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Biological control of invasive plants through collaboration between China and the United States of America: a perspective

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Abstract

For more than 100 years, classical biological control of invasive plants through screening, introducing and releasing of host-specific natural enemies from native regions has been regarded as one of the promising approaches to the management of invasive plants. Many invasive plants in the United States of America are native to China, and *vice versa*. China and the USA also share a number of invasive plant species, including water hyacinth (*Eichhornia crassipes*), alligator weed (*Alternanthera philoxeroides*) and cordgrass (*Spartina* spp.). Collaboration between the two countries on biological control benefits both the nations by reciprocal opportunities to research and exchange natural enemies, by exchanging information on common invasive species, and by providing training for students and professionals. Here we review the history of collaboration between China and the US on biological control of more than 20 invasive plants. Current collaborative projects associated with four plant species, *Polygonum perfoliatum* L., *Trapa natans* L. *Pueraria montana* (Lour.) Merr. var. *lobata* and *Ailanthus altissima* (Mill.) Swingle, are also covered. We prioritize 14 invasive plants as targets for future collaborative biological control based on information on their importance in introduced areas, natural enemy records, and their potential biocontrol risk to introduced ecosystems. They are: *Ampelopsis brevipendunculata*, *Celastrus orbiculatus*, *Dioscorea oppositifolia*, *Euonymus alata*, *Euonymus fortunei*, *Ligustrum sinense*, *Melia azedarach*, *Paulownia tomentosa*, *Sapium sebiferum* and *Ulmus pumila* for the US, as well as *Spartina alterniflora*, *Ambrosia artemisiifolia*, *Ambrosia trifida* and *Solidago canadensis* for China. In addition, we emphasize that we must very carefully consider any potential non-target effect when we intend to introduce and release new natural enemies. We anticipate that the high priority both countries have placed on control of invasive plants will stimulate increasing collaboration on biological control.

Introduction

Invasive plants pose a serious threat to biodiversity and economy worldwide. An estimated 5000 introduced plant species have escaped and now established in natural ecosystems in the USA and their economic losses and damages were estimated at a total of $34 billion annually (Pimentel et al. 2000). In China there are about 300 invasive plant species in agricultural fields, forests, and aquatic habitats that cause significant economic and environmental losses (Ding and Wang 1999; Ding and Xie 2001).

Man has played the most important role in facilitating biological invasion (Dybas 2004). Many plants used in agriculture, ornamental, horticulture or environmental protection, e.g. preventing soil erosion in America, were historically introduced from China, and recently many more exotic plants are being introduced from China, due to the dramatic increase in trading activity between the two countries (Dybas 2004). For example, among 58 invasive plants listed by Illinois Natural History Survey (http://www.inhs.uiuc.edu/inps/exotics.html), 24 species (41%) are native to eastern Asia or China, and another 20 species were originally introduced from Eurasia (Ding Jianqing, unpublished data). Similarly, some invasive plants in China were introduced from the USA, e.g. *Ambrosia artemissifolia* L. and *A. trifida* L., which are problematic weeds in more than 10 provinces in China where they cause allergic reaction due to their pollen (Wan et al. 1993). In addition, China and the US also share many invasive plants, e.g. water hyacinth (*Eichhornia crassipes* [Mart.] Solms.-Laubach), alligator weed (*Alternanthera philoxeroides* [Mart.] Griseb.), which are native to other continents, i.e. South America (Ding et al. 1995; Buckingham 2002; Center et al. 2002). Both China and the US are facing challenges in not only preventing from additional biological invasions, but also the management of invaded plants.

In the campaign against biological invasion in both China and the US, many approaches have been employed to control invasive species and prevent from further pest introduction. Strict quarantine, predicative models and early detection are critical for preventing potential new invasive plants becoming established. Manual removal could be effective for populations in small infestations but it may be impossible to eliminate the entire population, once an invasive plant invades in a large scale at state and national levels. This is especially the case for many invasive plants that reproduce largely by vegetative propagation, e.g. tree of heaven, *Ailanthus altissima* (Mill.) Swingle (Burch and Zedaker 2003). In addition, these efforts are labor-intensive and expensive. Mechanical control may be effective but prohibited when the plant grows on steep slopes. Invasive plants could be burned but this method is only applied in restricted areas. Effective control can be achieved through use of chemical herbicides for small infestations. However, large-scale and long-term herbicide application should raise environmental concern and it is also expensive and time-consuming.

Classical biological control through screening, introducing and releasing of host-specific natural enemies from native regions has been regarded one of the promising approaches against invasive plants worldwide for more than 100 years (Julien and Griffiths 1998). It will provide self-sustaining, broad-scale control of an invasive plan, when an insect biocontrol agent establishes its population successfully in its introduced areas, as the insect may spread by itself to find its food resource. This is in sharp contrast to manual, mechanical and chemical controls, which typically require repeated treatment and provide control only at or near the site of application. Although an entire research project from screening natural enemies to a successful control may be expensive, a whole weed control program can be inexpensive in the long time. A recent study by International Institute of Tropical Agriculture estimated that biological control of water hyacinth through introduction and mass rearing and releasing of two weevils, *Neochetina eichhorniae* Warner and *N. bruchi* Hustache, would yield a benefit–cost ratio of 124 : 1 in next 20 years in Benin (De Groote et al. 2003). Similarly, an earlier evaluation of the successful control of skeleton weed (*Chondrilla juncea*) demonstrated benefit–cost ratios of 112 : 1, by CSIRO, Australia (Marsden et al. 1980). In South Africa, it is estimated that biocontrol programs have already saved $276 million in weed control costs (Olckers et al. 1998). But as other approaches have their disadvantages, biological control is not always 'Perfect' either. Non-target effects of introduced biocontrol agents have been a growing concern recently (Louda et al. 1997). Processes associated with screening, introducing and releasing of biocontrol agents is needed to be reformed and improved (Pemberton 2000; Strong and Pemberton 2000).

Since many invasive plants in the USA were originally from China, and *vice versa*, and the two countries share similar physical and climatic environments, collaboration on biological control of invasive plants between the two countries not only benefits each other for the exchange of natural enemies screened from native areas either in China, or the US, but also helps to share knowledge and information on those plants that are invasive in both two countries. The purposes of this paper are: (1) to review the exchange of natural enemies between the US and China in the past 20 years, in particular the successful screening and introduction of natural enemies; (2) to report the current status of the on-going collaborative programs on biological control of invasive plants between the two countries; and (3) to evaluate the potential target weeds for biological control in the near future for both.

Exchanged natural enemies for control of invasive plants in China and the USA

History of exchange of natural enemies

Collaboration on biological weed control between China and the USA was initiated in the late 1980s, through the Institute of Biological Control, Chinese Academy of Agricultural Sciences (hereafter referring to IBC-CAAS) based in Beijing, China, and the U.S. Department of Agriculture, Agriculture Research Service (hereafter referring to USDA-ARS). In 1987, the USDA ARS scientists began surveys for natural enemies of invasive plants, e.g. leafy spurge *Euphorbia esula* L. and hydrilla, *Hydrilla verticillata* (L.f.) Royle in China (Pemberton 1988; Pemberton and Wang 1989). In 1988, the Sino-America Biological Control Laboratory (SABCL) was established in Beijing, under an agreement between CAAS and USDA ARS. The USDA Forest Service, International Program initiated efforts in China for biological control of invasive plants in 1996, when a collaborative project was developed among Forest Health Technology Enterprise Team (FHTET), USDA Forest Service, Morgantown, West Virginia and Invasive Plants Management Program of IBC-CAAS for mile-a-minute, *Polygonum perfoliatum* L., which is invasive in northeastern US but native to China (Ding et al. 2004).

About 20 insect and fungi species have been introduced from China to US for the study on potential biological control of seven invasive plants, i.e. *E. esula*, *H. verticillata*, *Polygonum perfoliatum* L., *Myriophyllum spicatum* L., *Tamarix* spp. and *Pueraria montana var. lobata*, between the late 1980s and 2004 (Table 1). Amongst them, three host specific insects (a leaf miner, *Hydrellia*

Table 1. Imported natural enemies for study on potential biocontrol of invasive plants in the US in 1980–2004.

Target weeds	Potential biocontrol agents	Status	US Agency	References
Euphorbia esula	*Aphthona chinchihi* Chen (Col: Chrysomelidae)	Under evaluation	USDA ARS	Pemberton and Wang (1989)
	Puccinia spp.	Unknown		Ma et al. (2004)
Tamarix sp.	*Diorhaabda elongata*	Released in 2001	USDA ARS	DeLoach et al. (2000)
Hydrilla verticillata	*Hydrellia sarahae sarahae*	Under evaluation	USDA ARS	Balciunas et al. (2002)
	Macroplea sp.	Unknown	US Army Corps	
	Bagous sp.	Unknown		
	Fungi *Mycoleptodiscus terrestris*	Unknown		
Myriophyllum spicatum	*Euhrychius* sp.	Unknown	USDA ARS	Ma et al. (2003)
	Phytobius sp.	Unknown	US Army Corps	Ma et al. (2003)
Polygonum perfoliatum	*Rhinoncomimus latipes*	USDA approved for release in 2004	USDA FS	Ding et al. (2004), Judy Hough-Goldstein, personal communication
	Tmanda griseata	Rejected due to broad host range		Price et al. (2003)
	Cletus schmidti	Under evaluation		Ding et al. (2004)
Pueraria montana (Lour.)	*Gonioctena tredecimmaculata*	Under evaluation	USDA FS	Judy Hough-Goldstein, personal communication
Merr. var. *lobata*	*Arges* sp.	Under evaluation		
Trapa natans	*Galerucella birmanica*	Under evaluation	USDA (since 1993) US EPA (since 2002)	Pemberton (1999) Ding et al. (2006)
Ailanthus altissima	*Eucryptorrhynchus brandti* and *E. chinensis*	Under evaluation	USDA FS	Ding et al. (2006)

pakistanae Deonier for *H. verticillata*, a leaf beetle, *Diorhabda elongata* Brullé *deserticola* for *Tamarix* spp. and a weevil, *Rhinoncomimus latipes* Korotyaev for *P. perfoliatum*) have been released after being approved by USDA APHIS. Other natural enemies are under evaluation for their potential as biological control agents for these invasive plants. In contrast, three biocontrol agents were introduced from the US and released in China for control of two invasive plants during this period. A brief introduction on each program is as follow.

Importing natural enemies from China for the control of invasive plants in the USA

Hydrellia pakistanae vs. Hydrilla verticillata

Hydrilla verticillata is a submersed, rooted aquatic plant that has a broad native region encompassing a large part of the Eastern Hemisphere and adjacent areas (Balciunas et al. 2002). It has invaded 16 states in south, north and west US (USDA Plants Database: http://plants.usda.gov/) since it arrived in Florida during the early 1950s (Schmitz et al. 1991). Scientists of USDA and CIBC (Commonwealth Institute of Biological Control, now CABI Bioscience) conducted extensive surveys for natural enemies of hydrilla in Asia in 1970–1980s. The Asian hydrilla leaf mining fly, *Hydrellia pakistanae* originally found in India and Pakistan was released in Florida in 1987 and a few years later a Chinese strain of this fly was released (Balciunas, personal communication). In 1989, another congener, *Hydrellia sarahae* var. *sarahae* Deonier, was also collected from China and shipped to Florida but no release was made due to its possible broad host range (Balciunas et al. 2002).

Diorhabda elongata Brullé deserticola (Coleoptera: Chrysomelidae) vs. Tamarix spp.

Saltcedars, *Tamarix ramosissima* Ledebour, *T. chinensis* Loureiro and hybrids between them and with *T. canariensis* Willdenow, are deciduous shrubs or small trees that are native to the Old World (Gaskin and Schaal 2002). These invasive saltcedars cause damage to riparian areas in the western US by displacing native communities and degrading wildlife habitat as well as reducing stream flow and groundwater level (DeLoach et al. 2000). The beetle, *Diorhabda elongata deserticola* imported originally from Xinjiang, northwestern China, was approved for introduction and release after host range tests and risk assessments indicated that it was a safe and potentially effective biological control agent (DeLoach et al. 2003). The beetle from Fukang of Xinjiang Province, China, and Chilik, Kazakhstan, was released into field in Texas, Colorado, Wyoming, Utah, Nevada and California during 1999 and 2001. Dramatic defoliation of saltcedar was observed in summer of 2002 at Lovelock, NV and good defoliation at Pueblo, Colorado (DeLoach et al. 2004).

Rhinoncomimus latipes vs. Polygonum perfoliatum

Mile-a-minute weed, *Polygonum perfoliatum* L. (Polygonaceae), also known as devil's tail tearthumb, is an annual or perennial herb. It is native to India, China, Korea, Japan, Bangladesh, and the Philippines (He et al. 1984; Wu et al. 2002). It has invaded eight states in the northeastern USA (Delaware, Maryland, New York, Ohio, Pennsylvania, Virginia, West Virginia, and Connecticut, and the District of Columbia) (Price et al. 2003). Infestation of mile-a-minute weed causes ecological problems in invaded areas, as the plant grows rapidly and covers shrubs and other vegetation, dominating in its new community. Field survey and screening of potential natural enemies were initiated in 1996 in China and about 111 arthropods were discovered from the plant (Ding et al. 2004). A geometrid, moth, *Timandra griseata* Petersen (Lepidoptera: Geometridiae), was firstly introduced from China to the quarantine in the US but it was rejected for the use in biological control as host range tests indicated it had a broad host range in Polygonaceae (Price et al. 2003). The Asian weevil, *Rhinoncomimus latipes* Korotyaev (Coleoptera: Curculionidae), was considered a promising biological control agent as it is a host-specific insect (Colpetzer et al. 2004). This weevil was released in Delaware and New Jersey in 2004 (Judy Hough-Goldstein, personal communication, University of Delaware, Newark, DE). The impact of this agent on mile-a-minute is under evaluation.

Importing natural enemies from the USA for control of invasive plants in China

Agasicles hygrophila Selman and Vogt vs. Alternanthera philoxeroides

Alligator weed, *Alternanthera philoxeroides* is an aquatic or semi-aquatic plant of South American origin. It is an invasive plant in both China and the USA. Biological control of alligator weed was initiated by the US Army Corps of Engineers and USDA ARS in the late of 1950s. A host specific leaf beetle, *Agasicles hygrophila* (Coleoptera: Chrysomelidae) was successfully screened from South America and then released in west and southern USA between 1964 and 1979 (Buckingham 2002). After its successful control for alligator weed in the US, the beetle was introduced into China in 1986 (Wang and Wang 1988). It was released in southern China in 1988 after host range tests with about 50 Chinese native plant species (Wang and Wang 1988). By 2001, the beetle was found in 14 provinces in China and suppressed the growth and reproduction of alligator weed significantly, in particular in aquatic habitats (Ma et al. 2003). In many water bodies in Southern China, alligator weed was no longer dominant after the beetle was released or dispersed by itself.

Neochetina eichhorniae and Neochetina bruchi vs. Eichhornia crassipes

Native to South America, water hyacinth, *Eichhornia crassipes* is considered one of the world's worst weeds (Holm et al. 1977). Like alligator weed, water hyacinth is an invasive aquatic plant in China and the US, invading lakes, ponds, canals, and rivers. It occurs in 17 provinces and is regarded as the most important aquatic invasive species in southern China (Ding et al. 1995). Three insects including two weevils *N. eichhorniae* and *N. bruchi*, and a pyralid moth *Niphograpta (=Sameodes) albiguttalis* (Warren), all originally from Argentina, have been released in the United States and led to dramatic decline of water hyacinth population in many sites (Center et al. 2002). Biological control of water hyacinth started in 1995 in China, when two *Neochetina* weevils were introduced from Florida, US, together with a colony from Argentina. The safety of using the weevils was re-confirmed through host range tests with 46 Chinese native plant species (Ding et al. 2002). These weevils were released in Zhejiang and Fujian provinces, southeastern China during 1996–2000. They successfully established their populations and overwintered in Wenzhou, Zhejiang provinces and significantly suppressed water hyacinth growth at some of the releasing sites (Ding et al. 2001).

Current programs

Mile-a-minute, Polygonum perfoliatum

In addition to the weevil, *Rhinoncomimus latipes*, which was introduced from China and released in the northeastern US, there are several more insect agents being evaluated in China for their potential for control of this weed (Ding et al. 2004). For example, a bug, *Cletus schmidti* Kiritehenko (Hemiptera: Coreidae) was collected on leaves and fruits of mile-a-minute weed throughout China. It feeds on the skin of immature fruit of mile-a-minute weed that might eventually influence seed germination. Its host range is restricted to plants of Polygoneceae (Zheng Leyi, Nankai University, China, personal communication). A leaf beetle, *Smaragdina nigrifrons* (Hope) (Coleoptera: Eumolpidae) was found heavily defoliating mile-a-minute weed in southern China (Ding et al. 2004). They may be introduced into quarantine for host range tests in the US in the near future (personal communication, Judy Hough-Goldstein, University of Delaware, Newark DE).

Tree of heaven, Ailanthus altissima

Tree of heaven is a deciduous tree indigenous to China but invasive in the US (Hu 1979) where it occurs in 42 states (http://plants.usda.gov/). It is a serious threat to ecosystems in introduced areas, as the plant is very competitive, especially due to chemicals that may inhibit growth of many native plants. Literature review in China indicated that 46 phytophagous arthropods and 16 fungi were associated with tree-of-heaven, some causing significant damage (Ding et al. 2006). Of the herbivores, two weevils, *Eucryptorrhynchus brandti* (Harold) and

Eucryptorrhynchus chinensis (Olivier), were major pests of the plant and they were only found on tree-of-heaven, showing promise as potential biological control agents in North America. Both weevils were shipped to the quarantine lab at Virginia Tech at Blacksburg, VA in 2004. Host range tests are being conducted in China and in US.

Kudzu, Pueraria montana (Lour.) Merr. var. *lobata* (Willd.) Maesen and Almeida

Kudzu is a perennial, semi-woody, climbing leguminous vine of Asian origin. It was originally introduced into the United States as an ornamental vine in Philadelphia in 1876 (Fairchild 1938). But kudzu is now widely distributed in 27 states (http://plants.usda.gov/), south as far as Florida, and as far west as eastern Oklahoma and Texas. The most severe infestations occur in Mississippi, Alabama, and Georgia (Britton et al. 2002). Kudzu poses a serious threat to biodiversity as it completely replaces existing vegetation and few plants can survive once smothered by kudzu. Field survey and screening of natural enemies of kudzu were initiated in China in 1999, through a joint collaborative effort of USDA Forest Service and Chinese scientists. About 200 arthropod species were discovered from kudzu in China by 2002 (Sun Jianghua, personal communication). A Chrysomelid beetle, *Gonioctena tredecimmaculata*, and a sawfly, *Arges* sp. were introduced into quarantine for host range tests in the US recently (personal communication, Judy Hough-Goldstein, University of Delaware, Newark DE).

Water chestnut, Trapa natans L.

Water chestnut (Trapaceae: *Trapa natans*) is an annual aquatic plant indigenous to Asia (Crow and Hellquist 2000). It remains unknown when and why water chestnut was introduced into the United States, but it was first observed in Sanders Lake, Schenectady, New York, in 1884 (Wibbe 1886). Currently, the species occurs from the northeast, west to the Great Lakes and south to the Chesapeake Bay (New York, Connecticut, Delaware, Maryland, Massachusetts, New Hampshire, Pennsylvania, Vermont, Virginia, and Washington DC) (Crow and Hellquist 2000). The plant has also invaded the Great Lakes Basin (Groth et al. 1996) and has recently been found in Quebec, Canada (Pemberton 2002). It can cover ponds, shallow lakes, and river margins, displaces native vegetation and causes great concerns for survival of native species and limits navigation and recreation (Kiviat 1993). In the United States biological control against water chestnut was conducted through extensive field surveys for natural enemies of water chestnut in China, Japan, Korea, Russia and Europe between 1991 and 1995, and a total of 12 insect species were discovered attacking the plant in northeast Asia but seven species in Europe (Pemberton 1999). Among them, an Asian leaf beetle, *Galerucella birmanica* Jacoby was found abundant and causing serious damage on water chestnut in most regions (Pemberton 1999, 2002). In 2002, a new project by Cornell University was started for evaluation of *G. birmanica* for its biological control potential against water chestnut. Preliminary host range tests with 20 plant species in 13 families showed the beetle could only complete its life cycle on water chestnut and watershield, *Brasenia schreberi* J.F. Gmel. (Ding et al. 2006). Host preference tests indicated that the beetle strongly preferred water chestnut to watershield in both caged and open-field conditions (Ding et al. 2006). However, whether the beetle is introduced into the US for biological control depends on future result from full host range tests with more close relative plants of the US.

In addition, the USDA ARS is working on giant reed, *Arundo donax* L. in collaboration with Asian partners for screening natural enemies in Asia including India and China (Ray Carruthers, personal communication). *A. donax* is invasive in Western and Southern US, in particular California (Dudley 1998). Our literature review on natural enemies of this plant in China will be available in 'Invasive Plants of Asian Origin Established in the United States and Their Natural Enemies, Volume 2', which will be published in 2006.

Selection of appropriate plants for potential targets for biocontrol

Since the invasion of alien plant species is an increasing threat to biodiversity in both China and the US, biological control will be continually regarded as one of the most important approaches against invasive plants. Currently about 100 invasive plants of Asian origin are problematic weeds in the US and most of them have not been targets for biological control (Zheng et al. 2004). Selection of appropriate plants for potential targets for biocontrol will be critical for a success of biocontrol program, especially in view of limited funding and politic implication. In addition, the potential risk of introduced biocontrol agents to native ecosystem will be highly considered for the future biological control programs. In North America almost all the reported non-target effects of introduced biocontrol agents have been associated with native plant species that are closely related to target weeds, therefore, potential risk of biological weed control could be predicated and avoided (Pemberton 2000). Hence invasive plant species that have few congeners in their introduced areas should be placed high priority for targets for biological control.

Potential target invasive plants for the US

In 2001, a collaborative project to develop an information system on about 100 invasive plants of Asian origin that have established in the US was initiated between the Institute of Biological Control, Chinese Academy of Agricultural Sciences and USDA Forest Service, Forest Health Technology Enterprise Team. We have reviewed many available Chinese literature for records of natural enemies of these plants in China (Zheng et al. 2004). Based on *the importance* (i.e. how big invaded areas) of those invasive plants in North America and *availability* of their associated host specific insects or pathogens in China, as well as *potential risk* of introduced agents to ecosystem (i.e. how many congeners in the US), 10 plants are placed top priority as target weeds for biological control in North America (Table 2). The information collected also included reviews on the biology and ecology of the plants in their native areas (e.g. distribution, abundance, habitats, etc.). Hence it will also be valuable for prevention and risk assessment for these plants in North America.

The top ten American invasive plant species of Asian origin for future biological control are: porcelain-berry, *Ampelopsis brevipendunculata*; oriental bittersweet, *Celastrus Orbiculatus*; Chinese yam, *Dioscorea oppositifolia*; winged burning bush, *Euonymus alata*; winter creeper, *Euonymus fortunei*; Chinese privet *Ligustrum sinense*; Chinaberry tree, *Melia azedarach*; Princess tree, *Paulownia tomentosa*; tallow tree, *Sapium sebiferum*; and Siberian elm *Ulmus pumila*. All of these plants have invaded in more then ten states in the US with exception of tallow tree which

Table 2. Potential target invasive plants for the US in the near future.

Scientific names	Common names	Invaded states	Congener species[a]	Natural enemies[b]	Potential agents[c]
Ampelopsis brevipendunculata	Porcelain-berry	10	2	22	4
Celastrus orbiculatus	Oriental bittersweet	25	1	9	5
Dioscorea oppositifolia	Chinese yam	23	3	41	5
Euonymus alata and *E. fortunei*	winged burning bush/ Winter creeper	21	4	40	13
Ligustrum sinense	Chinese privet	20	0	106	18
Melia azedarach	Chinaberrytree	21	0	31	7
Paulownia tomentosa	princesstree	26	0	128	19
Sapium sebiferum	tallowtree	9	0	113	10
Ulmus pumila	Siberian elm	41	6	>400	40

[a]Data from USDA Plant Database: http://plants.usda.gov on 10 October 2004.
[b]Phytophagous arthropods and pathogens associated with the plant in Chinese literatures. Data from Hao Zheng, Yun Wu, Jianqing, Ding, Dennis Binion, Weidong Fu, and Richard Reardon (eds.) Invasive Plants of Asian Origin Established in the United States and Their Natural Enemies, Volume 1, USDA Forest Service FHTET, Morgantown, West Virginia 2004–2005, Volume 2 is in press.
[c]Natural enemies with narrow host ranges limited in the same genus of the target plants. For detail, see: Hao Zheng, Yun Wu, Jianqing, Ding, Dennis Binion, Weidong Fu, and Richard Reardon (eds.) Invasive Plants of Asian Origin Established in the United States and Their Natural Enemies, Volume 1, USDA Forest Service FHTET, Morgantown, West Virginia 2004–2005. Volume 2 is in press.

occurs in nine states in south. Our literature review indicates that there were 3–40 potential host specific natural enemies recorded from these plants in China. No congeners for four species, *Ligustrum sinense Paulownia tomentosa Sapium sebiferum* and *Melia azedarach* grows in the US. Other six species, i.e. *Ampelopsis brevipendunculata*, *Celastrus orbiculatus*, *Dioscorea oppositifolia*, *Euonymus alata* and *Euonymus fortunei* have no more than five congeners with exception of *Ulmus pumila* which has six.

Invasive plants in China

No literature or reports are available on how many invasive plants in China are of North American origin. Nevertheless, several known invasive plants may be considered high priority for biological control in the near future, with regard to their importance and availability of potential biocontrol agents.

Spartina alterniflora Loisel., native to the Gulf coasts and the eastern seaboard of the United States, was introduced into China for prevention of erosion along coasts in 1960–70s (Ding and Xie 2001). But this plant together with *Spartina anglica* C.E. Hubbard has escaped from their original introduced areas and become very invasive in south and eastern China. A plant hopper, *Prokelisia marginata*, has been introduced from the eastern US and released at Willipa Bay, Washington, for the control of *S. alterniflora*. Impact of the insect on the plant is under evaluation (Daehler and Strong 1995; 1997; Grevstad et al. 2003). It may be introduced into China in the future. Also, more insects are being evaluated for their potential for control of *Spartina* sp. (Grevstad, F.S., personal communication). Biological control technology transfer through collaboration between two countries may be possible once more promising agents are discovered in the US.

Ambrosia artemisiifolia L. and *Ambrosia trifida* L. are two terrestrial plants of North American origin. They were introduced into China in 1930s (Wan et al. 1993). They have invaded in Northeastern, Central and Southeastern China. Biological control of *Ambrosia sp*. was started in China in late 1980s through introduction and releasing two insect agents, a leaf beetle, *Zygogramma suturalis* F. and a tortricid moth, *Epiblema strenuana* (Walker). *Z. suturalis* is a North American insect provided to Russia by Canada and the US and was subsequently introduced in China from Russia. It failed to establish its population, possibly due to native predators in China (Wan et al. 1993). *E. strenuana*, introduced into China from Australia via Mexico, has successfully established its population in Hunan, southern China and control impact is under evaluation (Ding and Wan 1993a, b). The phytophagous insect fauna associated with *Ambrosia* sp. was extensively surveyed in south California in 1970s (Goeden and Ricker 1974a, b; 1975; 1976a, b, c). Screening and introduction of more insect agents, e.g. *Euaresta bella*, *Tarachidia candefacta*, and *Liothrips* sp. from North America may be possible.

In southern China, Canada goldenrod, *Solidago canadensis* is also an invasive and aggressive plant, which is native to North America. No insects have been used for the control of this plant in the world. In early 1990s, the insect fauna of four species of goldenrods, *Solidago canadensis* var. *scabra*, *S. fistulosa*, *S. gigantea* and *S. leavenworthii*, was surveyed in Florida. About 122 phytophagous species were discovered and 14 of them were known to be restricted to goldenrods and *Aster* (Compositae). Eight insect species were considered as possible biological control agents of *Solidago* spp. (Fontes et al. 1994).

Discussion

All approaches have their advantages or disadvantages in the management of or prevention from invasive plants. Biological control will continue to be one of the most important methods against invasive plants, especially when the invasion is on a large scale. Collaboration between China and the US for exchange of natural enemies for control of invasive plants will be greatly improved in the near future. We believe more collaborative projects will be developed and established for biological control of invasive plants that are native to China or North America, or are invasive in both, to exchange or share natural enemies, although currently only five American invasive plants of Chinese origin, i.e. mile-a-minute, kudzu, tree of heaven, water chestnut and giant reed are target weeds for biological control under collaboration between scientists in both the countries.

In this paper we listed ten American invasive plant species as potential top priority to be considered in the US and four species for China, based on their importance, availability of potential natural enemies, and possible lower risk to introduced ecosystem as they have few congeners. However, this evaluation is only preliminary, as our database in our Information System project is not complete. Some other important invasive plants of Chinese origin were not included in our system as we had no information available for these plants when we started our literature search. Also, insect biodiversity associated with many plants have not yet been well documented in China and we are far from knowing the potential natural enemies on these plants, until extensive field surveys have been conducted. For example, only one insect, *Gastrophysa atrocyanea* (Coleoptera: Chrysomelidae) was reported attacking mile-a-minute in literature in China. However, after 5 years of extensive surveys in 23 provinces in China, a total of 111 phytophagous insect species representing 6 orders and 29 families were collected and identified from the plant (Ding et al. 2004). In addition, all the ten invasive plants with exception of *S. sebiferum* we selected in Table 2 have invaded more than ten states in the US and we did not include some invasive plants that only occur but may be very invasive in few states. For example, Yellow Himalayan raspberry, *Rubus ellipticus* Smith is very invasive in Hawaii but this plant does not occur in other areas of the US (http://www.nps.gov/plants/alien/fact/ruel1.htm). We did not list it in our Table 2 although there is potential of biological control of this weed in Hawaii (Ding Jianqing et al. unpublished data).

We must very carefully consider any potential non-target effect when we select our next target weed for a joint China–US biological control program. Although a diverse insect fauna and many potential biocontrol agents may exist in native areas of an invasive plant, prospect for future biological control of this plant may not be necessarily bright. For example, multiflora rose is native to China but very invasive in the US. The Chinese literature review indicated that more than 100 arthropod herbivores were associated with this plant in China and 16 of them have the potential of being biocontrol agents as they have very narrow host ranges (Zheng et al. 2004). But we do have concern with their potential non-target effect on native roses in the US, as there are as many as 56 native congeners of this species in the US (Amrine 2002). Classical biological control of multiflora rose using introduced insects should be processed with cautions for their potential damage on native plants. However, this is not necessarily implied that introduction of natural enemies for control of multiflora rose is impossible, as host-specific natural enemies may still exist in China. For example, we screened successfully the host specific weevil, *R.latipes* from China for biocontrol of mile-a-minute which has plenty of congeners in the US (Colpetzer et al. 2004), but the weevil was eventually released because of its host-specificity. Biological control is still applicable for weeds that have many relatives, but more host specificity tests, more risk assessments are needed (Pemberton 1996). With regard to our potential insect screening process for our listed top prioritized species, we should also be able to interpret appropriately host range test results conducted in lab and caged situations, to understand an insect's host range in real world. Moreover, we are facing great challenge that we need to understand fully both physiological and ecological host ranges of an insect before accepting or rejecting it as biocontrol agent (Strong and Pemberton 2000). Nevertheless, in terms of great loss of biodiversity and economy induced by invaded plant species, 'no action' will provide a greater threat. In addition to potential non-target effect, we may also have to meet challenges from politics and regulation issues for the future's exchange of natural enemies between China and the US. For the sake of preventing bio-terrorism attacks, inspection on shipment or carry-on of living organisms has been greatly enhanced at all customs in the world, especially in the US. A national law to manipulate import and export of biocontrol agents should be proposed and applied to facilitate battles of biological control against invasive plants.

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