Acta Ecologica Sinica xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Acta Ecologica Sinica

journal homepage: www.elsevier.com/locate/chnaes

The current status of biological control of weeds in southern China and future options

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ARTICLE INFO

Article history:
Received 1 December 2017
Received in revised form 11 January 2018
Accepted 15 January 2018
Available online xxxx

Keywords:
Biocontrol agents
Weeds
Southern China
Biocontrol options

ABSTRACT

China has become one of the countries most seriously affected by invasive alien weeds in the world. Weeds impact agriculture, the environment and human health, and conventional control methods such as herbicides are expensive, damaging to human health and unsustainable. As the impacts and costs of weed control in China increase, there is an urgent need to manage some of the more important weeds through more sustainable methods. Classical biological control of invasive alien weeds is environmentally-friendly and sustainable. Biological control in China began in the 1930s with the introduction of two agents into Hong Kong for the control of *Lantana camara*. Since then, a further seven biological control agents have been introduced into China to control four weed species. In addition, 11 biological control agents targeting seven weed species have naturally spread into China. Together, these biological control agents are helping to control some of China's worst weeds. However, these efforts are only a small portion of the weeds that could be targeted for weed biological control. This paper reviews the current status of weed biological control efforts against introduced weeds in ten provinces and regions in southern China and provides a platform to identify the most effective and appropriate weed biological control opportunities and programmes to pursue in the future. Introducing additional safe and effective biological control agents into China to help manage some of the worst weeds in the region should reduce the use of herbicides and impacts on human health and the environment, while increasing productivity and food security.

1. Introduction

Invasive alien weeds in China, as in many parts of the world, can affect ecosystem processes and change community structure, resulting in a loss of biodiversity [1,2]. Weeds are also one of the most important factors in agricultural production, as they affect the yield and quality of crops through competition for nutrients, light, water and space [3,4]. Weeds affect fishing enterprises, reduce water supply by blocking irrigation channels and can interfere with hydro-electricity stations. Weeds can also cause human and animal health issues [2,5,6], by providing habitats for harmful insects that transmit arboviruses and may act as alternate hosts for pathogens and other organisms [6,7]. Economic losses due to alien invasive species in China exceed US$14 billion per year [8].

The control of weeds through manual removal or chemical application is often costly, both in labour and in the use of herbicides. For example, over US$12 million per year was spent in China on the manual removal of *Eichhornia crassipes* (Mart.) Solms (Pontederiaceae) (water hyacinth) between 1991 and 2001, but it was not effective [6]. In addition, long-term and large-scale herbicide applications have many negative impacts on the environment, biodiversity, agricultural ecosystems, fisheries, and human and animal health [9,10]. Consequently, there is an urgent need to find environmentally-friendly and economically-sustainable solutions to existing and emerging weed problems. Classical biological control using host-specific, co-evolved natural enemies of the target weeds from the native ranges of the weed, is a safe and self-sustainable alternative used to control many weeds worldwide [11–14]. Classical biological control of weeds has been widely practiced for more than 100 years, with over 480 biological control agents being deliberately released against over 180 weed species. More than 90 countries have deliberately introduced at least one classical biological control agent, with Australia, Canada, New Zealand, South Africa and the USA being the most active in terms of overseas exploration, host specificity testing and field release [14]. The benefit/cost ratio of successful classical biological control is very high, ranging up to several thousand times return on investment, and biological control of weeds

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https://doi.org/10.1016/j.chnaes.2018.01.003
1872-2032/

Please cite this article as: S. Shen, et al., The current status of biological control of weeds in southern China and future options, Acta Ecologica Sinica (2018), https://doi.org/10.1016/j.chnaes.2018.01.003

has achieved great ecological and social benefits in many countries and regions [11,12,15–18].

Classical weed biological control began in mainland China in the mid 1980's with the introduction of the flea-beetle *Agasicles hygrophila* Selman & Vogt (Coleoptera: Chrysomelidae), a biological control agent for *Alternanthera philoxeroides* (Mart.) Griseb. (Amaranthaceae) (alligator weed). However, the seed fly *Ophiomyia lantanae* (Froggatt) (Diptera: Agromyzidae) and the flower-feeding plume moth *Lantanophaga pusillidactyla* (Walker) (Pterophoridae), both biological control agents for *Lantana camara* L. (Verbenaceae), had been deliberately released into Hong Kong in 1933. *Lantanophaga pusillidactyla* had actually been reported in Hong Kong by 1900, although the source of that introduction is unknown [14]. There had also been attempts and even community campaigns promoting the use of pathogens as bioherbicides in the 1960's [12,19].

By 2012, nine classical biological control agents had been deliberately introduced and released in China to control five weed species, namely *A. philoxeroides*, *Ambrosia artemisiifolia* L. (Asteraceae), *E. crassipes*, *L. camara* and *Mikania micrantha* Kunth (Asteraceae), with six biological control agents establishing [14]. Apart from the deliberately introduced biological control agents, another seven agents had spread naturally into China by 2012 and are established on six weed species [14]. It is not known from where these biological control agents came, but most likely neighboring countries where they were deliberately introduced. Of the 13 classical biological control agents that had established in China by 2012, *A. hygrophila* is considered the most successful in China [12,14]. *Epiblema strenuana* (Walker) (Lepidoptera: Tortricidae) and *Ophraella communa* LeSage (Coleoptera: Chrysomelidae) are also considered to be very effective against their host plant, *A. artemisiifolia* [14,20].

The number of weeds that have been deliberately targeted for classical biological control in China is only a fraction of the number of weed species present in China that have been targeted for biological control in other countries [14]. The high costs, limitations and problems associated with long-term conventional weed management options, along with the increasing rate of new weed incursions due to China's surging economic growth through increased international trade and travel, makes biological control even more advantageous [21,22]. Thus, there is a historic opportunity for increasing the emphasis on classical weed biological control in China by using safe and very effective biological control agents that have been used elsewhere in the world to help control some of its worst weeds, such as *Chromolaena odorata* (L.) R. M. King & H. Rob. (Asteraceae), *M. micrantha* and *Parthenium hysterophorus* L. (Asteraceae) [23–25].

The idea of using classical biological control agents that have been released elsewhere to control some of China's worst invasive weeds is not new. Li et al. [26] and Waterhouse [19] listed several weeds in China that have been successfully controlled by classical biological control agents in other countries. This paper reviews the current status of classical biological control efforts against introduced weeds in ten provinces and regions in southern China (Fujian, Guangdong, Guangxi, Guizhou, Hainan, Hong Kong, Hunan, Jiangxi, Macau and Yunnan) and identifies safe and effective biological control agents that could be introduced into China to help manage some of the worst weeds in the region. These results are critical to providing a platform to help land holders with weed management, reduce dependency on herbicides, lower production costs and increase productivity [27,28].

2. Materials and methods

Literature searches were conducted to identify all invasive alien weeds that have been recorded in the southern provinces and regions of China namely: Fujian, Guangdong, Guangxi, Guizhou, Hainan, Hong Kong, Hunan, Jiangxi, Macau, and Yunnan [4,25,29–50]. This weed list was then reduced to only plant species that have been targeted for classical biological control in at least one country worldwide, according to Winston et al. [14]. Biological control agents that are viruses or have been used as mycoherbicides were not considered, as they are not classical biological agents and populations cannot be sustained naturally in the field without re-application. Weeds that have recently become targets for biological control and were not included in Winston et al. [14] were subsequently added, to yield a comprehensive list of weeds (and their distribution in southern China) that have been targets for classical weed biological control elsewhere.

This weed list was further reduced to include only those weed species for which safe and effective biological control agents are available in at least one other country [14]. Biological control agents were considered safe if they have been tested for host specificity and have not been observed causing significant non-target impacts in the field. Biological control agents may differ in their impact from country to country. Herein, biological control agents were considered effective if they cause at least moderate to high impacts against their target weed(s) in at least one other country.

A second list was constructed using Winston et al. [14] to include all biological control agents both deliberately and naturally introduced into southern China and their current status and distribution. This list was updated using recent information not in Winston et al. [14,51,52], as well as results of recent field surveys conducted in Yunnan province in December 2016 and June 2017, to yield an up-to-date record of classical weed biological control activities in southern China.

Combining both the weed list and the biological control agent list revealed the safe and effective agents that could be introduced into and/or redistributed within southern China. We deliberately did not prioritize which weed species should be controlled or studied first, as we believe this decision is best left to the appropriate departments or organizations in each province. We have, however, identified the safest and most effective biological control agents that could be utilized if particular weed species in each province are considered important.

3. Results

A combined total of 278 exotic weed species representing 51 families have been reported or found in the 10 southern China provinces and regions investigated. Of these, 40 species representing 17 families are targets for weed biological control elsewhere. Twelve weed species were removed due to a lack of safe and effective agents, leaving 28 weed species, representing 14 families that have had safe and effective agents released against them in at least one other country [14] (Table 1).

Nine biological control agents have been deliberately introduced into China, targeting five weed species. Of these, six biological control agents have established against four weed species and are causing slight to high impacts to their respective target weeds (Table 2). A total of 11 biological control agents targeting seven weed species have spread naturally into China (Table 3). Four of these were found on *L. camara*, three of which were found in China for the first time during the 2016 and 2017 surveys. Two of the nine intentionally introduced biological agents and five of the 11 that naturally spread into China were reported to be present in Yunnan for the first time, following the 2016 and 2017 field surveys (Tables 2 & 3). In addition to these bona fide biological control agents being found in China and/or Yunnan for the first time, *Orthezia insignis* Browne (Ortheziidae) was also found on *L. camara*; it is reported herein for the first time as being present in China. This insect is reported as a pest on several plant species and so is not considered a biological control agent, nor is it recommended for re-distribution.

Sixteen classical biological control agents are currently present in China, affecting nine weed species. These biocontrol agents have not been reported in all provinces and regions where their respective target weeds are recorded. The provinces and regions to which these biological control agents could be re-distributed are shown in Table 4. *Agasicles hygrophila*, which is very effective in controlling *A. philoxeroides*, could potentially be introduced into another two provinces and regions

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