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# Initiation of biological control against *Parthenium hysterophorus* L. (Asteraceae) in South Africa

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The annual herbaceous plant, *Parthenium hysterophorus* L. (Asteraceae) (parthenium), has been a major weed of global significance for several decades, with wide-ranging impacts on agriculture, biodiversity conservation, and human and animal health. Despite this, in 2003, South Africa became the first African country and only the third country worldwide to implement a biological control programme against the weed. It seems that a suite of agents is needed to achieve effective biological control of parthenium under different environmental conditions and in different regions. The rust fungus, *Puccinia abrupta* Dietel & Holw. var. *partheniicola* (H.S. Jacks.) Parmelee (Pucciniales: Pucciniaceae), is already present in South Africa. Three agents have been imported and evaluated, namely the leaf rust fungus *Puccinia xanthii* Schwein. var. *parthenii-hysterophorae* Seier, H.C. Evans & Á. Romero (Pucciniales: Pucciniaceae), which was released in 2010, and both the leaf-feeding beetle *Zygogramma bicolorata* Pallister (Coleoptera: Chrysomelidae: Cassidinae) and the stem-boring weevil *Listronotus setosipennis* (Hustache) (Coleoptera: Curculionidae), for which permission to release is being sought. A stem-galling moth *Epiblema strenuana* (Walker) (Lepidoptera: Tortricidae), seed-feeding weevil *Smicronyx lutulentus* Dietz (Coleoptera: Curculionidae), and stem-boring moth *Carmenta* nr. *ithacae* (Beutenmüller) (Lepidoptera: Sesiidae) are also under consideration. Studies conducted in South Africa prior to the release of biological control agents, demonstrated an extensive, but highly variable, soil seed bank. In 2005, the South African biological control programme was extended to Ethiopia through an international cooperative programme. Parthenium has the potential to become more widespread and problematic in sub-Saharan Africa, and the implementation of biological control could assist in reducing this risk.

**Key words:** parthenium, *Puccinia abrupta* var. *partheniicola*, *Puccinia xanthii* var. *parthenii-hysterophorae*, *Zygogramma bicolorata*, *Listronotus setosipennis*, *Epiblema strenuana*, *Smicronyx lutulentus*, *Carmenta* nr. *ithacae*.

## INTRODUCTION

*Parthenium hysterophorus* L. (Asteraceae: Heliantheae) (Fig. 1), hereafter referred to as parthenium, is an annual herbaceous plant of Central and South American origin, and is a global invader that causes severe economic losses in several parts of Africa (McConnachie *et al.* 2010; Nigatu *et al.* 2010), Asia (Nath 1988; Adkins *et al.* 2005) and Australia (Navie *et al.* 1996). Prior to the 1970s, parthenium was not reported as problematic anywhere (Evans 1997). Australia and India were among the first countries to recognize its invasive status. Parthenium was first observed in Australia in 1955, but it was from a separate introduction in 1958 that the weed spread rampantly in Queensland (Haseler 1976; Auld *et al.*

1983; McFadyen 1992; Chippendale & Panetta 1994). Parthenium was accidentally introduced into India in 1955 (Rao 1956) and has subsequently invaded most of the sub-continent, including Pakistan (Adkins *et al.* 2005), Sri Lanka (Jayasuriya 2005), Bangladesh, Nepal (S. Adkins, pers. comm.), southern China and Vietnam (Nath 1988), Taiwan (Peng *et al.* 1988), Israel (Joel & Liston 1986), as well as some Pacific islands (McFadyen 1992). In Africa, parthenium is present in South Africa, Swaziland, Zimbabwe, Mozambique, Tanzania, Kenya, Uganda, Ethiopia, Somalia, Eritrea and also occurs on the islands of Madagascar, Mauritius, Réunion and the Seychelles (McConnachie *et al.* 2010). The weed has only recently been detected in some countries on the continent. Climatic modelling indicates that much of sub-Saharan Africa is at risk

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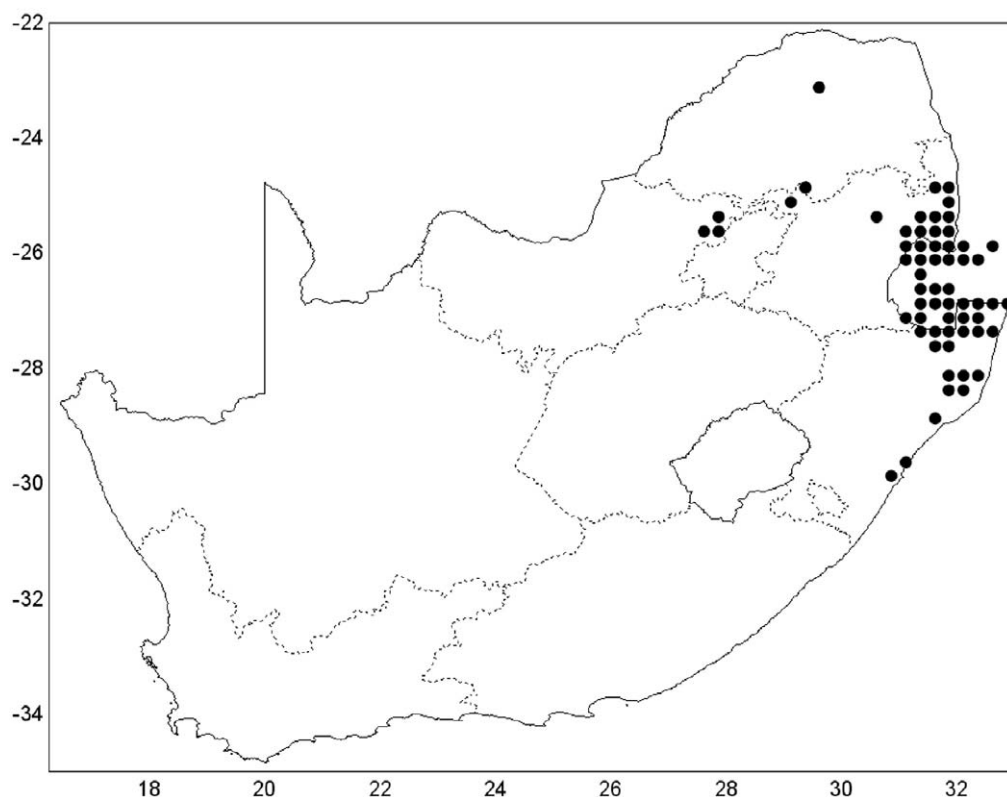


**Fig. 1.** *Parthenium hysterophorus*. (Drawn by M. Steyn; first published in Henderson (2001), ARC-Plant Protection Research Institute, Pretoria.)

of invasion by parthenium (McConnachie *et al.* 2010). *Parthenium* is increasing in Africa and globally, with wide-ranging impacts (Dhileepan & Strathie 2009; McConnachie *et al.* 2010), and although there are few active control programmes against the weed, there is growing awareness of the need for such initiatives. In some cases, particularly in developing countries, knowledge of the impending threat of the weed is lacking.

Despite decades of control efforts against parthenium in Australia (McFadyen 1992; Dhileepan 2001) and India (Jayanth 1987a), no national control programme had been undertaken against this weed in Africa, until South Africa initiated a biological control programme in late 2003 (Strathie *et al.* 2005). This was undertaken under the auspices

of the 'Emerging Weeds Programme' funded by the Department of Water Affairs' *Working for Water* Programme in which five plant species that were considered promising candidates for biological control were targeted during the early stages of their invasion (Olckers 2004). The South African programme against parthenium has relied extensively on progress achieved with biological control of the weed in Australia. Efforts undertaken so far in South Africa have included studies on the weed's distribution and aspects of its population dynamics, and an assessment of the suitability of selected biological control agents. In addition, the South African biological control programme has been extended to Ethiopia, through an international cooperative programme.



**Fig. 2.** Distribution of *Parthenium hysterophorus* in South Africa and Swaziland. (Drawn by L. Henderson; data source: SAPIA database, ARC-Plant Protection Research Institute, Pretoria.)

The aim of this review is to provide general information on parthenium and to document the biological control efforts undertaken in South Africa since late 2003. Aspects that are considered include: (i) a summary of the weed's biology, ecology, impact, and management; (ii) the biological control agents that have been studied so far in South Africa; and (iii) the extension of biological control from South Africa to Ethiopia.

### **PARTHENIUM HYSTEROPHORUS**

#### **Biology and ecology**

The biology and ecology of parthenium have been reviewed extensively (see Dale 1981; McFadyen 1992; Navie *et al.* 1996). The plant is native to the countries around the Gulf of Mexico including the West Indies, and to central South America (Rollins 1950). It was first recorded in South Africa in 1880 (Wood 1897) but only became widespread during the 1980s (Anon. 1998). Infestations now occur in KwaZulu-Natal, Mpumalanga

and North West provinces in subtropical north-eastern South Africa (Fig. 2).

Parthenium can germinate at any time of the year (given sufficient rainfall), rapidly reaches a maximum height of 2 m, in good soils, flowers within four to six weeks of germination, and is a prolific seed-producer, with up to 30 000 seeds per plant (Haseler 1976; McFadyen 1992; Navie *et al.* 1996, 2004; Adkins *et al.* 2005). Wind, water, animals, vehicles, agricultural and earth-moving machinery facilitate seed dispersal (Navie *et al.* 1996). The white-flowering form of *P. hysterophorus* is common in its native range, and has invaded South Africa and other parts of the world, but a yellow-flowering form is also native to Argentina, Bolivia, Chile, Paraguay, Peru and Uruguay (Dale 1981). The production of phenolics and sesquiterpene lactones, such as parthenin, by roots, stems and leaves of parthenium contribute to the plant's invasive capabilities by inhibiting surrounding plant growth (Kanchan & Jayachandra 1979; Reinhardt *et al.* 2006; Belz *et al.* 2007). Picman &

Towers (1982) concluded that parthenium from Verulam, South Africa, was chemically similar (with parthenin as the major sesquiterpene lactone, as well as coronopilin and tetraeurin-A) to populations from North and Central America, Venezuela, India, Australia, and a sample from Jamaica, suggesting a likely North American origin, presumably around the Gulf of Mexico. Unlike North American samples, South American populations were diverse in their chemical composition and most contained hymenin as the major sesquiterpene lactone (Picman & Towers 1982).

The soil seed-banks of parthenium have not been well studied with the exception of investigations conducted in Australia (Navie *et al.* 2004; Adkins *et al.* 2005). Consequently, studies have been conducted annually in South Africa since 2006, to understand and quantify the weed's germinable seed bank prior to the introduction of biological biological control agents. Up to 95 800 seeds/m<sup>2</sup> were recorded at some sites, while in other years the number was much lower, although still substantial (914 seeds/m<sup>2</sup>) (L.W. Strathie & A.J. McConnachie, unpubl.). The large annual variability in the extent of soil seed banks was most likely related to rainfall. The soil seed-banks recorded in South Africa exceed those reported in Australia (Navie *et al.* 2004; Adkins *et al.* 2005), but this may be due to the impact of biological control agents there. During soil seed-bank germination studies conducted under tunnel conditions (minimum 18 °C, maximum 30 °C) in South Africa, some parthenium seeds germinated within 24 hours and many seedlings emerged before other species. Soil disturbance resulted in a subsequent flush of parthenium seedlings (Taylor 2007; L.W. Strathie & A.J. McConnachie, unpubl.).

### Impact of parthenium

Parthenium rapidly colonizes disturbed ground such as roadsides, cultivated lands and overgrazed pastures, and causes severe losses to agricultural production (Chippendale & Panetta 1994; Adamson & Bray 1999; Tamado *et al.* 2002). The plant causes allergic eczematous dermatitis after prolonged skin contact, and respiratory problems such as allergic rhinitis, bronchitis or asthma from the pollen (Towers & Subba Rao 1992; McFadyen 1995; Evans 1997). Parthenium is also reputed to taint the meat and milk of livestock (Tudor *et al.* 1982). Despite the extent of invasion of parthenium in

southern Africa and Ethiopia, and its effect on the livelihoods of millions of people, there is a lack of information quantifying the impact of the weed on agricultural production, biodiversity conservation, and human and animal health.

### Control options

Successful management of parthenium is possible through a combination of control methods including biological control, chemical control, containment strategies, the utilization of competitive plant species and other cultural control methods (Navie *et al.* 1996; Adkins *et al.* 2005; O'Donnell & Adkins 2005). Parthenium can be controlled using herbicides and several are known to be effective in South Africa (Goodall *et al.* 2010). The cost of chemical control of parthenium along road verges in parts of KwaZulu-Natal Province was estimated at R177 (US\$25) per hectare in 2008 (M. Braack, pers. comm.). Continual follow-up is required to remove new emerging plants and provide effective, long-term suppression of parthenium (Goodall *et al.* 2010). Financial constraints may render chemical control unfeasible for many land owners in Africa. Hand-weeding is a labour-intensive, although common weed control practice in Africa (Akobundu 1991), but it carries health risks associated with frequent contact with parthenium. Subsistence farmers are particularly affected by parthenium that invades grazing and arable land that is subject to high levels of disturbance (Nigatu *et al.* 2010). Reducing grazing pressure by lowering livestock densities is an effective means of managing parthenium (Holman 1981), but it may be difficult to achieve this in unfenced, tribal or community pastoral systems in Africa. Limited research has been conducted on the use of competitive grass species to control parthenium in South Africa (van der Laan 2006). Considering all of these management problems and constraints, biological control using introduced natural enemies offers a promising supplemental control option for management of parthenium in Africa.

### BIOLOGICAL CONTROL OF PARTHENIUM

Extensive surveys of the natural enemies associated with parthenium were undertaken in North and South America, and in the Caribbean, from 1975 onwards, as part of the Australian biological control programme (Bennett 1976; McFadyen 1976, 1979, 1992; McClay 1985; McClay *et al.* 1995).

From several hundred phytophagous arthropods and pathogens encountered on parthenium in its native range, 11 species were released, from 1981 onwards, after assessment in Australia (McFadyen 1992), of which at least seven insect agents and two rust fungi have established. However, some agents have not reached the desired population levels, or have restricted distributions so their impact is limited (Dhileepan & Strathie 2009). A suite of agents is required to achieve adequate control of the weed under different conditions in different regions (McFadyen 1992). Even so, biological control has formed an important part of the integrated management of parthenium in Australia (Dhileepan 2007; Dhileepan & Strathie 2009), in conjunction with strategies that include vehicle wash-down facilities for seed removal to reduce spread (S. Adkins, pers. comm.), and chemical control along roadsides, reduced stocking densities and improved pasture management (all factors that affect existing infestations) (Adkins *et al.* 2005). India, the only other country to have implemented a biological control programme for parthenium, has released only the leaf-feeding beetle *Zygogramma bicolorata* Pallister (Coleoptera: Chrysomelidae: Cassidinae), in 1984, which established widely and has had a substantial impact (Jayanth & Bali 1994; Jayanth & Ganga Visalakshy 1996).

#### Phytophagous species associated with parthenium in South Africa

A preliminary survey of native insects and pathogens associated with parthenium in northern KwaZulu-Natal Province in 2003, revealed that the plants were mostly devoid of any South African phytophagous species, and showed no obvious signs of herbivory or fungal infection. However, the leaf-rust fungus *Puccinia abrupta* Dietel & Holw. var. *partheniicola* (H.S.Jacks.) Parmelee (Pucciniales: Pucciniaceae) was recorded at a few sites only, around the town of Ingwavuma (27°08.032'S 31° 59.872'E) on the Swaziland border, out of about 12 localities surveyed in KwaZulu-Natal Province. Although several plants were infected with the rust fungus, it did not appear to have a significant impact (T. Olckers & C. van Rooi, unpubl.).

*Puccinia abrupta* var. *partheniicola* was first recorded near Brits (25°35'S 27°46'E) in the North West Province in 1995 (Wood & Scholler 2002). It is presumed to have been introduced along with its

host plant. The rust fungus has similarly been inadvertently introduced into other countries, *e.g.* India (Kumar & Evans 2005) and Kenya (Parker *et al.* 1994), and Ethiopia (Tessema 2004). The rust fungus is native to Mexico and northern South America (Parmelee 1967), where, in semi-arid, high-altitude localities it is reported to reduce vegetative growth of young plants, and seed production in older plants, by infecting leaves, stems and inflorescences (Evans 1987). In surveys of coastal regions and more humid lowland areas, infections were found to be light and restricted to the older rosette leaves (Evans 1987).

Post-inoculation temperature and the duration of leaf wetness affect the ability of *P. abrupta* var. *partheniicola* to infect plants; 15 °C and 12 hours of leaf wetness are optimal for infection, with a required minimum of six hours leaf wetness for some infection to occur (Fauzi *et al.* 1999). Considering these requirements, it is predicted that this rust fungus will thrive in the colder, high-altitude areas of South Africa (where it was first discovered) and have little impact in the warmer, low-altitude areas of KwaZulu-Natal and Mpumalanga provinces, where dense infestations of parthenium occur, but where the rust fungus has seldom been observed.

One of five isolates of *P. abrupta* var. *partheniicola* collected in Mexico as part of the Australian biological control programme, was extremely virulent on the Australian biotype of parthenium and was subsequently released, after testing, in Australia in 1991 (Parker *et al.* 1994). Localized establishment occurred only in the central Queensland area, but with limited impact and dispersal (Dhileepan *et al.* 2006). This isolate could be considered for introduction into South Africa in future, provided it is shown to be sufficiently host specific and highly pathogenic on the local parthenium biotype.

#### Agent selection

Various factors must be taken into consideration for the success of biological control of parthenium in South Africa. Climatic suitability is important as biological control agents must be able to withstand seasonally dry periods that occur in the range invaded by parthenium. Other factors to consider are that (i) some biological control agents available for introduction are not strictly monophagous; (ii) some have an erratic history of establishment and/or impact in other countries; and (iii) multiple agents will probably be required to achieve an

adequate level of control. Even with four agents established on parthenium in Central Queensland, the level of control was considered inadequate (McFadyen 1992). As parthenium is present from southern Africa through to Ethiopia, the ability of some agents to disperse readily should also be considered when assessing their host range and their suitability for introduction.

Australian researchers were consulted from the inception of the South African biological control programme on parthenium. The rationale for the agents prioritized for assessment in South Africa (Table 1) was based on their impact on the plant and their likely adaptability to the local climate. Consequently, the stem-boring weevil *Listronotus setosipennis* (Hustache) (Coleoptera: Curculionidae), leaf-feeding beetle *Z. bicolorata*, stem-galling moth *Epiblema strenuana* (Walker) (Lepidoptera: Tortricidae), and rust fungus *P. xanthii* Schwein. var. *parthenii-hysterophorae* Seier, H.C. Evans & Á. Romero (Pucciniales: Pucciniaceae) were selected for further assessment. The first two agents are damaging and have a soil-diapausing phase during seasonally dry periods. The stem-galling moth spread widely and rapidly in Australia, and was also damaging to parthenium. The rust fungus was considered to be better suited to the warmer, wetter regions of South Africa where parthenium infestations are more prolific, than the congeneric *P. abrupta* var. *partheniicola* already present in the country. As a suite of agents is required to achieve the level of impact necessary to reduce parthenium infestations throughout its range, the seed-feeding weevil *Smicronyx lutulentus* Dietz (Coleoptera: Curculionidae), and the day-flying moth, that has root crown-boring larvae *Carmenta* nr. *ithacae* (Beutenmüller) (Sesiidae), were additionally considered for inclusion later in the programme. Details on these agents are presented in the following sections. Certain agents such as *Bucculatrix parthenica* Bradley (Lepidoptera: Bucculatricidae), *Conotrachelus albocinereus* (Coleoptera: Curculionidae) and others (Table 1), have not been considered for the South African biological control programme due to their lack of establishment or limited success in Australia (Dhileepan & Strathie 2009).

#### *Puccinia xanthii* var. *parthenii-hysterophorae*

*Puccinia xanthii* var. *parthenii-hysterophorae* was previously known as *P. melampodii* Dietel & Holw. *Puccinia melampodii* was restricted to plant species

in the tribe Heliantheae and *P. xanthii* to species in the Ambrosiae (Arthur 1922; Parmelee 1969). However, all plant species previously allocated to the tribe Ambrosiae have now been placed in the tribe Heliantheae (Bremer 1994). In a recent study Seier *et al.* (2009) concluded that despite some morphological differences between *P. xanthii* and *P. melampodii*, they should be regarded as belonging to a single morphospecies, based on molecular evidence and because demonstrated host specificity within the complex lies at the level of host species and not tribes. These host-specific varieties are assigned names based on the host with which the particular fungus is associated, hence the new name of *P. xanthii* var. *parthenii-hysterophorae* (Seier *et al.* 2009).

Owing to the temperature limitations of *P. abrupta* var. *partheniicola*, a very damaging isolate of *Puccinia xanthii* var. *parthenii-hysterophorae* from Mexico that can cause plant mortality (Seier *et al.* 1997), was released in Australia in 1999 (Dhileepan *et al.* 2006). It established over a wide geographical range in Australia (Dhileepan *et al.* 2006), and contributed substantially to the control of the weed during periods of favourably high rainfall (Dhileepan 2007). This particular isolate was imported from the Alan Fletcher Research Station, Brisbane, Australia into the South African Agricultural Research Council-Plant Protection Research Institute (ARC-PPRI), Stellenbosch, quarantine laboratory in 2004, where it was confirmed to be pathogenic on the local biotype of parthenium. Considering the extensive host-range testing that had already been conducted in Australia (Seier *et al.* 1997), only a few additional plant species were selected for host-specificity testing in South Africa. These included seven genera from the tribe Heliantheae, most of them indigenous, and 13 commercial *Helianthus annuus* L. (sunflower) (Asteraceae) cultivars. The rust fungus was shown to be highly specific to parthenium (K. Ntushelo & A. Wood, unpubl.). A single occurrence of three pustules that developed on two leaves of the native *Spilanthes mauritiana* (A.Rich. ex Pers.) DC. (Asteraceae) was considered to be a false host range expansion, a common phenomenon found under glasshouse conditions when using high inoculum loads for testing (Evans *et al.* 2001). No symptoms were observed on this species following subsequent inoculations. An application to release the rust fungus was submitted to the South African regulatory authorities in 2007 and approved in

**Table 1.** Date of importation and origin of candidate agents that variously damage *Parthenium hysterophorus* and their status in biological control studies in South Africa.

Order/Family	Agent	Date imported	Source country (origin)	Damage	Status in South Africa
<b>Coleoptera</b>					
Chrysomelidae: Cassidinae	<i>Zygogramma bicolorata</i> Pallister	2005	Australia (Mexico)	Leaf-feeding	Evaluated; application for release
Curculionidae	<i>Listronotus setosipennis</i> (Hustache)	2003	Argentina	Stem-boring	Evaluated; application for release
	<i>Smicronyx luteiventris</i> Dietz	2010	Australia (Mexico)	Seed-feeding	In culture; undergoing host-specificity testing
	<i>Conotrachelus albocinereus</i> Fiedler	–	Australia (Argentina)	Stem-galling	Not under consideration
<b>Lepidoptera</b>					
Tortricidae	<i>Epiblema strenuana</i> (Walker)	2003 2005 2010	Argentina Australia (Mexico) Australia (Mexico)	Stem-galling	Failed to establish culture Failed to establish culture In culture; undergoing host-specificity testing
	<i>Platphalonidia mystica</i> (Razowski & Becker)	–	Australia (Argentina)	Stem-boring	Not under consideration; it did not establish in Australia
	<i>Carmenta</i> nr. <i>ithacae</i> (Beutenmüller)	2010	Australia (Mexico)	Stem/root crown-boring	Insufficient for culture establishment; to be introduced when available
Sesidae					
Bucculatricidae	<i>Bucculatrix parthenica</i> Bradley	–	Australia (Mexico)	Leaf-mining	Not under consideration
<b>Hemiptera</b>					
Delphacidae	<i>Stobaera concinna</i> Stål	–	Australia (Mexico)	Sap-sucking	Not under consideration; it did not establish in Australia
<b>Pucciniales</b>					
Pucciniaceae	<i>Puccinia abrupta</i> Dietel & Holw. var. <i>parthenicola</i> (H.S.Jacks.) Parmelee	Unknown; discovered 1995	Unknown	Leaf pustules	Already present; not widespread
	<i>Puccinia xanthii</i> Schwein. var. <i>parthenii-hysterophorae</i> Seier, H.C. Evans & Á. Romero	2004	Australia (Mexico)	Leaf pustules	Evaluated; approved for release in 2010; released in 2010

2010. The first releases commenced in December 2010.

### *Listronotus setosipennis*

The stem-boring weevil *L. setosipennis* oviposits primarily in parthenium flowers, or if these are unavailable, in leaf petioles, stem surfaces or axillary buds, sealing each egg with a black, frass cap. Adult feeding on leaves and flowers causes little damage, but larval feeding within the stem pith or beneath the epidermis can be very damaging. Feeding by several larvae can kill seedlings and mature plants (Wild *et al.* 1992). Larvae tunnel down to the base of the plant where they exit and pupate in a chamber constructed in the soil, before eclosing as adults, which can live up to eight months (Wild *et al.* 1992). Development from egg to adult takes about 23 days at a constant temperature of 30 °C (Z. Shoba, unpubl.).

*Listronotus setosipennis* occurs from southern Brazil to northwestern Argentina (Wild *et al.* 1992), and has only been introduced into Australia. Some 55 000 adults originating from collections made in Brazil were released there from 1982 to 1986, and later collections from Tucuman Province, Argentina were released in 1991 (R. McFadyen, pers. comm.), but the weevil spread slowly and damage was negligible and masked by damage from the widespread stem-galling moth *E. strenuana* (Wild *et al.* 1992). Dhileepan (2003a) determined that at least five larvae per plant are required to prevent flowering, and at least two larvae per rosette-stage plant are required to have a measurable impact. Damage was significant only when initiated at the rosette stage (Dhileepan 2003a). In Australia, the weevil generally occurs at levels that are too low to have an adverse impact on plants, although at some sites their numbers exceed the minimum damage threshold (Dhileepan 2003a). This is the second most widely distributed agent in Australia, following *E. strenuana*, but it has not naturally spread to all parthenium sites (Dhileepan 2003a). However, *L. setosipennis* is the only agent that is suited to areas with prolonged dry periods and erratic rainfall. Additionally, no larval parasitoids have been observed on it in Australia (Dhileepan 2003a), which bodes well for the weevil should it be approved for release in South Africa.

In December 2003, larvae of *L. setosipennis* were opportunistically collected from root crowns of yellowish-flowered *P. hysterophorus* at three sites in the provinces of Santiago del Estero (27°26.372'S

66°55.129'W), Salta (25°20.078'S 64°56.158'W) and Jujuy (23°45.484'S 64°41.960'W) in northern Argentina, a region which experiences dry periods, and imported into the ARC-PPRI's Cedara quarantine laboratory in South Africa. Some 24 adults were reared from the material and combined to establish a culture which has since been maintained in the Cedara quarantine facilities. Despite some intraspecific differences, the weevil identity was confirmed by R. Oberprieler, CSIRO, Australia (pers. comm.) to be the same as voucher specimens of stocks of *L. setosipennis*, originating from Brazil, that were released in Australia in 1985 and 1986.

*Listronotus setosipennis* was tested on 18 species of Asteraceae (including six sunflower cultivars) as well as 50 species from 25 families prior to its release in Australia (Wild *et al.* 1992). Additional tests were conducted on native and locally economically-important species in South Africa. Of the 38 native and economically-important Asteraceae species (from 11 tribes) and 13 commercial *H. annuus* cultivars selected for no-choice tests in South Africa, eggs were deposited on five native species as well as on Jerusalem artichoke, *Helianthus tuberosus* L. (Asteraceae), on the invasive cocklebur, *Xanthium strumarium* L. (Asteraceae), and on almost all of the 13 sunflower cultivars. However, the number of eggs laid on these test plants was always less than 15 %, and mostly less than 5 %, of the number deposited on parthenium (L.W. Strathie, unpubl.). Multiple-choice tests were conducted on species or cultivars that the weevils had used for oviposition in the no-choice tests. These tests revealed no oviposition on the five native species, but eggs were deposited on *X. strumarium* and eight sunflower cultivars, although not more than 6.6 % of the number that was deposited on parthenium (L.W. Strathie, unpubl.). In larval development trials on selected sunflower cultivars, larvae developed to at least the pupal stage (trials were terminated after three weeks) and developmental rates did not differ from those of larvae on parthenium (L.W. Strathie, unpubl.). Similarly, eggs were laid on sunflower cultivars in tests conducted in Australia, but as oviposition was less than 1 % of that on parthenium, and less than 2 % of those eggs survived to adulthood, *L. setosipennis* was concluded to be suitable for release there (Wild *et al.* 1992). *Listronotus setosipennis* has not been recorded as a pest of sunflower crops in either its native range or

in Australia (R.E. McFadyen, pers. comm.). An analysis is therefore continuing to quantify the potential risk to non-target plants should *L. setosipennis* be released in South Africa, in preparation for an application for release.

Aspects of the thermal physiology of *L. setosipennis* have been examined which, in conjunction with data on the native and introduced range of the species, is being used to develop a climate-based model of the potential distribution of the agent in South Africa (Z. Shoba, unpubl.). Sites that are determined as optimal for development will be prioritized for release of the weevils.

### *Zygogramma bicolorata*

The leaf-feeding beetle *Z. bicolorata* lays small, yellow/orange eggs, singly or in small clusters, on leaves, flowers, stems and buds. Larvae feed voraciously, entirely defoliating parthenium plants, and mature larvae pupate within an earthen chamber before eclosing as adults, which also defoliate the plants. Egg to adult development takes place within 23 days at a constant temperature of 27 °C (King 2008). Depending on rainfall and food availability, up to four generations per year have been recorded in the field in Australia (McFadyen 1992). Decreasing day length and cooler temperatures induce the adult beetles to diapause in the soil; they emerge in response to rainfall, higher temperatures and increased day length in spring (Dhileepan *et al.* 2000).

*Zygogramma bicolorata*, originating from Mexico, was introduced into Australia in 1980 (McFadyen & McClay 1981) and to India in 1984 (Jayanth 1987a). It established rapidly in India (Jayanth & Ganga Visalakshy 1996) but took longer in Australia, although ultimately it spread over an area of 12 000 km<sup>2</sup> (Dhileepan *et al.* 2000). Outbreaks of *Z. bicolorata*, inflicting 90–100% defoliation, significantly reduced plant height, flower production (unless defoliation was initiated at late stages of plant growth), biomass, and density (Jayanth & Ganga Visalakshy 1996; Dhileepan *et al.* 2000). Repetitive defoliation of parthenium by the beetle significantly reduces the plant's competitive ability leading to the re-establishment of native vegetation (Jayanth & Ganga Visalakshy 1996), but the effectiveness of this agent is strongly influenced by both total rainfall and the timing of the onset of rainfall (Dhileepan 2003b).

*Zygogramma bicolorata* collected on parthenium at Timor Station, Injune in Queensland, Australia

(25°42.226'S 148°28.218'E) was imported into a quarantine glasshouse at the ARC-PPRI facilities at Cedara, South Africa, in January 2005. A culture has since been maintained while host-specificity tests were conducted. The host range of *Z. bicolorata* was tested on 51 species (25 Asteraceae) in 27 families in Australia (McFadyen 1980; McClay 1985). Adult feeding was recorded on four species, while eggs were laid on 18 species (<3 % of the total number of eggs that were laid on parthenium), including sunflower (McClay 1985). Following the importation of *Z. bicolorata* into South Africa, a total of 47 native and economically important Asteraceae species (from 11 tribes), including 12 commercial sunflower cultivars, were assessed in no-choice tests. Feeding was recorded on 13 species (including seven native species and 11 of 12 cultivars of sunflower tested), and eggs were laid on 15 species (including ten native species and four cultivars of sunflower) (A.J. McConnachie, unpubl.). Feeding damage (total number of leaves fed upon) ranged from 11–75 % of that on parthenium, on the 12 cultivars of sunflower tested. The area fed on, however, was significantly less than that on parthenium. Oviposition on test plants was significantly less (<4 %) than on parthenium (A.J. McConnachie, unpubl.). Multiple-choice trials revealed no feeding or oviposition on 12 of the 22 test plant species that were utilized in the no-choice trials. Larval development trials were conducted on the remaining four species (including six sunflower cultivars) that displayed feeding damage and/or were used for oviposition, in the multiple-choice trials (A.J. McConnachie, unpubl.). Complete development of *Z. bicolorata* was recorded on six cultivars of sunflower, contrary to results obtained in laboratory host-specificity testing in Australia and India where larvae did not feed or complete development on sunflower (McFadyen 1980; Jayanth & Nagarkatti 1987). The continual development of new cultivars of commercial crops may therefore result in novel and confounding results not obtained elsewhere, indicating the need for appropriate testing in countries where the beetle is intended for introduction.

Although *Z. bicolorata* was observed occasionally feeding on young leaves of sunflower plants adjacent to defoliated parthenium in India, this was demonstrated to be a response to an accumulation of parthenium pollen on sunflower plants from weed stands that surrounded the sunflower fields (Jayanth *et al.* 1993). Additionally, the number of

adults on sunflower was negligible compared to that on parthenium, and adult beetles moved away from the crop after a few days (Jayanth & Ganga Visalakshy 1994). Adult beetles did not lay eggs after feeding on sunflower, while young larvae would not feed on sunflower plants, and it was concluded that *Z. bicolorata* would not become a pest of sunflower (Jayanth *et al.* 1998).

To assess the potential threat to sunflower in South Africa, a risk analysis model using the principles suggested by Wan & Harris (1997) was applied to the *Z. bicolorata* host-range data from the multiple-choice and larval development trials. All six sunflower cultivars (AGSUN 5383, AGSUN 5671, AGSUN 8251, PAN 7034, PAN 7049, AFG 271) showed a very low risk (<0.2 %) of supporting feeding damage in the field, and an extremely low risk (<0.15 %) of supporting viable populations of *Z. bicolorata* in the field, relative to parthenium (A.J. McConnachie, unpubl.). Based on these results, and the fact that *Z. bicolorata* has not been recorded as a pest of sunflower in either its native range (McClay 1980), nor in its introduced range in Australia (Dhileepan & Strathie 2009; R. McFadyen, pers. comm.), an application for permission to release the insect in South Africa is currently being prepared.

A climate-based model that was developed by incorporating aspects of the thermal physiology of *Z. bicolorata* in conjunction with native- and introduced-range distributional data, suggested that much of South Africa is suitable for the development and proliferation of the beetle (King 2008). The climate model will assist in prioritizing release sites.

### *Epiblema strenuana*

The stem-galling moth *E. strenuana* has a wide native distribution in North America and parts of the Caribbean, primarily occurring on *Ambrosia* species (Asteraceae), but also on *P. hysterophorus* in the southern part of its range (McClay 1987). It spread widely and rapidly following its introduction into Australia in 1982 (McFadyen 1985). Eggs are laid on the young leaves, and larvae enter the stem at the apical or terminal buds (McFadyen 1992). Their feeding induces the formation of a gall that acts as a mineral and nutrient sink, in which they pupate, before the adult ecloses through an epidermal window (Florentine *et al.* 2005). Galling during the early stages (rosette and pre-flowering) of parthenium plant growth reduces plant height,

main stem height, flower and leaf production, and shoot and root biomass (Dhileepan & McFadyen 2001). Termination of diapause is triggered by increasing temperature and photoperiod, and is independent of rainfall. Adults therefore may emerge before parthenium has begun to germinate, resulting in extremely low moth populations, particularly if the onset of rainfall is delayed (McFadyen 1992). Both the timing of onset and the total quantity of rainfall regulate the effectiveness of this agent (Dhileepan 2003b) and levels of control can therefore be highly variable (McFadyen 1992; Dhileepan 2003b). In Australia, the moth utilizes annual ragweed *Ambrosia artemisiifolia* L. (Asteraceae) and *X. strumarium* when parthenium is not available (McFadyen 1985).

Early attempts to establish a culture of *E. strenuana* in the Cedara quarantine laboratory in South Africa from some 12 individuals collected on parthenium in Jujuy Province, Argentina (23°45.484'S 64°41.960'W) in December 2003, and from some 400 individuals from galls collected on *A. artemisiifolia* at Fig Tree Pocket, Brisbane (27°32.224'S 152°57.859'E) and on parthenium at Timor Station, Injune (25°42.226'S 148°28.218'E) in Queensland, Australia in January 2005, failed. A later collection of some 200 *E. strenuana* galls on parthenium at Wycarbah (23°31.996'S 150°13.771'E) and Grace mere (23°26.233'S 150°25.613'E) in Queensland, Australia, in March 2010 resulted in the establishment of a culture, due to improved rearing conditions in the Cedara quarantine facilities. Host-specificity testing is currently under way.

*Epiblema strenuana* was rejected as a potential agent in India due to its ability to complete development on the oil-seed crop *Guizotia abyssinica* (L.f.) Cass. (Asteraceae) during laboratory trials (Jayanth 1987b), although McFadyen (1992) considered that this would be unlikely to occur in the field. However, as *G. abyssinica* is an important crop in parts of East Africa, *G. abyssinica* cultivars have been included in host-specificity tests, initiated in 2010, in South Africa, despite this crop having no current economic value in southern Africa.

### *Smicronyx lutulentus*

The small, seed-feeding weevil *S. lutulentus*, originates from Mexico and Texas, U.S.A. Adults feeding on young leaves create a 'shot-hole' appearance, with, apparently, negligible impact on the plant. Eggs are deposited in flower buds and newly opened flowers; larvae each hollow out

a single achene (McFadyen & McClay 1981). Mature larvae exit seeds that fall to the ground and pupate in the soil. There is a lengthy pre-pupal stage that is influenced by temperature (McFadyen & McClay 1981). Rainfall stimulates adult emergence from the soil, with peaks in spring and autumn (McFadyen & McClay 1981). Up to 30% seed destruction was attributed to *S. lutulentus* in Mexico (McClay 1985). The weevil only oviposits on *P. confertum* and *P. hystrophorus*, and was released in Australia in 1981. It was recorded as established about 15 years later, but with sporadic and localized incidence. Its impact in Australia is considered to be limited, but has not been quantified (Dhileepan & Strathie 2009). Some 1200 adult weevils were collected on parthenium plants at Stanwell in Queensland, Australia (23°28.987'S 150°17.112'E) and imported into the Cedara quarantine laboratory in South Africa in March 2010. Rearing techniques were refined, and a culture was established. Host-specificity testing of closely-related native and economically-important flora is under way. The rationale for considering this agent for South Africa is its host specificity, its soil-inhabiting stage, and its effect on seed production in its native range.

#### *Carmentia* nr. *ithacae*

The day-flying moth *Carmentia* nr. *ithacae*, native to eastern U.S.A. and Mexico (McClay *et al.* 1995), is under consideration for South Africa due to its host specificity and the damage that it causes on parthenium (McFadyen & Withers 1997; Withers *et al.* 1999). Mature larvae feed internally and externally in the plant crown and roots; high numbers lead to plant mortality (McFadyen & Withers 1997). Following its release in Australia from 1998 until 2002, it failed to establish at several sites, although its incidence and abundance is now slowly increasing at some sites (Dhileepan 2009). Field surveys for the moth in 2010 yielded too few individuals to enable importation into South Africa, so it will be introduced later for assessment of its host specificity.

### COOPERATIVE MANAGEMENT OF PARTHENIUM IN AFRICA

In 2005, a four-year project on the integrated control of parthenium, coordinated by Virginia State University in the U.S.A., was initiated in eastern and southern Africa under the auspices

of the United States Agency for International Development (USAID)-funded Integrated Pest Management Collaborative Research Support Program (IPM CRSP). Research was conducted in South Africa, Swaziland, Botswana, Uganda and Ethiopia. The distribution and impacts of parthenium and the efficacy of various control methods were assessed.

Notable achievements arising from this project included the mapping of the current distribution of parthenium in parts of southern and eastern Africa, indicating a much wider distribution than had previously been recorded, and the development of a climatic model to determine areas suitable for the growth of parthenium, which indicated that much of sub-Saharan Africa is prone to invasion by the weed (McConnachie *et al.* 2010). Additionally, parthenium was demonstrated to have significant socio-economic impacts in Ethiopia, where it was ranked as the primary or one of the most important weeds by farmers (Tamado & Milberg 2000). The weed impacts negatively on above-ground species diversity and evenness, grass species density, and critically impacts on the biodiversity of grazing land in Ethiopia (Nigatu *et al.* 2010). Various cultural control methods such as mowing, burning, and over-sowing with selected competitive plant species were investigated for pasture management.

As part of the project, South African scientists gave theoretical and practical training in weed biological control to researchers from Ethiopia, where biological control has not been practiced. An approved, basic weed biological control quarantine facility was established at the Ethiopian Institute of Agricultural Research (EIAR) Plant Protection Center, at Ambo, west of Addis Ababa. Starter cultures of *Z. bicolorata* and *L. setosipennis* were supplied from South Africa to the Ethiopian quarantine facility in 2007 and 2009, respectively. Host-range testing of *Z. bicolorata* on selected native Asteraceae and crops of economic importance to Ethiopia was undertaken and permission for release of *Z. bicolorata* was granted by Ethiopian authorities. Releases will commence once USAID has granted permission (M. Negeri & K. Zewdie, pers. comm.). The IPM CRSP parthenium project has since been extended until 2014. Biological control remains a key component of this project and additional agents may be considered for introduction.

Factors impeding the biological control of

parthenium in Africa include a lack of legislation underpinning the practice of weed biological control (for the importation, evaluation, and release of agents) in some countries, a lack of appropriate quarantine facilities or expertise in weed biological control, and a lack of collaboration with countries that have the appropriate expertise. The IPM CRSP parthenium project has gone some way towards addressing the latter deficiency by fostering collaboration between some countries affected by parthenium, but greater collaboration and action is required in Africa. Ultimately there is a dire need for cost-effective control mechanisms, such as biological control, to manage this weed in Africa.

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