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History, progress and prospects of classical biological control in India

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ABSTRACT

First successful classical biological control of a weed (prickly pear) was achieved unintentionally in India when cochineal insect, *Dactylopius ceylonicus* was mistakenly introduced from Brazil in place of *D. cacti* to produce dye from *Opuntia vulgaris*. This incident led to biological control of weeds. From 1863 to 1868, it was introduced to southern India, which was first successful intentional use of an insect to control a weed. In 1926, *D. opuntiae*, a North American species, was imported from Sri Lanka and its colonization resulted in spectacular suppression of *Opuntia stricta* and related *O. elatior*. So far in India, about 30 exotic biological control agents have been introduced against weeds, of which six could not be released in the field, 3 could not be recovered after release while 21 were recovered and established. From these established bioagents, 7 are providing excellent control, 4 substantial control and 9 partial control. Biological agents, mainly insects provided excellent biological control of prickly pear, *Opuntia elatior* and *O. vulgaris* by *D. ceylonicus* and *D. opuntiae*; *Salvinia molesta* by weevil, *Cyrtobagous salviniae*; water hyacinth by weevils *Neochetina bruchi* and *N. eichhorniae* and galumnid mite *Orthogalumna terebrantis*; and *Parthenium hysterophorus* by chrysomelid beetle *Zygogramma bicolorata*. Some introduced bioagents did not prove success but providing partial control like of *Lantana* by agromyzid seedfly, *Ophiomyia Lantanae*, tingid lace bug, *Teleonemia scrupulosa, Diastema tigris, Uroplata girardi, Octotoma scabripennis* and *Epinotia lantanae*; *Chromolaena odorata* by *Pareuchaetes pseudoinsulata*; *Ageratina adenophora* by gallfly, *Procecidochares utilis*; submerged aquatic weeds such as *Vallisneria* spp. and *Hydrilla verticillata* in fish ponds by grass carp. There are many bioagents which have been introduced in other countries and have shown varying degree of success through combined effect. In Australia, 9 bioagents have been introduced against *Parthenium* alone. Such successful bioagents need to be introduced in India against some of the problematic weeds like *Parthenium*, water hyacinth, *Pistia*, alligator weed *etc*.

Key words: *Ageratina adenophora*, Biological control, *Chromolaena odorata, Lantana, Parthenium*, water hyacinth, *Salvinia molesta*

Weeds play an important role in human affairs in most of the areas of the earth. The major characteristics of weeds are their unwanted occurrence, undesirable features and ability to adapt to a disturbed environment (Combellack 1992). Despite measures adopted for their control, weeds are estimated to reduce world food supplies by about 11.5% annually (Combellack 1992). Many of our problem weeds are of exotic origin, having been introduced accidentally or deliberately as ornamental plants, *etc*. They flourish in the new environment as they have escaped from the natural enemies, which suppress their vigour and aggressiveness in their native lands. Alien species are recognized as the second largest threat to biological diversity, the first being habitat destruction. Exotic pests cause unprecedented damage in the absence of their natural antagonists. Economic impact of invasive pests is tremendous. Exotic weeds (terrestrial, aquatic and parasitic) interfere with cultivation of crops, loss of biodiversity and ecosystem resilience, loss of grazing and livestock production, poisoning of humans and livestock, choking of navigational and irrigation canals and reduction of available water bodies. Biological control, *i.e.* introduction, augmentation and conservation of exotic natural enemies, has been accepted as an effective, environmentally non-degrading, technically appropriate, economically viable and socially acceptable method of pest management.

Biological control of weeds involves the use of living organisms to attack a weed population to keep at or below desirable level without significantly affecting useful and wanted plants.It is evidently proved that biological control methods do best on large infestation of a single weed species, which usually occurred in rangelands or in water bodies. In spite of much good success in classical biological

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weed control in wasteland and fallow land or large water bodies, it has not developed to the point that it has any appreciable impact on to suppress weeds in cropping situations. Biological control includes the classical (inoculative), bioherbicides (inundative) approaches and herbivore management. Insects, mites, nematodes, plant pathogens, animals, fish, birds and their toxic products are major weed control biotic agents. Singh (2004) concluded that in India, maximum degree of success with classical biological control agents was achieved in biological control of aquatic weeds (55.5%); homopterous pests in crop situations (46.7%) followed by terrestrial weeds (23.8%). McFadyen (2000) listed 44 weeds, which were successfully controlled somewhere in the world using introduced insects and pathogens. Biological control programs have saved millions of dollars and, despite the high initial costs, are very cost-effective. This paper elucidates recent information on classical biological control research in India and prospects of this approach.

History of biological control in India

The history of biological control of weeds dates back to the seventeenth century and since then a great deal of success has been achieved in biological methods of weed control. In fact, the first unintentional outstanding success of biological control of prickly pear in India during 1795 by cochineal insect led the word to use natural enemies against exotic weeds (Sushilkumar 1993, Singh 2004).

Systematic biological control research in India, started with the establishment of the Indian station of Commonwealth Institute of Biological Control (CIBC) at Bengaluru in 1957 with need based 23 substations at various places in different states. The All-India Co-ordinated Research Project on Biological Control of Crop Pests and Weeds (AICRP-BC&W) was established in 1977 with 10 centres, which increased to 16 under the aegis of Project Directorate of Biological Control (PDBC), an institute of Indian Council of Agricultural Research. During XIth plan, PDBC was upgraded as National Bureau of Agriculturally Important Insects (NBAII) to act as a nodal agency for biological control of crop pests. In the XIIth five year plan, the Bureau was re-named as National Bureau of Agricultural Insect Resources (NBAIR) with changed mandate. Meanwhile, National Research Center for Weed Science (NRCWS) came into existence in 1989 at Jabalpur with a modest beginning of biologiocal control of weeds in 1990s. The centre upgraded to Directorate of Weed Science Research in 2009 and renamed as Directorate of Weed Research (DWR) in 2015. Now with the change in mandate of NBAIR, the DWR shall deal on issues related to weed management including biological control of weeds in India with the help of its 23 AICRP-WM centres.

In past, some attempts have been made to review the biological control of agricultural, forest and aquatic weeds of India (Sen-Sarma and Mishra 1986, Ahmad 1991, Singh 1989, Sushilkumar 1993, Jayanth 1994, Singh 2004, Sushilkumar 2009 and 2011).

Progress of classical biological control of weeds in India

Classical biological control aims at introducing the exotic natural enemies of inadvertently introduced alien organisms, which have become pests in the absence of natural checks in the new environment in order to re-establish the balance between the pests and natural enemies. Work on biological control of weeds in India in general and *Parthenium* and aquatic weeds in particular has been dealt by Sushilkumar (1993) and Singh (2004) and Sushilkumar (2009, 2011), respectively. So far in India, about 30 exotic biological control agents have been introduced against weeds, of which six could not be released in the field, 3 could not be recovered after release while 21 were recovered and established. From these established bioagents, 7 are providing excellent control, 4 substantial and 9 partial control. Singh (2004) concluded maximum degree of success of aquatic weeds (55.5%) followed by homopterous pests (46.7%) of crop pests and terrestrial weeds (23.8%) by classical biological control agents in India. Significant research and development efforts over a long period, have led to several successful case studies that have provided great impact in classical biological control of weeds in India. Such weed species are listed (Table 1) and are discussed below:

Prickly pear

The prickly pear (cacti), *Opuntia* spp., (cactaceae) native of North and South America were deliberately introduced into India for cochineal trade. *Opuntia* spp. (*O. vulgaris, O. stricta* (= *O. dillenii*) (Origin: Florida, USA and West Indies) and *O. elatior* gradually spread from the cultivated fields to other lands and eventually became a severe weed pest in North and South India. The first outstanding biological suppression of this weed in India occurred unintentionally by the insect *Dactylopius ceylonicus (=O. indicus)*. It was imported in 1795 from Brazil to produce commercial dye in believe that it is the true cochineal insect *D. cacti*, used to get high quality dye from *Opuntia* spp. The dye produced by *D. ceylonicus* was much inferior to *D. cacti,* hence the dye producing factories eventually stopped to produce dye due to its uneconomic yield. But, *D. ceylonicus* readily established on *Opuntia vulgaris* (its natural host) in North and Central India bringing about spectacular suppression. Gradually, areas that were impenetrable due to prickly pear, became suitable for cultivation within 6 years. Subsequently by 1865, *D. ceylonicus* was introduced into Sri Lanka from South India, where it controlled *O. vulgaris* in large area. This was the first intentional transfer of a natural enemy for biological control of weeds from one country to another country in the world (Sushilkumar 1993).

D. ceylonicus, being restricted to *O. vulgaris*, did not control *O. stricta*, an another species of cactus, which gradually became a problem in South India. In 1926, *D. opuntiae*, a North American species, was imported from Sri Lanka to India, which resulted spectacular suppression of *O. stricta* and related *O. elatior* within five to six years. Due to sustainable occurrence and attack, currently *O. vulgaris* and *O. stricta* are not a problem in India.

Lantana camara

Lantana camara Linnaeus (Verbenaceae), a Central and South American weed was introduced into India in 1809 as an ornamental plant. It spread soon into open areas in forest land, and pastures forming dense thickets. It is a perennial, straggling shrub with prickly stems, spreading by seed, but re-growing vigorously after cutting. It competes with young trees in the forest area and in plantations thus not allowing them to grow. *Lantana* flowers throughout the year in warm areas. The seeds are eaten by birds, which facilitate the rapid dispersal of the plant. Apart from several drawbacks of this plant such as competitive displacement, it has been reported to be a symptomless carrier of sandal spike disease.

In India, it has by now spread everywhere in all the states. Global Invasive Species Information Network (GISIN) now identifies *Lantana* among the top ten invasive species in the world based on the number of countries where these species are considered invasive (GISIN, 2012).Current estimates suggest that *Lantana* has invaded more than 5 Mha in Australia, 13 Mha in India and 2 Mha in South Africa (Bhagawat *et al,* 2012). *Lantana* is known to pose serious threat to biodiversity in several world Heritage sites and Endangered Ecological Communities in Australia (e.g. rainforest of Northern Queensland, Fraser Island and the Greater Blue Mountains), the Fynbos of South Africa, and biodiversity hotspots in India (*e.g.* the Western Ghats and Eastern Himalayas) (Shaanker *et al.* 2010). Consumption of leaves and berries of *Lantana camara,* which contains pentacyclic triterpenoids (akin to steroids) in starvation led to the death of the spotted deers (Naveen 2013). *Lantana* invasion and proliferation has resulted in loss of biodiversity and decline in other ecological services in Corbett Tiger Reserve, Kalesar National Park and Pachmarhi Biosphere Reserve (Babu 2009).

Great success of biological control of *Lantana* by exotic insects in Hawaii followed by Fiji and Australia between 1902-1910 opened the way for biological control throughout the world. In 1916. Government of India, appointed Dr. Rao to conduct an enquiry to know the efficiency of the indigenous insect fauna of *Lantana*. He recorded 148 insect species from India and Myanmar (Burma) (Rao, 1920). In 1921, the agromyzid seed fly, *Ophiomyia lantanae* was introduced from Hawaii (origin: Mexico) and released in South India for the suppression of *L. camara*. Though established, it did not provide spectacular suppression. It is now widely distributed in India. Thakur *et al.* (1992) identified three indigenous insect as potential biocontrol agent for *Lantana viz., Asphondylia lantanae* Felt (flower feeder), *Hypena laceratalis* (a flower and leaf defoliator) and *Archips micaceana (Homona micaceana, a* borer of ripe fruits, however, *H. laceratalis* was found to be hightly parasititzed in south India by two ichneumonid parasites *Casinaria* sp. and *Enicospilus xanthosephalus (*Visalakshy and Jayanath 1990). Sushilkumar and Saraswat (2001) concluded that as many as 9 exotic insect species were introduced in India against *Lantana*.

Tingid lace bug, *Teleonemia scrupulosa*, a native of Mexico, was introduced from Australia in 1941 at Dehra Dun by Forest Research Institute. During, host specificity test, the bug was reported to feed on teak flowers, hence the culture was destroyed in the quarantine. But the insect escaped from quarantine and was recovered later on after about 10 years. Gradually, the insect spread to all the *Lantana* stands in the country, but so far, it has not been found to attack teak or any other economic plant in India in spite of the abundance of teak (Sushilkumar, 1993, Sushilkumar and Saraswat, 2001). This is one of the examples of no risk magnitude by biological control agents as advocated by Suckling and Sfroza (1914) after rigorously analyzing biological agents releaes since inception of biological control programmes in the world. Till today, this bug is a partial success and is not able to kill the *Lantana* in spite of good defoliation during rainy season. Heavy parasitism (up to 85%) of *T. scrupulosa* eggs by *Erythmelus teleonemiae* in Bengaluru impaired the population build up of *T. scrupulosa*. Several other host specific insects such as *Diastema tigris*, *Salbia* (*Syngamia*) *haemorrhoidalis, Uroplata girardi, Octotoma scabripennis* and *Epinotia lantanae* have been introduced from time to time for the biological suppression of *Lantana*. *U. girardi and O. scabripennis* have established in India (Table 1).

Siam weed

Chromolaena odorata (Linnaeus) R. King and H. Robinson (Asteraceae), a native of West Indies and continental America, is a serious weed of pastures, forests, orchards and commercial plantations in South and North-East India. It was introduced in Assam during the First World War (1914-18), where it is locally known as Assam-lata or Assam-lota. It is now well distributed in North-Eastern and Southern states, particularly in Assam, Andhra Pradesh, Karnataka, Kerala, Maharashtra, Odisha, Tamil Nadu and West Bengal. By 1990s, its mild infestation was noticed in Jagdalpur area of Chhattisgarh, which achieved the status of one of the worst weeds of forest and wasteland by 1915 (Sushilkumar, personal observations). It has been rapidly spreading towards mainland of Chhattisgarh and it is feared that it may enter into Madhya Pradesh from this route. It has become a menace in coconut, cocoa, cashew, rubber, oil palm, tea, teak, coffee, cardamom, citrus and other plantation, orchards and forests. During the dry season, it can be a serious fire risk in the forests. The allelopathic effect of this weed in addition to other ill effects has been demonstrated (Ambica and Jayachandran 1980).

The CIBC Indian Station introduced defoliator *Pareuchaetes pseudoinsulata* and a flower and seed feeding weevil *Apion brunneonigrum* (Coleoptera: Apionidae) from Trinidad, but all attempts failed (Singh 2004). During October 1984, a nucleus culture of about 500 larvae of the Sri Lankan strain of *P. pseudoinsulata* was supplied to Kerala Agricultural University (KAU), Thrissur. Further mass multiplication and release of this insect in Kerala, Tamil Nadu and Karnataka brought initial success and large area of *C.* o*dortata* was found defoliated in Kerala and Karnataka by 1988. But, gradually, this insect lost its potential and became non-effective due to heavy parasitism. Ahmad (1991) again tried to establish this bioagent in the forests of Tamil Nadu and Kerala, but he could find only faint recovery of larvae at some places of release. At present, *P. pseudoinsulata* is not considered a potential bioagent.

The Sri Lankan strain of *P. pseudoinsulata* was also supplied to the University of Guam through the CIBC Indian Station. Field releases of this insect in Guam resulted in immediate establishment and extensive defoliation. By 1989, *C. odorata* was reported to have lost its status as the predominant weed in Guam (Singh 2004).

A gall fly *Cecidochares connexa* was introduced from Indonesia in 2002. It was released at 2 locations in Bengaluru, Karnataka during July-October 2005 on naturally rowing *Chromolaena odorata*. The gall fly soon established and due to action of gall fly, plant height was reduced by 11.6 and 16.7% at 30 and 60 days after oviposition in galled plants over control. Significant reduction in number of branches per plant (35.6%), number of panicles per plant (45.4%), number of capitula per panicle (12.07%), and number of seeds per head (10.89%) was evident in galled plants over the control due to oviposition (Bhumannavar *et al.* 2007). The gall fly was also introduced in Kerala and Chhattisgarh (Sushilkumar, personal observations). In Kerala, it has been well established in dense patches and galls occurrence was common after 8 years of its introductions, however, only small number of galls have been recorded at Jagdalpur (Chhattisgarh) after three years of its introduction (Sushilkumar, personal observations). Survey made by the author in Bengaluru and Thrissur revealed good number of galls on each plants but complete killing of plants was not observed. It was concluded that although gall flyies are able to reduce branch formation, flower produciton up to some extent but are not able to bring substantial suppression of *C. odorata*.

Crofton weed

Ageratina adenophora (*Eupatorium adenophorum)* (Sprengel) R. King and H. Robinson (asteraceae), a native of Mexico has spread to the hilly areas of North and South India, forming dense thickets up to some 3 meters on valuable grazing land. The weed has also occupied vacant places in tea, teak, rubber and other forest plantations. Banerjee (1958) noted its presence throughout the Himalaya from Shimla to Bhutan including Nepal. It has assumed a serious status in Nepal (Kapoor and Malia 1978) and Himachal Pradesh (Singh *et al.* 1992)

The gallfly, *Procecidochares utilis* (origin: Mexico) was introduced from New Zealand in 1963 and released in the Nilgiris (Tamil Nadu), Darjeeling and Kalimpong areas (West Bengal) for biological control of *A. adenophora*. The insect has established

Table 1. Name of bioagents , source of country, year of introudciton in India and thier current status

).	Exotic natural enemies (Order: Family) imported in India	Source country/year of introduction and weed plant	Current status/Reference
.	*Dactylopius ceylonicus* (Hemiptera: Dactylopiidae)	Brazil, 1795, prickly pear	It was mistakenly introduced in the belief to produce good quality carmine dye but it was the species of *D. coccus*. It readily established on pear, *Opuntia vulgaris* (its natural host) in North and Central India and resulted spectacular suppression. Later on, introduced in South India during 1863-1868, where it also did excellent control of prickly pear (Sushilkumar 1993, Singh 2004).
2	*Dactylopius opuntiae* (Hemiptera: Dactylopiidae)	USA via Sri Lanka via Australia, 1926; pricly pear	Caused spectacular suppression of *Opuntia stricta* and related *O. elatior* (Singh 2004).
3	*Pareuchaetus pseudoinsulata* (Lepidoptera: Arctiidae)	Trinidad, West Indies via Sri Lanka, 1984 ; against weed species *Chromolaena odorata*	Established in 1988 in Dakshina Kannada district (Karnataka). Good suppression was recorded by 1990. Also recovered from Kerala and Tamil Nadu; partially successful (Ahmad 1991, Thakur *et al*. 1992, Sushilkumar 1993, Singh 2004).
4	*Procecidochares utilis* (Diptera: Tephritidae)	From Mexico via Hawaii, USA via Australia via New Zealand, 1963 ; against Crofton weed *Ageratina adenophora*	Released in the Nilgiris (Tamil Nadu), Darjeeling and Kalimpong areas (West Bengal) against Crofton weed; established and is spreading naturally, but efficacy hampered by indigenous parasitoids; has spread to Nepal, where it has become well distributed; partially successful (Swaminathan and Raman 1981, Bennet and Vanstaden 1986, Sushilkumar 1993, Singh 2004).
5	*Zygogramma bicolorata* (Coleoptera; Chrysomelidae)	From Mexico, 1983; against *Parthenium hysterophorus*	Released for control of *Parthenium;* established by natural spread and by concentrated efforts by Directorate of Weed Research (Jabalpur), established well in many states of India; naturally entered from India to Nepal and Pakistan; successful bioagent (Jayanth 1982; Sushilkumar 2005, 2009, 2014).
6	*Neochetina bruchi* (Coleoptera: Curculionidae)	Argentina via USA, 1982/1983; against water hyacinth	Well distributed and established on water hyacinth, spread to different parts of the country; doing good control of weed along with *N. Eichhorniae* (Jayanth 1988, Singh 2004, Sushilkumar 2011).
7	*Neochetina eichhorniae* (Coleoptera: Curculionidae)	Argentina via USA, 1983 agaisnt water hyacinth	Well distributed and established throughout India in different water bodies. It is successful in stagnated ponds and lakes but not effective in running water like river (Jayanth 1987, Singh 2004, Sushilkumar 2011).
8	*Orthogalumna terebrantis* (Acari: Orthogalumnidae)	Argentina via USA, 1986; against water hycienth	Well established in all released sites and is spreading on its own; doing good control of weed along with *Neochetina* spp. (Jayanth 1996, Singh 2004, Sushilkumar 2011).
9	*Epinotia lantanae* (Lepidoptera: Tortricidae)	Mexico, unintentional accidental introduction in 1919 on *Lantana*	Established on *Lantana camara* in several places, partially effective (Sushilkumar 2001, Singh 2004).
0	*Lantanophaga pusillidactyla* (Lepidoptera: Pterophoridae)	Mexico, unintentional accidental introduction, 1919 against *Lantana*	Established on *Lantana* but not effective (Sushilkumar 2001, Singh 2004).
1	*Octotoma scabripennis* (Coleoptera: Chrysomelidae)	Mexico via Hawaii via **Australia, 197;** against *Lantana*	Established on *Lantana* but not effective (Sushilkumar 2001, Singh 2004).
2	*Ophiomyia lantanae* (Diptera: Agromyzidae)	Mexico via Hawaii, 1921; against *Lantana*	Established on *Lantana* at several places, but not effective (Sushilkumar 2001, Singh 2004).
3	*Orthezia insignis* (Hemiptera: Ortheziidae)	Mexico, unintentional accidental introduction, **1915l** against *Lantana*	Established on *Lantana* at several places, partially effective (Sushilkumar 2001, Singh 2004).
4	*Teleonemia scrupulosa* (Hemiptera: Tingidae)	Mexico via Hawaii via Australia, 1941; against *Lantana*	Reported to feed on teak flowers at Dehradun, hence culture was destroyed in quarantine. But the insect 'escaped' quarantine and presently found on all *Lantana* stands in India; partially effective.
5	*Uroplata girardi* (Coleoptera: Chrysomelidae)	Brazil via Hawaii via Australia, 1969 to 1971; against *Lantana*	Established on *Lantana,* not effective (Sushilkumar 2001, Singh 2004).
6	*Cyrtobagous salviniae* (Coleoptera: Curculionidae)	Brazil via Australia, 1982/1983; against *Salvinia molesta*	Initially released in Bengaluru; later released at Kuttanad (Kerala), well established, did excellent control (Jayanth 1996, Singh 2004, Sushilkumar 2011).
7	*Ctenopharyngodon idella* (Pisces: Cyprinidae)	China via Hong Kong & Japan, 1959/1962; against submerged aquatic weeds	Introduced to control submerged aquatic weeds such as *Vallisneria* spp. and *Hydrilla verticillata* in fishponds; established in different parts of the country; very effective (Singh 2004, Sushilkumar 2011).

Sl. No.	Exotic natural enemies (Order: Family) imported in India	Source/year of introduction and weed plant	Current status
18	*Hypophthalmichthysmolitrix* (Pisces: Cyprinidae)	China via Hong Kong & Japan, 1959/1962	Released and established in different water bodies and feeds on various aquatic weeds and algae.
19	*Oreochromismoss ambicus* (Pisces: Cichlidae)	Africa, 1953; against submerged aquatic weeds	Established in different water bodies and feeds on various aquatic weeds and algae; partially effective (Singh 2004).
20	*Osphronemus goramy* (Pisces: Osphronemidae)	Java, Indonesia; Mauritius, 1916; against submerged aquatic weeds	Established in different water bodies and feeds on various aquatic weeds and algae partially effective (Singh 2004).
21	*Paulinia acuminata* West Indies, 1983 (Orthoptera: Acrididae)	West Indies, 1983; against *Salvinia molesta*	Released and recovered from water fern, *Salvinia molesta* in Thiruvananthapuram (Kerala); not effective (Singh 2004).
22	*Cecidochares connexa* (Diptera: Tephritidae)	South America via Indonesia, 2003 against *Chromolaena odorata*	Established at Bengaluru (Karnataka), Thrissur (Kerala); also released at Jagdalpur (Chhattisgarh); partially successful (Bhumannavar and Ramani 2007, Sushilkumar personal observations)
23	*Phytomyza orobanchia* (Diptera: Agromyzidae)	Yugoslavia, 1982; against broomrape *Orobanche* sp	Recovered occasionally. partially established (Singh 2004, Kannan *et al*, 2014).
24	*Dactylopius confuses* (Hemiptera: Dactylopiidae)	South America via South Africa, 1836; against prickly pear	Introduced but not recovered on *Opuntia vulgaris* (Singh 2004).
25	*Apion brunneonigrum* (Coleoptera: Apionidae)	Trinidad, West Indies, 1972-1983; against *Chromolaena odorata*	Introduced but not recovered on *Chromolaena odorata* (Singh 204).
26	*Salbia haemorrhoidalis* (Lepidoptera: Pyralidae)	Trinidad, West Indies, 1972-1983; against *Lanatana*	Introduced but not recovered on *Lantana camara* (Sushilkumar 2001, Singh 2004).
27	*Mescinia parvula* (Lepidoptera: Pyralidae)	Trinidad, West Indies, 1986 Mexico via Australia, 1985; *Chromolaena odorata*	Imported but failed in host specificity test; culture destroyed (Singh 2004)
28	*Epiblema strenuana* (Lepidoptera: Tortricidae)	Mexico, 1983; against *P. hysterophorus*	Did not breed in laboratory (Singh 1989, Sushilkumar 2005, 2009)
29	*Smicronyx lutulentus* (Coleoptera: Curculionidae)	Mexico, 1983; against *P. hysterophorus*	Failed in host specificity test hence culture destroyed (Singh 1989, Sushilkumar 2005, 2009)
30	*Leptobyrsa decora* (Hemiptera: Tingidae)	Peru & Colombia via Australia, 1971; against *Lantana*	Failed in host specificity test, culture destroyed (Mishra and Sen-Sarma 1986, Sushilkumar 2001).

and is spreading naturally. Its effectiveness is hampered by attack of indigenous parasitoids. *P. utilis* has spread into Nepal from India, where it has become well-distributed. Bennett and Vanstaden (1986) studied gall formation process in detail in this weed.The exit holes cut by the inhabiting larvae enable access by microorganisms that induce decay. High galling intensity results in plant mortality. In the high-altitude regions of Tamil Nadu (India) (2000–2300 masl), four hymenopteran parasitoids, *Diameromicru skiesenwetteri* (Meyr) (Hymenoptera: Torymidae), *Syntomopus* sp. (Hymenoptera: Pteromalidae), *Bracon* sp. (Hymenoptera: Braconidae) and *Eurytoma* sp. (Hymenoptera: Eurytomidae) were recorded on *P. utilis* (Swaminathan and Raman 1981). Parasitism by *Bracon* sp. was as high as 80% and was considered to be the primary cause for the failure of the gall fly to control crofton weed in India.

Carrot weed

Parthenium hysterophorus Linnaeus (Asteraceae), globally known as feverfew, ragweed or *Parthenium* is a weed of world significance. It is most popularly known as ‘congress grass’ throughout India while in Hindi speaking belt known by the popular name of ‘gajarghas’(carrot grass). It degrades natural ecosystems by reducing biodiversity (Holm *et al*. 1997) and can cause serious allergic reactions in man and animals (Chippendale and Panetta 1994, Sushilkumar 2012). In India, it has invaded almost all types of crops and has become a serious threat for agricultural production. Sushilkumar and Varshney (2010) estimated infestation of *Parthenium* in 18.78, 14.25 and 2.0 Mha lands in barren, fallow, wasteland including land under non-agricultural uses, crop area under cultivation and forest areas, respectively. In India, this weed is a serious problem in states like, Andhra Pradesh, Bihar, Haryana, Karnataka, Madhya Pradesh,Tamil Nadu and Uttar Pradesh.

Parthenium is regarded as one of the worst weeds because of its immense capacity of reproduction and ability to thrive in varied climatic conditions. Its low photorespiration under arid conditions, photo and thermo-insensitivity, C_3/C_4 intermediate mechanism, more biomass production at elevated atmospheric CO_2 conc. compared to the normal in a rapidly changing climate make it more invasive (Pandey *et al*. 2003, Naidu and Paroha 2008, Tang *et al*. 2009, Naidu 2013, Sushilkumar 2014). Now, *Parthenium* has invaded about 35 Mha of land throughout India (Sushilkumar and Varshney 2010). After being established in India, *Parthenium* has gradually spread into most of its neighbouring countries like Pakistan (Shabbir and Bajwa 2006), Sri Lanka (Jayasurya 2005), Bangladesh (Rahman *et al.* 2008, Karim 2009) and Nepal (Adhikari and Tiwari 2004, Shrestha *et al.* 2014).

Manual, mechanical and chemical methods have been advocated for the control of this weed but these methods are expensive and provide only short-term control. Biological control has been considered most effective method against *Parthenium*. Now, much emphasis has been given to control *Parthenium* through various biological agents like pathogens, insects and plants. Sushilkumar (2009) has reviewed the status of biological control of *Parthenium* by insects, pathogens and competitive plants in India. Indigenous insect *Nupserha* sp. was reported to attack large number of *Parthenium* plants (5-95%), and caused reduction in flower production (Sushilkumar 2009, 2012).

Classical biological control of *Parthenium* in India started in 1983 with the import of three insects namely defoliating beetle *Zygogramma bicolorata* Pallister (Coleoptera: Chrysomelidae), the flower feeding weevil *Smicronyx lutulentus* Dietz (Coleoptera: Curculionidiae) and the stem boring moth *Epiblema strenuana* (Walker) (Lepidoptera: Tortricidae) (Singh 1989, Sushilkumar 1993, 2009). *S. lutulentus* could not be multiplied in the laboratory while *E. Strenuana* was found to complete its life cycle on a oil seed crop niger (*Guizotia abyssinica* L. (Asteraceae), hence its culture was destroyed (Jayanth 1987) in spite of the fact that this insect was considered to be a potential biocontrol agent in Australia (McFadyen 2000, Dhileepan 2009). After host specificity test, *Z. bicolorata* was released which spread over 2 million sq km area by 1994 (Jayanth and Visalakshy 1994). Soon after release, *Z. bicolorata* involved in controversy about its host specificity due to its occasional feeding on sunflower which forced Govt. of India to impose ban in 1991 for its intentional release (Sushilkumar and Bhan 1996). But, after in depth studies under the supervision of a Fact Finding Committee constituted by Government of India, the insect was declared safe and ban was lifted in 1999 for its release (Sushilkumar 2009).

After first release of *Z. bicolorata* in Bengaluru in 1984 in India (Jayanth 1987) and later on due to its intensive introductions to different regions of the country after the year 2000 by Directorate of Weed Research (DWR), Jabalpur, it has widely spread across the country (Sushilkumar 2005, 2009 and 20014; Sushilkumar and Varshney 2007). Incidence of *Z. bicolorata* has been recorded mild to heavy in most of the states wherever it was introduced. An economic benefit of 12150% was recorded by 6th years after its initial release comparing single application of herbicides (Sushilkumar 2006). Sushilkumar (2005) after observing the widespread establishment of *Z. bicolorata* in Ludhiana up to Bagha border (Punjab) forecasted the bioagent entry from this route to Pakistan. Later on, Javaid and Shabbir (2006) spotted this bioagent first time from Lahor and Changa Manga Forest area of Pakistan. In Nepal too, the bioagent was entered from the nearby released places of Uttar Pradesh (Shreshta *et al*. 2012).

In India, this widespread establishment of Z. *bicolorata* is in contrast to earlier predictions of Jayanth and Bali (1993), who suggested that *Z. bicolorata* would not be suitable for hot regions of Central and West India and cold regions of Himachal Pradesh, Uttarakhand, Punjab and Western Uttar Pradesh. Dhileepan and Senaratne (2009) and Sushilkumar (2014) have also found the occurrence of *Z. bicolorata* in very hot and cold regions of India. Diapause in *Z. bicolorata* was considered a negative attribute which hampers its activity (Jayanth and Bali 1993a). The diapause was broken by regulation of temperature and females were able to lay eggs normally after breaking of diapause (Sushilkumar and Ray 2010). In crop situations, *Z. bicolorata* was found to have limited scope due to disturbance of soil during agricultural activities. However, biological control approach may be viable through augmentation of the bioagent as was demonstrated by Sushilkumar and Ray (2011). The augmentation of bioagent may be achieved through large scale multiplication in net houses (Sushilkumar 2005).

Nefalata

The climber *Mikania micrantha* HBK (asteraceae), locally known as Refugee-lata is a perennial vine of Neotropical origin, with a native range from Mexico to Argentina. It has become an important invasive weed in many countries within the humid tropical zones of Asia and Pacific (Zhang *et al.* 2004). It started appearing in about 1948 in tea gardens in Bengal and in the forests of North-Eastern region (Jha 1959). Heavy flood in Bengal and Assam helped its dispersion into forests. Its menace was more in those plantation areas, which were clear felled. It has become a major menace in natural forests, plantations, agricultural systems in North-East and South-West India (Sushilkumar 1991, Ragubanshi *et al*. 2005). Palit (1981) estimated invasion of *Mikania* in about 11% area of high forests and 38% in plantation forests in West Bengal. *M. Micrantha* is posing a serious threat to unique eco system and biodiversity of Chitwan National Park in Nepal (CNP), which has been included in the World Natural heritage site by UNESCO. Its present infestation is estimated to be over 20% of the entire national park.

Under a biological control programme, Cock (1982) listed 8 major and 20 minor insect species from Latin America but none of these has been tried in South and South-East Asia. A tropical American rust fungus (*Puccinia spegazzinii*), collected in Trinidad, was selected and screened at CABI- UK against 175 plant species and was approved for release in six countries including India. Initial release was made in Assam and Kerala in 2005 in India. Initial symptoms of attack were noticed but it did not proof potential bioagent so far. Despite the rust failing to persist in the field in India and China, the potential of *P. spegazzinii* is recognised by Taiwan, Fiji where it has established and causing significant damage to *M. micrantha* (Ellison *et al.* 2014). Natural enemies of *M. micrantha* from Kerala have been reported by Abraham eta al. (2002).

Giant sensitive plant

Mimosa diplotricha C. Wright (fabaceae), also known as the giant sensitive plant, a native from Brazil, is a species in the Fabaceae family. The tangled and thorny growth of *Mimosa* hampers movement and access to food and other resources for wild animals like the one-horned rhinoceros (*Rhinoceros unicornis*) in Kaziranga National Park in North-East India. So far, no classical biological control has been tried in India.

In Australia in 1988 in North Queensland, a native insect species *Heteropsylla spinulosa* was imported from Brazil and released after host specificity test. During the 1988/89 summer, a dramatic reduction in the vigour of *M. diplotricha* was observed and seed production was suppressed by over 88%. Seedling establishment was reduced and some mature plants killed (Lockett and Ablin 1990). *H. spinulosa* is now well established (Willson and Garcia 1992), has spread significantly (Cullen and Delfosse 1990), and caused a dramatic reduction in vigour and seed production of *M. diplotricha* in Australia (Parsons and Cuthbertson 1992, Julien 1992). This species was intended to introduce in Kaziranga National Park by erstwhile Project Directorate of Biological control, Bengaluru, but authority of National Park refuged to give permission on the pretext that exotics are not allowed in National Park.

Water fern

Salvinia molesta D.S. Mitchell (salviniaceae), a native of South-Eastern Brazil has invaded many water bodies of Asia, Africa and Australia. It was introduced into India through Botanical gardens. *Salvinia*, first observed in 1955 in Vole Lake (Kerala), assumed the pest status since 1964 and affects large water bodies in Keral including rice fields. It choked rivers, canals, lagoons, and covered Kakki and Idukki reservoirs. In some areas cultivation of paddy had to be abandoned on account of *Salvinia* infestation (Joy 1978). In Australia, introduction of bioagent *Cyrtobagous salvinae* controlled *Salvinia* successfully and combined benfit: cost ratio was estimated 25.5:1, while it was 53:1 in Sri Lanka (Doeleman 1989). For the biological suppression of *S. molesta*, the weevil, *Cyrtobagous salviniae*, a native of Brazil, was imported from Australia in 1982 and released in Bengaluru in 1983-84. Within 11 months of the release of the weevil, *Salvinia* plants collapsed (Jayanth 1987a). Later on, bioagent was released in many parts of Kerala. Within a span of 3 years after its release, most of the canals abandoned due to the weed menace have become navigable once again (Joy et al. 1995). By 1988 in the case of paddy cultivation, where Rs. 235 had to be spent per hectare for manual removal, the savings on account of labour alone were about Rs. 6.8 million annually. The control of *Salvinia* has brought back the aquatic flora of Kerala back to the pre-*Salvinia* days (Singh 2004). The two isolates designated as '*WF(Sm)37'* and '*WF(Sm)38*' were identified as *Phoma glomerata* and *Nigrospora sphaerica* were found potential pathogen for the biological control of *Salvinia* (Sreerama *et al*. 2007).

Water hyacinth

Eichhornia crassipes (Martius) Solms-Laubach (Pontederiaceae), a free floating aquatic weed of South American origin, ranks among the top ten weeds and has spread to at least 50 countries around the globe. After first introduced into Bengal around 1896 as an ornamental plant, it has spread throughout India and occupies over 200,000 ha of water surface. Water hyacinth is considered to be the most damaging aquatic weed in India. It now occurs in all fresh water ponds, tanks, lakes, reservoirs, streams, rivers and irrigation channels. Water hyacinth has also become a serious menace in flooded rice fields, considerably reducing the yield. It has entered into major river systems–Brahmaputra, Cauvery, Ganges, Godavari, Satluj and Beas. Due to construction of dams on major river systems water hyacinth is no longer flushed out to sea. It interferes with the production of hydro-electricity, blocks water flow in irrigation projects (40 to 95% reduction), prevents the free movement of navigation vessels, interferes with fishing and fish culture and facilitates. The weed is responsible for great water loss (1.26 to 9.84%) due to evapo-transpiration from the luxuriant foliage of water hyacinth. In view of the high cost of manual control and water pollution problems associated with use of herbicides, attention has now been turned to biological control (Sushilkumar 2011).

Three exotic natural enemies were introduced in India, *viz*. hydrophilic weevils – *Neochetina bruchi* (Ex. Argentina) and *N. eichhorniae* (Ex. Argentina) and galumnid mite *Orthogalumna terebrantis* (Ex. South America) from their original home via USA in 1982 for the biological suppression of water hyacinth. Field releases of mass bred weevils in different water tanks in Karnataka and other parts of country were done which resulted in suppression of water hyacinth in many water bodies within 4 years. These efforts have resulted in establishment of the weevils in different parts of the country. The annual savings due to suppression of the weed by the weevils was estimated to be Rs. 11.2 lakhs in Bengaluru alone during 1987. In India spectacular success has been achieved at Hebbal tank in Bangalore causing 95% control within a span of two years (Jayanth 1988), Loktak lake in Manipur (Jayanth and Visalakshi 1989) and several ponds in Jabalpur (Sushilkumar 2011) and Hyderabad (personal observations). However, there were instances where weevil releases have been a total failure, for example, Kengeri tank in Bangalore (Anon. 1994). Wilson *et al*. (2007) were of the opinion that decline of water hyacinth in lake Victoria was due to the action of *Neocheitna* spp.

Kannan and Kathiresan (1999) reported varied numbers of weevils required to control different growth stages of water hyacinth. Ray *et al*. (2009) studied minimum required inoculation load of weevils of *Neochetina* spp. on three growth stages of water hyacinth, based on fresh biomass, plant height and number of leaves. The small growth stage was controlled early corresponding to the increase in number of weevils/plant. Four and eight weevils could control the small growth stage in 50 and 40 days while 8, 12, 16 and 20 weevils could control in 10 days only. Middle growth stage was completely killed in ten days by 16 and 20 weevils per plant while 4, 8 and 12 weevils per plant took 70, 60 and 50 days, respectively . The large plants could not be controlled even with the inoculation pressure of 20 weevils/plant and required more inoculation load. This study suggested that comparative high number of inoculation load of *Neochetina* spp. should be release for control of large size of water hyacinth in a water body.

Weeds can be controlled by pathogens like fungi, bacteria, viruses and virus like agents. Among the classes of plant pathogens, fungi have been used to a larger extent than bacteria, virus or nematode pathogens. In some cases, it has been possible to isolate, culture, formulate and disseminate fungal propagules as mycoherbicides. So far, not even a single successful mycoherbicide has been employed against any aquatic weed in India in spite of many reports of fungal pathogen infesting many aquatic weeds severly (Aneja *et al.* 1993, Kauraw and Bhan 1994, Ray *et al.* 2008b). Ray *et al*. (2008c) studied the combined impact of various pathogens for integrated management of *E. Crassipes* (Mart.) Solms. The combined effect of various pathogens was more effective than any of the pathogens tested alone. Martin *et al.* (2013) demonstrated that in water hyacinth (*Eichhornia crassipes*), weevil *Neochetina eichhorniae* reduced the photosynthetic rates almost equally to the 37% decrease due to entry of deleterious microbes into plant tissues on which they feed.

Biological and chemical integration was applied by Sushilkumar (2011) to achieve the early control as more time is taken by bioagents alone. After 9 months of biological and chemical integration, the first cycle of complete control was achieved. This early collapse of weed within a period of 9 month could be possible due to integration of herbicide and bioagents which would otherwise have taken minimum 24-36 months by the bioagents alone. After some time, again water hyacinth population increased due to new germination from buried seeds or from the left stolons of water hyacinth. This second wave of water hyacinth was again collapsed in 12 months due to integration of one spray of herbicides after one month of regrowth.

Biological control of submerged aquatic weeds

Submerged weeds are those that remain below water surface and may be rooted, *e.g. Hydrilla, Najas, Potamogeton, Vallisneria, Ottelia* and *Nechamandra* or rootless (*e.g. Ceratyphyllum* and *Utricularia*). Submerged aquatic weeds cause serious navigational problems in different water bodies particularly in lakes, which attract large numbers of tourists. The grass carp *Ctenopharyngodon idella*, a native of Siberia, Manchuria and China, was introduced from Japan in 1959 to control submerged aquatic weeds such as *Vallisneria* spp. and *Hydrilla verticillata* in fish ponds and it has since been distributed to different parts of the country. The grass carp was released in Rajasthan to control submerged aquatic weeds Mehta and Sharma 1972). The fish feeds primarily upon submerged plants but also consume small floating plants like *Spirodella, Lemna, Wolffia* and *Azolla*. Judicious manipulation of stock density and size depending on the nature of water body, type and quantum of weed infestation are important factors for successful control of weeds. Singh *et al*. (1967) found grass carp of 600 g size to be effective against most submerged weeds under stocking density of 250 to 500/ha. Fish of about 100 g size can be used to control most of the common water weeds in small farm ponds, if free from predators. Bigger fish of 0.5–1 kg can be employed to control weeds in larger waters.

The submerged weeds preferred by grass carp are *Hydrilla, Najas, Ceratophyllum, Potamogeton, Utricularia* and *Myriophyllum*. The fish will also control *Ottelia, Nechamandra, Vallisneria, Trapa, Limnophila* and *Salvinia* (to some extent). However, water hyacinth and *Pistia* are not completely consumed except small bites.

For control of floating weeds grass, carp of about 10 cm length (about 15 g) are stocked at 1000-2000/ha according to weed density. For other weeds use fish of about 20–30 cm (100–250g) and stocked at 200–1000/ha. Regular inspections are needed to determine whether control is proceeding satisfactorily and if required, more fish can be added. After the weed has been cleared the fish may be carefully netted out of the water and transferred for use elsewhere. As grass carp is good to eat, and easily caught by angling, precautions against poaching are necessary. If predatory fishes are present then the grass carp should be at least 1 kg in weight before being introduced (Anon. 1971).

The other fishes which are considered useful in controlling some aquatic weeds are *Puntius javanicus*, *Pulchellus pulchellus*, *Tilapia mossambica, T. melanopleura* and *Ophronemus gorami*. Grass carp normally consumes choiced aquatic weeds, at least 50% of their body weight in a day. About 300–400 fish, each of about 0.5kg weight, are enough to clear 1 ha of *Hydrilla* infested water body in about a month. Normally *Hydrilla* infestation density ranges from 5–25 kg/m^2 (Tyagi and Gireesha 1996).

Prospects of biological weed control in India

Although many attempts in past have been made in India to control exotic terrestrial and aquatic weeds, but so far, spectacular success could not be achieved to suppress or eradicate them as happened in case of *Dactylopius vulgaris* (prickly pear) by wrongly import of cochineal insect *D. ceylonicus* in place of *D. cacti*, intended to produce commercial dye. This is an eye opening example that how taxonomy plays an important role in selection of an appropriate species. The beetle *Zygogramma bicolorata* has also shown spectacular success in suppression of *Parthenium* in many states of India, but complete control of this weed is impossible due to immense reproductive and survival potential of the weed. In many countries, introduction of multiple species of bioagents against a single weed species has shown encouraging results. For example, introduction of 9 bioagents against *Parthenium* in Australia contributes to suppress the weed significantly at different time of the year.

Although rate of success of classical biological control in India is low but still there are well founded hopes that the rate of success will increase in future projects. It is a well documented fact that classical biological control is especially suited to control of alien weed species which dominate the native vegetation in relatively stable environment. In Indian situation, following research areas on biological weed control have high prospects.

1. In India, relatively little work has been done on new introduction of bioagents against weeds after 1980s. Therefore, there is a great scope of introduction of natural enemies against invasive weeds of terrestrial and aquatic situations.
2. Weeds like C. *odorata, A. adenoforum, M. mikarantha* and *Miomosa diplotricha* have assumed serious status in forestry plantations and

now spreading their tentacles to agricultural and wastelands. There is urgent need to explore the introduction of new bioagent against these weeds.

3. The use of native biotic agents may be of high value against those weeds on which there is no scope for introduction of additional and more effective biocontrol agents from other geographical areas. Some indigenous insects do extremely well to suppress weeds hence they need encouragement by augmenting their population in a particular locality. For example, indigenous *Lantana* gall fly *Asphondylia lentenee* and defoliator *Hypena laceralata* are slow in dispersal. There is need to introduce and disseminate them to newer areas where they may prove more effective under new environment. Therefore, extensive survey for indigenous natural enemies of weeds from different climatological zones of India is required to enhance the biotic pressure.

4. In India, there is great scope of introduction of some well proven exotic insect enemies like dipterous leaf minor *Coteomvze lanatanae* from Australia and noctuid *Neogulea esula* from Hawaii against *Lantana.*

5. Many alien weeds are great problems in protected forests. The problem may be reduced by release of proven bioagents under classical biological control. The authorities of protected areas such as National Parks do not give permission to release bioagents in the pretext of ban to introduce exotics in PA, in spite of the fact that bioagent had already been introduced in the country by due permission of Government of India. It is also true that in due course, an introduced bioagent will reach on its suitable host inside the protected areas, without man's efforts. This need retrospection by the forest authorities to hasten the biological control process.

6. Although, in other countries great emphasis is being given to use plant pathogens but in India this potential field has been totally neglected hence there is an urgent need to explore the use of pathogens and their products (bioherbicides) against problematic weeds. Many pathogens gave promising results as biological control agents of water hyacinth in different countries. Among them are *Uredo eichhorniae*, suitable as a classical biocontrol agent and *Acremonium zonatum, Alternaria eichhorniae, A. alternata, Cercospora piaropi, Myrothecium roridum,* and *Rhizoctonia solani*, which are widely distributed in different continents, as bioherbicides.

7. Integrated weed management (IWM) approach is lacking in India. It has been seen that the effect of biological agents can be greatly enhanced through augmenttion as has been demonstrted by Sushilkumar and Ray (2010) to manage Parthenium in crops. Therefore, it seems desirable that there should be a close collaboration between biological weed control workers, silviculturists, agronomists, plant breeders and crop protection entomologists in order to utilize full advantage of the potential of biological agents.

8. There are known bioagents, which have shown promising results in suppression of weeds like water hyacinth, alligator weed, *Pistia* etc. in the countries of their introduction. Many of such bioagents have not been introduced yet in India, which need immediate attention. Some of these like *Listronotus setosipennis, Smicronyx latulentus, Stobaero concimma, Buccalatrix parthenica, Epiblema strenuana, Puccinia abrupt* on *Parthenium*; a flea beetle *Agasicles hygrophila* for alligator weed *Alternanthera philoxeroides*; *Sameodes albiguttalis* Warren (Lepidoptera: Pyralidae) on water hyacinth, *Neohydronomous affinis* (Hustache) on *Pistia stratiotes*, *Heteropsylla spinulosa* (Homoptera: Psyllidae) on *M. diplotricha* have been effective in controlling aquatic growth of the weed in many areas in USA and Australia.

Conclusion

Being a mega diversity country, India has contributed significantly in classical biological control at global level by providing Indian biological control agents to other countries. In fact classical biological control of weeds in the world had its beginning in India. Overall, the classical biological control offers highly effective and environment friendly solutions to the problem of invading alien weeds. A strong national and regional policy is required to accelerate the effective implementation of biological control programmes. Some pest species are widely distributed in different continents, but their natural enemies are effective in one area and absent in others, hence suitable species could be considered for study and introduction from one area to another.

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