragaceae	*Myriophyllum aquaticum* (Vell.) Verdc.	Parrot's feather	South America	*	*			*	*
Malvaceae	*Sida acuta* Burm. f.	Spinyhead sida	Tropical America	*	*	*	*	*	*
	Sida rhombifolia L.	Paddy's lucerne, common sida	Tropical America	*	*			*	*
Melastomataceae	*Clidemia hirta* (L.) D. Don	Koster's curse	Tropical Central and South America					*	*
Myrtaceae	*Melaleuca quinquenervia* (Cav.) S. T. Blake	Broad-leafed paperbark	Australia		*			*	*
Poaceae	*Arundo donax* L.	Giant reed	Mediterranean Europe, Asia		*		*	*	
Pontederiaceae	*Eichhornia crassipes*	Water hyacinth	South America	*	*	*	*	*	*
Salviniaceae	*Salvinia molesta* D.S. Mitch.	Salvinia	Brazil		*	*		*	
Solanaceae	*Solanum sisymbriifolium* Lam.	Wild tobacco	South America		*				
	Solanum viarum Dunal	Tropical soda apple	South America		*		*	*	*
Verbenaceae	*Lantana camara*	Lantana	Central and South America	*	*	*	*	*	*

Countries: KHM, Cambodia; CHN, China; LAO, Laos; MMR, Myanmar; THA, Thailand; VNM, Vietnam.
*Indicates in which country the weed is present.

Table 4 Weed biocontrol agents established elsewhere in Asia that are causing moderate to high impacts against the target weed and that could be released into the Greater Mekong Subregion countries where the target weed occurs

Weed family	Weed species	Biocontrol agent family	Biocontrol agent species	Guild	No. of countries agent present	Asian countries agent present	Average impact	KHM	CHN	LAO	MMR	THA	VNM
Asteraceae	*Ambrosia artemisiifolia*	Chrysomelidae	*Zygogramma bicolorata* Pallister	Leaf-feeding	6	India, Nepal, Pakistan	Medium		*				
	Chromolaena odorata	Tephritidae	*Cecidochares connexa*	Stem-galling	14	India, Indonesia, Philippines, Timor Leste	Medium to high	*	*	*	*	*	*
	Mikania micrantha	Pucciniaceae	*Puccinia spegazzinii*	pathogen	6	Taiwan	High	*	*	*	*	*	*
	Parthenium hysterophorus	Chrysomelidae	*Zygogramma bicolorata*	Leaf-feeding	6	India, Nepal, Pakistan	Variable to medium		*		*	*	*
	Xanthium strumarium	Pucciniaceae	*Puccinia xanthii* Schwein.	Pathogen	4	Sri Lanka, Timor Leste	Variable to medium		*			*	*
Cactaceae	*Opuntia elatior*	Dactylopiidae	Dactylopius opuntiae Cockerell	Sap-sucking	2	India, Indonesia	High					*	
	Opuntia ficus-indica	Dactylopiidae	*Dactylopius opuntiae*	Sap-sucking	5	Israel	High	*	*				*
	Opuntia monacantha	Dactylopiidae	Dactylopius ceylonicus Green	Sap-sucking	5	India, Sri Lanka	High		*			*	*
	Opuntia stricta	Dactylopiidae	*Dactylopius opuntiae*	Sap-sucking	6	India, Sri Lanka	High		*				*
Fabaceae	*Mimosa diplotricha*	Psyllidae	Heteropsylla spinulosa Muddiman, Hodkinson & Hollis	Sap-sucking	14	Timor Leste	High	*	*	*	*	*	*
Salviniaceae	*Salvinia molesta*	Erirhinidae	Cyrtobagous salviniae Calder & Sands	Leaf-feeding	21	India, Indonesia, Malaysia, Sri Lanka	High		*	*		*	
Verbenaceae	*Lantana camara*	Chrysomelidae	*Octotoma scabripennis* Guérin-Méneville	Leaf-mining	7	India	Medium	*	*	*	*	*	*
			Uroplata girardi Pic	Leaf-mining	24	India, Philippines	Medium	*	*	*	*	*	*

Countries: KHM, Cambodia; CHN, China; LAO, Laos; MMR, Myanmar; THA, Thailand; VNM, Vietnam.
*Indicates in which country the weed is present.

Table 5 Biological control agents that are not present in Asia but are causing moderate to high impacts elsewhere and could be introduced into the Greater Mekong Subregion countries where the target weed occurs

Weed family	Weed species	Biocontrol agent family	Biocontrol agent species	Guild	Total countries agent is present	Average impacts elsewhere	KHM	CHN	LAO	MMR	THA	VNM
Amaranthaceae	*Alternanthera philoxeroides*	Pyralidae	*Arcola malloi* Pastrana	Leaf-feeding	3	Variable to high		*	*	*	*	*
Apocynaceae	*Cryptostegia grandiflora*	Chaconiaceae	*Maravalia cryptostegiae* (Cummins) Ono	Pathogen	2	Variable					*	
Araceae	*Pistia stratiotes*	Curculionidae	*Neohydronomus affinis* Hustache	Leaf-feeding	19	High	*	*	*	*	*	*
Asteraceae	*Elephantopus mollis*	Tephritidae	*Tetraeuaresta obscuriventris* Loew	Stem-galling	5	Slight to medium						*
	Parthenium hysterophorus	Curculionidae	*Listronotus setosipennis* Hustache	Flower-feeding	2	Variable to high		*		*	*	*
		Curculionidae	*Smicronyx lutulentus* Dietz	Seed-feeding	2	Variable		*		*	*	*
Azollaceae	*Azolla filiculoides*	Erirhinidae	*Stenopelmus rufinasus* Gyllenhal	Leaf-feeding	17	High	*	*		*		
Bignoniaceae	*Dolichandra unguis-cati*	Tingidae	*Carvalhotingis visenda* Drake & Hambleton	Sap-sucking	2	Medium		*				
Cactaceae	*Cereus jamacaru*	Pseudococcidae	*Hypogeococcus festerianus* Lizer y Trelles	Sap-sucking	1	High						*
		Cerambycidae	*Nealcidion cereicola* Fisher	Cladode-boring	1	High						*
	Opuntia ficus-indica	Pyralidae	*Cactoblastis cactorum* Berg	Cladode-boring	19	Medium to high	*	*				*
	Opuntia monacantha	Pyralidae	*Cactoblastis cactorum*	Cladode-boring	19	Medium to high		*			*	*
	Opuntia stricta	Pyralidae	*Cactoblastis cactorum*	Cladode-boring	19	Medium to high		*				*
Cucurbitaceae	*Coccinia grandis*	Curculionidae	*Acythopeus cocciniae* O'Brien & Pakaluk	Leaf-mining	3	Medium to high	*	*			*	*
		Sesiidae	*Melittia oedipus* Oberthür	Stem-boring	3	Medium to high	*	*			*	*
Fabaceae	*Acacia cyclops*	Cecidomyiidae	*Dasineura dielsi* Rübsaamen	Flower-galling	1	Variable to high					*	
		Curculionidae	*Melanterius servulus* Pascoe	Seed-feeding	1	Variable to high					*	
	Acacia dealbata	Curculionidae	*Melanterius maculatus* Lea	Seed-feeding	1	Medium		*				
	Acacia decurrens	Curculionidae	*Melanterius maculatus*	Seed-feeding	1	Medium						*
	Acacia longifolia	Curculionidae	*Melanterius ventralis* Lea	Seed-feeding	1	High				*		*
		Hymenoptera	*Trichilogaster acaciaelongifoliae* Froggatt	Flower-galling	2	High				*		*
	Acacia mearnsii	Cecidomyiidae	*Dasineura rubiformis* Kolesik	Flower-galling	2	Variable to high		*				*
	Acacia melanoxylon	Curculionidae	*Melanterius acaciae* Lea	Seed-feeding	1	High					*	
	Acacia saligna	Curculionidae	*Melanterius compactus* Lea	Seed-feeding	1	High						*
		Pileolariaceae	*Uromycladium tepperianum* (Sacc.) McAlpine	Pathogen	1	High						*
	Mimosa pigra	Curculionidae	*Chalcodermus serripes* Fåhraeus	Seed-feeding	1	High	*	*	*	*	*	*
		Geometridae	*Macaria pallidata* Warren	Leaf-feeding	1	Variable to high	*	*	*	*	*	*
		Chrysomelidae	*Nesaecrepida infuscata* Schaeffer	Leaf-feeding	1	High	*	*	*	*	*	*
		Gracillariidae	*Neurostrota gunniella* Busck	Leaf-feeding	1	High	*	*	*	*	*	*
	Prosopis juliflora	Gelechiidae	*Evippe* sp. #1	Leaf-feeding	1	Variable	*			*	*	*
	Vachellia (syn. Acacia) nilotica	Geometridae	*Chiasmia assimilis* Warren	Leaf-feeding	1	Variable to high				*		*
Haloragaceae	*Myriophyllum aquaticum*	Chrysomelidae	*Lysathia* sp.	Leaf-feeding	2	High	*	*			*	*

Malvaceae	*Sida acuta*	Chrysomelidae	*Calligrapha pantherina* Stål	Leaf-feeding	5	High	*	*	*	*	*	*
	Sida rhombifolia		*Calligrapha pantherina*	Leaf-feeding	5	High	*	*			*	*
Melastomataceae	*Clidemia hirta*	Phlaeothripidae	*Liothrips urichi* Karny	Sap-sucking	4	Variable to high					*	*
Myrtaceae	*Melaleuca quinquenervia*	Psyllidae	*Boreioglycaspis melaleucae* Moore	Sap-sucking	2	Medium to high		*			*	*
		Cecidomyiidae	*Lophodiplosis trifida* Gagné	Leaf-galling	1	High		*			*	*
		Curculionidae	*Oxyops vitiosa* Pascoe	Leaf-feeding	2	Slight to high		*			*	*
		Pucciniaceae	*Puccinia psidii* G. Winter	Pathogen	1	High		*			*	*
Poaceae	*Arundo donax*	Eurytomidae	*Tetramesa romana* Walker	Stem-boring	2	High		*		*	*	
Pontederiaceae	*Eichhornia crassipes*	Mycosphaerellaceae	*Cercospora piaropi* Tharp	Pathogen	3	Slight to high	*	*	*	*	*	*
		Miridae	*Eccritotarsus catarinensis*	Sap-sucking	3	Variable to high	*	*	*	*	*	*
Solanaceae	*Solanum sisymbriifolium* Lam.	Chrysomelidae	*Gratiana spadicea* Klug	Leaf-feeding	1	Medium		*				
	Solanum viarum Dunal		*Gratiana boliviana* Spaeth	Leaf-feeding	1	High		*		*	*	*
Verbenaceae	*Lantana camara*	Eriophyidae	*Aceria lantanae* Cook	Flower-galling	5	Variable to high	*	*	*	*	*	*
		Miridae	*Falconia intermedia* Distant	Sap-sucking	2	Medium to high	*	*	*	*	*	*
		Agromyzidae	*Ophiomyia camarae* Spencer	Leaf-mining	11	Variable to high	*	*	*	*	*	*

Countries: KHM, Cambodia; CHN, China; LAO, Laos; MMR, Myanmar; THA, Thailand; VNM, Vietnam.
*Indicates in which country the weed is present.

and resources (qualified people and funding) [22]. The introduction of biological control agents invariably involves importing agents into a quarantine facility. For many countries, this is not practical or feasible, and they must rely on testing conducted elsewhere and on funding from donor organizations [24].

As some countries do not have the capacity or processes in place to implement biological control, or have strategic plans to manage weeds, farmers and land managers are often left controlling weeds in an *ad hoc* fashion. In some cases, invasive species are utilized for pig food (*E. crassipes*) [25], firewood (*L. camara*) [13] or medicinal purposes (*Mikania micrantha*) [26]. Invasive species are typically inferior to other species in terms of these uses, and their combined detriments often exceed their minimal benefits. Still, once invasive species are being utilized, they can be perceived as useful and therefore should not be controlled, exacerbating the reluctance to implement biological control [23, 26, 27]. With weeds becoming an ever-increasing problem affecting agriculture, food security and livelihoods, and with conventional control such as the use of herbicides being unsustainable and costly, there are tremendous opportunities to establish or expand weed biological control programmes in GMS countries. The benefits of weed biological control are enormous, not just economically but also in terms of human and environmental health through the reduction in the use of herbicides, which can poison users, crops and waterways [14].

The benefit:cost ratios of weed biological control for various countries range from 11:1 in Zimbabwe to over 4000:1 in South Africa [28]. In Australia, where the average benefit:cost ratio for all weed biological control projects is approximately 23:1, the benefit of the cactus biocontrol programme alone is over 300:1. Much of this is due to *Opuntia stricta* (Haw.) Haw. (Cactaceae) (prickly pear) being successfully controlled by *C. cactorum* for over 85 years [29]. In Sri Lanka, the benefits of biological control of *S. molesta* in Sri Lanka was estimated at 53:1 in terms of production and over 1600:1 in terms of labour costs [30]. Doeleman [30] highlights the high financial benefits from the biological control of *S. molesta* and how biological control opens up new prospects for other weeds where chemical control is not feasible.

In the GMS region, the number of alien invasive weeds that have been deliberately targeted for biological control (nine) is only a fraction of the total number of weeds in the region that have been targeted for weed biological control elsewhere (45). This demonstrates the huge potential for expanding weed biological control programmes in the region to manage some of the region's worst weeds. Even within the region, established biological control agents causing medium to high impacts on their target weed in at least one country could be moved into another GMS country where they are not already present.

Utilizing low-risk and effective agents, particularly from within the same region, is highly successful [14, 24]. First, the agents are climatically adapted and likely to establish.

Table 6 Biological control agents that are not present in Asia but have been recently released elsewhere, and are showing early promise in controlling their target weed, and could be introduced into the Greater Mekong Subregion countries where the target weed occurs

Weed family	Weed scientific name	Agent family	Agent scientific name	Guild	Total countries agent released	KHM	CHN	LAO	MMR	THA	VNM
Asteraraceae	*Ageratina adenophora*	Pucciniosiraceae	*Baeodromus eupatorii* (Arthur) Arthur	Pathogen	1		*	*		*	*
Basellaceae	*Anredera cordifolia*	Chrysomelidae	*Plectonycha correntina* Lacordaire	Leaf-feeding	1		*				
Bignoniaceae	*Dolichandra unguis-cati*	Buprestidae	*Hedwigiella jureceki* Obenberger	Leaf-mining	2		*				
	Spathodea campanulata	Eriophyidae	*Colomerus spathodeae* Carmona	Leaf-galling	1		*	*		*	
	Tecoma stans var. stans	Coccinellidae	*Mada polluta* Mulsant	Leaf-feeding	1					*	
		Agromyzidae	*Pseudonapomyza* sp.	Leaf-mining	1					*	
Fabaceae	*Parkinsonia aculeata*	Geometridae	*Eueupithecia cisplatensis* Prout	Leaf-feeding	1	*		*		*	*
			Eueupithecia vollonoides Hausmann	Leaf-feeding	1	*		*		*	*
Poaceae	*Arundo donax*	Diaspididae	*Rhizaspidiotus donacis* Leonardi	Sap-sucking	2		*		*	*	
Pontederiaceae	*Eichhornia crassipes*	Delphacidae	*Megamelus scutellaris* Berg	Sap-sucking	2	*	*	*	*	*	*
Verbenaceae	*Lantana camara*	Uropyxidaceae	*Prospodium tuberculatum* (Spegazzini) Arthur	Pathogen	2	*	*	*	*	*	*

Countries: KHM, Cambodia; CHN, China; LAO, Laos; MMR, Myanmar; THA, Thailand; VNM, Vietnam.
*Indicates in which country the weed is present.

Second, these agents have been thoroughly tested and have often been present in the field for many years. Therefore, any non-target impacts would have been detected by now. This provides greater confidence that the agents are host specific and may circumvent the need for additional host specificity testing. For instance, *A. hygrophila* could be introduced into Lao PDR, Myanmar and Vietnam from China and/or Thailand where the agent has established and is causing high impacts on its target weed, *A. philoxeroides*. Similarly, the two beetles *N. bruchi* and *N. eichhorniae*, introduced to control *E. crassipes*, could be introduced into several GMS countries where they are not already present [15].

For biological control agents found outside the region, i.e. Australia, the Pacific or South Africa, it might be necessary to test a few additional plant species prior to importation, depending on what species have been tested previously. Agents tested prior to their release in one country may not have been tested against locally important related plant species found in other countries where the agents are being considered for release. For instance, *N. bruchi*, a biological control agent for *E. crassipes*, was tested on over 260 plant species in total in ten countries [25], prior to being deliberately released in over 35 countries [15]. The rust pathogen *Puccinia spegazzinii* de Toni (Pucciniaceae) was tested against a combined 287 species in five countries, prior to being imported into numerous countries for the control of *Mikania micrantha* Kunth (Asteraceae) [26]. Both agents have been present in the field for many years and have not been observed causing non-target impacts.

Prior to releasing any biological control agent, it may be prudent to conduct field surveys to determine if the particular species is already present in the country. Biological control agents can and do disperse into new areas, as many weed infestations are contiguous across province and country borders. *Calycomyza lantanae* Frick (Diptera: Agromyzidae), a biological control agent for *L. camara*, was released into only three countries worldwide (Australia, Fiji and South Africa), but it is now found in another 26 countries, including 12 countries in Asia [13, 15]. Twenty-five biological control agents targeting 14 weed species have spread naturally into at least one of 25 countries in Asia [15].

Because the six GMS countries have not released any biological control agents recently, or in some cases ever, it would be advantageous to investigate ways to highlight the importance of invasive plants and promote weed biological control in the region. Workshops could be held for scientists and regulators on the occurrence, distribution and socio-economic impacts of invasive weeds, which would raise the awareness and importance of invasive species in the region. Workshops and training programmes could be conducted to cover all aspects of weed biological control, including potential benefits and risks, as well as the processes involved in implementing biological control programmes. Field visits should be

considered, which would give participants the chance to view weed infestations, assess their impacts on agriculture and the environment, and the opportunity to view biological control agents in action, whether they were deliberately introduced or spread naturally into the country. Host specificity testing experiments could also be conducted to demonstrate how biological control agents are evaluated prior to their release in the field. Numerous projects involving invasive species and biological control have incorporated citizen science components, videos and other information packages. Many of these are freely available on various websites (e.g. http://www.cabi.org).

Ultimately, it is up to individual countries to take the initiative to manage invasive species. This paper has outlined opportunities to decrease the impacts of invasive weeds in GMS countries through weed biological control. By incorporating a complete package involving all aspects of weed biological control, weed management in the GMS countries can be improved, and the impacts of weeds on productivity and the environment, as well as the use of herbicides can be decreased.

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