Biological control of *Hakea sericea* Schrad. & J.C.Wendl. and *Hakea gibbosa* (Sm.) Cav. (Proteaceae) in South Africa

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Hakea sericea Schrad. & J.C.Wendl. and *Hakea gibbosa* (Sm.) Cav. (Proteaceae), are small trees or shrubs that originate from Australia. *Hakea sericea* has become highly invasive and problematic in South Africa while *H. gibbosa* is less widespread and abundant but nevertheless problematic. Biological control against *H. sericea* started in 1970 with the release of two seed-attacking insects, a seed-feeding weevil, *Erytenna consputa* Pascoe (Coleoptera: Curculionidae), and a seed-moth, *Carposina autologa* Meyrick (Lepidoptera: Carposinidae). Both of these agents, together with an indigenous fungus, *Colletotrichum acutatum* J.H. Simmonds f.sp. *hakeae* Lubbe, Denman, P.F. Cannon, J.Z. Groenew., Lampr. & Crous (*Incertae sedis*: Glomerellaceae), and manual clearing have reduced the abundance, and possibly the invasiveness, of *H. sericea,* but large infestations still persist in the coastal mountains of the Cape Floral Region in the Western and Eastern Cape provinces of South Africa. The release in 1979 of a weevil, *Cydmaea binotata* Lea (Coleoptera: Curculionidae), which bores in the terminal shoots and young needles of *H. sericea* has had a negligible effect. To enhance the levels of biological control, two new agents, a stem-boring beetle, *Aphanasium australe* (Boisduval) (Coleoptera: Cerambycidae), and a flowerbud feeder, *Dicomada rufa* Blackburn (Coleoptera: Curculionidae), were released in 2001 and 2006, respectively. The focus in this review is on progress since 1999 with the biological control and management of *H. sericea.* Releases of *E. consputa* and *A. australe* on *H. gibbosa* have met with limited success, the reasons for which are also reviewed.

Key words: conservation, Cape Floral Region, *Erytenna consputa, Carposina autologa, Colletotrichum acutatum, Dicomada rufa, Aphanasium australe,* integrated control.

INTRODUCTION

Research on biological control against two invasive, alien hakea species, *Hakea sericea* Schrad. & J.C.Wendl. (Fig. 1) (silky hakea) and *Hakea gibbosa* (Sm.) Cav. (Proteaceae) (rock hakea), in South Africa, has been ongoing for nearly 50 years (Kluge & Neser 1991). Both *H. sericea* and *H. gibbosa* are erect, single-stemmed, small trees or shrubs from eastern Australia that grow to a height of 2–5 m. These, and some other *Hakea* species, were introduced into South Africa in 1858 at a time when the public was encouraged to plant 'useful' exotic trees, such as hakeas and the Australian acacias (Shaughnessy 1986). Hakeas are strongly serotinous, meaning that their hard, woody follicles (fruits) are retained on the plant and accumulate until it dies, sometimes after several decades. Each follicle contains a pair of winged seeds that are released *en masse* when the fruits dehisce after the death of the plant, usually as a result of fires (Richardson *et al.* 1987). *Hakea sericea,* and to a far lesser extent *H. gibbosa,* rapidly spread into many of the coastal mountain ranges and water catchments of the Western and Eastern Cape provinces (Fig. 2) forming dense impenetrable stands (Fugler 1979; van Wilgen & Richardson 1985). *Hakea sericea,* in particular, constitutes a severe threat to the unique 'fynbos' vegetation of the Cape Floral Region (CFR) (Cowling *et al.* 1997; Latimer *et al.* 2004) which has been named 'the world's hottest hot-spot' for plant species diversity and endemism', leading to the conservation areas therein having been recognised by UNESCO as a World Heritage Site since 2004 (UNESCO 2011).

Explanations for the invasiveness of *H. sericea* including, mainly, copious seed production and serotiny, have been discussed by Fugler (1979), Richardson *et al.* (1987) and Gordon (1999). At present, an estimated 190 000 ha of land are infested to various degrees, down from an estimated 530 000 ha in 1979 (Esler *et al.* 2010). This decline has been largely attributed to an active mechanical clearing campaign in the mountain catchment areas of the Western Cape (Fenn 1980).

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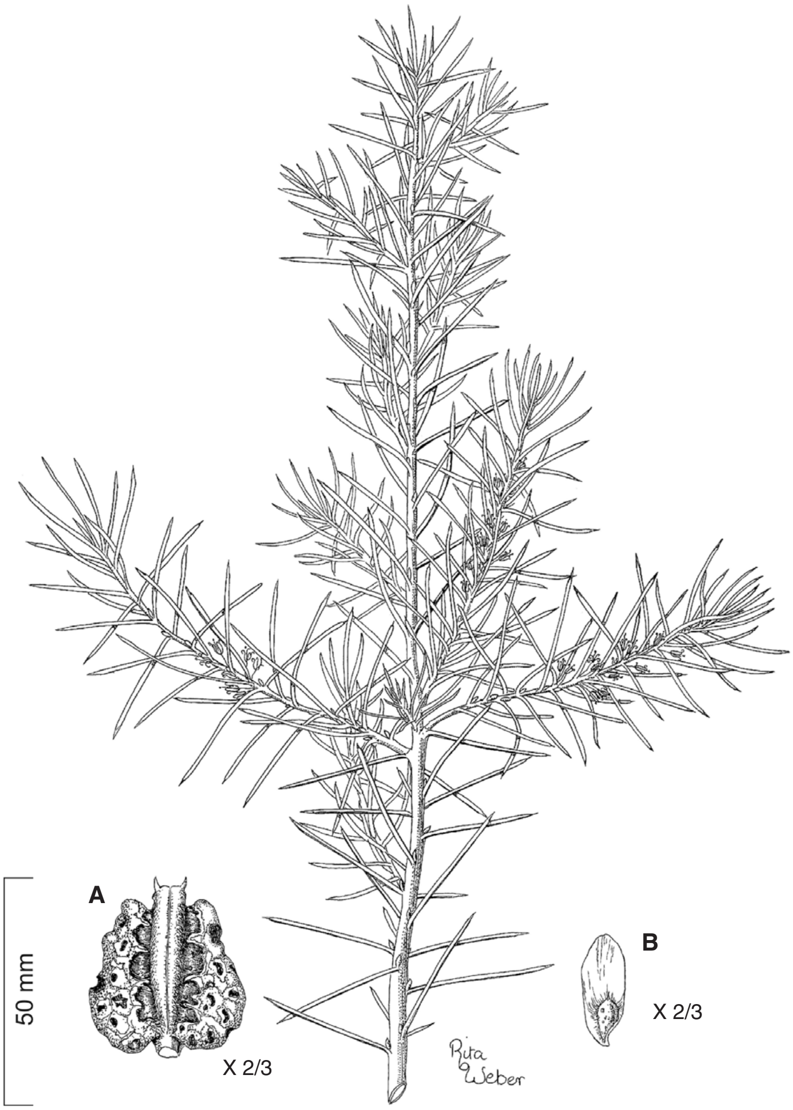

Fig. 1. *Hakea sericea.* **A**, follicle (fruit); **B**, winged seed. (Drawn by R. Weber, first published in Stirton (1978), South African National Biodiversity Institute, Pretoria.)

This campaign went through a slump in the 1980s due to budgetary cuts, but was revived in 1996 with the inauguration of the *Working for Water* Programme (WfW) of the Department of Water Affairs. The techniques used to control *H. sericea* mechanically are largely effective but, as most of the infestations are in mountainous areas, clearing costs are high and many of the infestations are remote or inaccessible. *Hakea gibbosa* does not produce as many seeds as *H. sericea*, and is far less widespread. Slow germination and relatively low viability of the seeds have also contributed to the limited impact of *H. gibbosa* as an invasive plant in South Africa (Richardson *et al.* 1987).

Biological control of *H. sericea* in South Africa commenced in 1970 with the release of two seed-destroying agents, a seed-feeding weevil, *Erytenna consputa* Pascoe (Coleoptera: Curculionidae), and a seed-moth, *Carposina autologa* Meyrick (Lepidoptera: Carposinidae) (Kluge & Neser 1991). In 1979 a leaf and shoot borer, *Cydmaea binotata* Lea (Coleoptera: Curculionidae), was released (Kluge

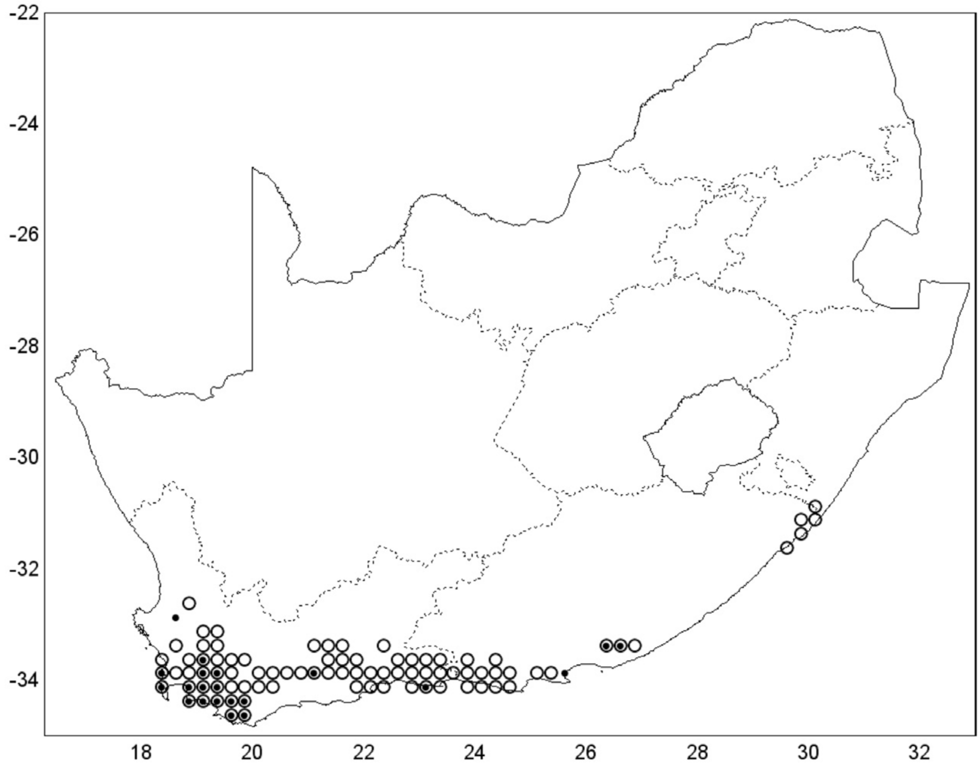

Fig. 2. Distribution of *Hakea sericea* (O) and *H. gibbosa* (•) in South Africa. (Drawn by L. Henderson; data source: SAPIA database, ARC-Plant Protection Research Institute, Pretoria.)

& Neser 1991) but with little or no apparent effect. In the 1960s, an indigenous fungus was found to be damaging and killing *H. sericea* in the field in South Africa (Taylor 1969). This was referred to as *Colletotrichum gloeosporioides* (Penz.) Sacc. (Morris 1991; Lubbe *et al.* 2004) until molecular taxonomic techniques showed it was *Colletotrichum acutatum* J.H. Simmonds f.sp. *hakeae* Lubbe, Denman, P.F. Cannon, J.Z. Groenew., Lampr. & Crous (*Incertae sedis*: Glomerellaceae). The most characteristic symptoms of the disease are stem and branch cankers accompanied by gum exudates from the infected areas. The cankers gradually girdle the trunk and stems and kill the host plant (Morris 1982b). From 1990, *C. acutatum* was used as a mycoherbicide with limited success (Morris *et al.* 1999).

Despite all these interventions, extensive infestations of *H. sericea* persist in South Africa (Te Roller 2004) showing that there is a need to increase the contribution being made by biological control. Towards this end, a stem-boring beetle, *Aphanasium australe* (Boisduval) (Coleoptera: Cerambycidae) and a flowerbud-feeding weevil, *Dicomada rufa* Blackburn (Coleoptera: Curculionidae), were released in South Africa during 2001 and 2006, respectively (Gordon 1999, 2003).

This paper is a report on progress with biological control since 1999. *Hakea gibbosa* is given brief mention only. Accounts are given of the contribution being made by the long-established agents and on the release and establishment of the two species of recently-released agents. The role of biological control in the overall integrated management of *H. sericea* is discussed along with efforts to implement biological control against *H. gibbosa.*

THE BIOLOGICAL CONTROL AGENTS ON *HAKEA SERICEA*

The well-established agents

The early stages in the use of the seed-weevil, *E. consputa,* the hakea seed-moth, *C. autologa,* and the fungus, *C. acutatum,* against *H. sericea* in South Africa were reviewed by Kluge & Neser (1991), Morris (1991) and Gordon (1999). Larvae of *E. consputa* feed in the developing green follicles destroying the seeds while *C. autologa* larvae feed on the ripe seeds of mature follicles and *C. acutatum* infects the vegetative parts of the plant, eventually causing the trees to die.

The seed-moth is not as widespread as the seed weevil, largely due to slow population growth and dispersal and difficulties with releasing the moth (Dennill *et al.* 1987; Gordon 1993a,b). Considerable effort has gone into manually distributing *C. autologa* by harvesting fruits of *H. sericea* from the field during May, at sites where *C. autologa* is already abundant. The fruits are inspected in the laboratory for *C. autologa* eggs which are laid in fissures on the surface of the fruits. The egg-bearing fruits are segregated out and subsequently glued onto egg-free fruits in the field. Although this is labour-intensive and time consuming it is the most successful method for getting the moths established at new localities (Gordon 1999) and is being managed under the auspices of WfW, satisfying their requirement to provide people with biological control experience and employment. In May 2010, the proportion of fruits collected from the field that bore *C. autologa* eggs varied between 2.2 and 28.6 % depending on the collecting site (Gordon 1993a,b; A.J. Gordon, unpubl.). The number of eggs found on the fruits ranged from 1–8 (mean 2.07, n = 292). During June 2010, 1665 egg-bearing fruits were put out in five *H. sericea*-infested sites in the Western Cape (A.J. Gordon, unpubl.)

The shoot-boring weevil, *C. binotata,* which feeds on and develops in the succulent foliage, has become established at a number of sites in both the Western and Eastern Cape provinces. However, although not formally quantified, it seems not to have become abundant at any particular locality and does not seem to have fulfilled its originally-intended role of enhancing infection rates by the hakea fungus *C. acutatum* (Kluge & Neser 1991; A.J. Gordon, pers. obs.). This weevil has received little attention since 1985 and it is no longer being intentionally distributed to new release sites.

The hakea gummosis fungus, *C. acutatum,* has continued to receive attention in the period under review. There are a number of references recording the ability of *C. acutatum* (then called *C. gloeosporioides*) to debilitate and kill *H. sericea* plants, for instance: 'a local fungus, has killed off two large patches of *Hakea* in the Southwestern Cape' (Taylor 1969); 'Large numbers of plants have been killed in many areas and dense hakea stands have been considerably thinned' (Morris 1982a); '*H. sericea* (stands have been noted) with more than 90 % natural infection (by the fungus) and (with) many dead plants' (Fugler 1983), 'Large-scale mortality in *H. sericea* stands (has been observed)' (Richardson & Manders 1985), and 'an increasing number of trees (have been) killed by *C. gloeosporioides*' (Dennill *et al.* 1987).

Aphanasium australe

A stem-boring beetle, *A. australe,* the larvae of which tunnel at the base of the stems and in the sub-surface roots, was identified as a potential additional agent of *H. sericea* in South Africa and, following host-specificity testing, was cleared for release in 2001 (Gordon 2003). The technique used to collect adult beetles was to excavate hakea stumps containing mature larvae or pupae in Australia and airfreight the stumps to South Africa where they were kept in cages until adults emerged (Smith & Gordon 2009). Initially the adults were allowed to mate and lay eggs onto *H. sericea* plants maintained in quarantine. These eggs were collected and attached to healthy plants in the field, a process that was laborious and did not prove to be very successful (A.J. Gordon, pers. obs.). Latterly, direct release of adults was found to be preferable. Since 2001, a total of 1788 eggs and 2219 adults have been released at 57 sites throughout the range of the weed in South Africa (Table 1).

To determine the rate of establishment of *A. australe,* checks are made around the base of the *H. sericea* plants for signs of larval frass which resembles saw dust and which is pushed out by larvae feeding in the stems. It is most noticeable during late spring (November) when the larvae are nearly full-grown. By February 2008, *A. australe* was found to have established at 22 of the release sites. Sixteen sites showed no signs of larval activity, six sites were destroyed by wild fires, five sites were chopped out by mechanical clearing teams, and eight sites were not re-visited.

Population levels of *A. australe* have since been monitored at three sites, Slanghoek (33°33.001′S 19°12.246′E), Waboomskraal (33°50.344′S 22°21.284′E) and Genadendal (34°03.295′S 19°31.797′E) (A.J. Gordon, unpubl.). Owing to the long development time of the larvae (they take up to two years to reach maturity) (Gordon 1999), populations are increasing slowly and it will be some time before redistribution can take place.

Table 1. Details of releases of *Aphanasium australe* eggs* and adults in the Western and Eastern Cape, from 2001–2007.

Locality	Coordinates	Number and year released	Present status
Stettynskloof*	33°44.025′S 19°20.479′E	300 (2001/2)	Established
Paardenkloof*	34°18.312′S 19°13.579′E	456 (2001/2)	Burnt
Knorhoek*	34°06.505′S 18°56.475′E	537 (2001/2)	Established
Paradyskloof*	35°38.490′S 18°53.078′E	195 (2001/2)	Burnt
Lente*	34°19.162′S 19°23.255′E	300 (2001/2)	Not visited
Grahamstown	33°19.935′S 22°34.782′E	8 (2002/3)	Not established
Grahamstown	33°19.920′S 26°34.829′E	62 (2005/6)	Burnt
Grahamstown	33°21.235′S 26°29.796′E	27 (2005/6)	Established
Grahamstown	33°20.004′S 26°36.745′E	30 (2006/7)	Cleared
Grahamstown	33°19.924′S 26°36.716′E	30 (2006/7)	Not established
Kareedouw	33°56.245′S 24°15.855′E	26 (2005/6)	Not established
Kareedouw	33°57.716′S 24°23.407′E	26 (2006/7)	Not established
Uniondale	33°46.418′S 22°44.459′E	22 (2006/7)	Cleared
Uniondale	33°46.408′S 22°45.427′E	23 (2006/7)	Cleared
Misgund	33°45.992′S 23°26.655′E	46 (2005/6)	Not visited
Kammanassie	33°40.779′S 22°56.282′E	30 (2006/7)	Not visited
De Vlugte	33°46.618′S 23°05.615′E	30 (2006/7)	Not visited
Nolsholte	33°46.401′S 22°45.415′E	25 (2005/6)	Established
Haarlem	33°45.247′S 23°24.459′E	66 (2005/6)	Not visited
Haarlem	33°45.892′S 23°23.877′E	25 (2005/6)	Not visited
Langkloof	33°45.064′S 22°57.734′E	25 (2005/6)	Established
Campher	33°50.209′S 22°26.416′E	25 (2005/6)	Burnt but present
Waboomskraal	33°50.18′S 22°21.22′E	40 (2002/3)	Established
	ditto	71 (2002/3)	
Waboomskraal	33°50.637′S 22°21.043′E	60 (2005/6)	Not visited
Waboomskraal	33°50.682′S 22°21.068′E	30 (2005/6)	Established
Waboomskraal	33°50.233′S 22°21.192′E	17 (2006/7)	Not established
Waboomskraal	33°51.216′S 22°22.241′E	35 (2006/7)	Established
Waboomskraal	33°50.817′S 22°21.466′E	41 (2006/7)	Established
Waboomskraal	33°51.061′S 22°21.979′E	35 (2006/7)	Established
Kleinbrak river	34°01.482′S 22°08.419′E	84 (2004/5)	Burnt
Riviersonderend	34°04.443′S 19°37.823′E	21 (2005/6)	Not established
Paardenkloof	34°18.312′S 19°13.579′E	48 (2002/3)	Burnt
	ditto	16 (2004/5)	
Voorstekraal	34°02.439′S 19°32.330′E	20 (2006/7)	Established
Genadendal	34°03.295′S 19°31.797′E	24 (2004/5)	Established
	ditto	32 (2005/6)	
Genadendal	34°03.295′S 19°31.797′E	29 (2006/7)	
Greyton	34°11.490′S 19°35.822′E	38 (2005/6)	Uncertain
Greyton	34°04.628′S 19°33.481′E	26 (2006/7)	Not established
Dwaalhoek	34°09.411′S 19°32.549′E	13 (2002/3)	Established
	ditto	96 (2005/6)	
Caledon	34°15.206′S 19°26.077′E	11 (2005/6)	Uncertain
Caledon	34°12.952′S 19°24.290′E	25 (2006/7)	Not established
Caledon	34°12.724′S 19°34.123′E	25 (2006/7)	Not established
Theewaterskloof Dam	34°04.225′S 19°17.539′E	25 (2006/7)	Established
Theewaterskloof Dam	34°04.739′S 19°16.849′E	21 (2006/7)	Established
Waaihoek	33°33.184′S 19°20.202′E	42 (2005/6)	Burnt
Steenboksberg	33°30.517′S 19°08.265′E	25 (2005/6)	Not visited
Elandskloof	33°56.217′S 19°17.435′E	14 (2006/7)	Cleared
Goudini Spa	33°33.160′S 19°12.203′E	49 (2002/3)	Established
	ditto	131 (2002/3)	
	ditto	99 (2005/6)	

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Table 1 (*continued*)

Locality	Coordinates	Number and year released	Present status
Slanghoek	33°33.001′S 19°12.246′E	28 (2002/3)	Established
	ditto	9 (2005/6)	
Slanghoek	33°33.160′S 19°12.203′E	62 (2006/7)	Established
	ditto	25 (2006/7)	
Rawsonville	33°72.145′S 19°27.994′E	25 (2006/7)	Not established
Rawsonville	33°72.854′S 19°26.545′E	25 (2006/7)	Not established
Stettynskloof	33°73.076′S 19°34.835′E	25 (2006/7)	Established
Groot Drakenstein	33°52.330′S 19°00.114′E	32 (2006/7)	Established
Du Toitskloof pass	33°44.742′S 19°03.344′E	25 (2006/7)	Not established
Wolseley	33°24.784′S 19°10.129′E	31 (2006/7)	Not established
Pearl Valley	33°48.370′S 18°59.686′E	50 (2006/7)	Cleared
	33°49.024′S 19°00.445′E	42 (2006/7)	Not established
Groot Drakenstein	33°52.330′S 19°00.114′E	6 (2006/7)	Established

Nevertheless there has been a steady increase in the populations of the beetles in South Africa. At Waboomskraal, 9.3 % of the sample trees (n=82) had signs of larval activity in 2010. No trees had died from the beetle damage but this was expected because the trees at this site are over thirty-years old, their large size making them less vulnerable than small plants to damage caused by the larvae. At Genadendal, 5.3 % of the trees had died and 5.3 % had signs of larval activity. At Slanghoek, where relatively few adult insects were released (Table 1) (A.J. Gordon, unpubl.), the beetles had killed approximately 6 % of the sample trees (n=795) by 2010. An additional 9.8 % of the plants showed signs of larval activity. The combined impacts, and interactions of *A. australe* and *C. acutatum* on one another, if any, are still to be investigated.

Dicomada rufa

The bud-feeding weevil, *D. rufa,* whose larvae feed on the flower buds and succulent foliage, was regarded as a priority agent because it is able to disperse rapidly (R. Kluge, pers. comm.) and because it has the potential to limit seed production during the hiatus, after fires, when the slowly-dispersing *E. consputa* weevils are scarce while the maturing *H. sericea* plants are producing their first crops of fruits (A.J. Gordon, pers. obs.).

Dicomada rufa was first introduced from Australia into quarantine in South Africa, in 1976. Some host-specificity testing was completed in quarantine. However, problems were experienced with rearing the insects through the larval stages (B. Gunn, unpubl.). The weevil was reintroduced in 1997 for host-specificity testing when oviposition- and no-choice feeding tests were completed. To supplement the laboratory tests in South Africa, further observations on host-choice, using a fixed-plot survey method, were undertaken in the field in Australia (Kluge & Gordon 2004). Based on the results, permission to release *D. rufa* was granted in 2006.

Three collecting trips were made to Australia between 2006 and 2008 (Table 3) (A.J. Gordon, unpubl.) during which 17 612 *D. rufa* adults were obtained (Table 2) (A.J. Gordon, unpubl.). Of these, a total of 15 017 weevils were released at 31

Table 2. The number and source of *Dicomada rufa* adults imported into South Africa from Australia from 2006–2009.

Date	Locality	Coordinates	Number collected
May 2006	Mittagong/Bargo	34°21.329′S 150°32.952′E	341
May 2006	Nowra	34°55.696′S 150°36.301′E	1360
May 2006	Nowra	34°55.147′S 150°36.706′E	3398
May 2007	Nowra	34°55.087′S 150°36.768′E	2310
May 2007	Nowra	34°55.103′S 150°36.671′E	3078
Jun. 2008	Nowra	34°55.087′S 150°36.768′E	4525
Jun. 2008	Nowra	34°55.103′S 150°36.671′E	2600

Table 3. Details of releases of *Dicomada rufa* adults in South Africa for biological control of *Hakea sericea.*

Date	Release site	Coordinates	Number released
24 May 2006	Slanghoek 1	33°36.053′S 19°13.693′E	477
24 May 2006	Slanghoek 2	33°33.001′S 19°12.246′E	450
18 Jun. 2008	Slanghoek 3	33°33.015′S 19°12.148′E	500
25 May 2006	Stanford	34°19.326′S 19°23.365′E	450
25 May 2006	Genadendal	34°09.416′S 19°32.551′E	450
25 May 2006	Greyton	34°03.904′S 19°37.668′E	450
01 Jun. 2006	Waboomskraal 1	33°50.682′S 22°21.068′E	400
23 May 2007	ditto	ditto	400
01 Jun. 2006	Waboomskraal 2	33°50.637′S 22°21.043′E	400
23 May 2007	ditto	ditto	400
24 Jun. 2008	Waboomskraal 3	33°49.313′S 22°20.597′E	245
01 Jun. 2006	Campher	34°50.054′S 22°25.664′E	400
23 May 2007	ditto	ditto	400
01 Jun. 2006	Haarlem 1	34°45.640′S 23°23.038′E	400
24 May 2007	ditto	ditto	500
25 Jun. 2008	Haarlem 2	33°45.359′S 23°18.384′E	245
25 Jun. 2008	Haarlem 3	33°46.228′S 23°19.448′E	245
02 Jun. 2006	Herold 1	33°46.417′S 22°44.458′E	400
02 Jun. 2006	Herold 2	33°45.060′S 22°57.740′E	400
24 May 2007	ditto	ditto	400
24 May 2007	Herold 3	33°46.417′S 22°44.458′E	400
24 Jun. 2008	Herold 4	33°50.319′S 22°26.081′E	245
02 Jun. 2006	Nolsholte	33°46.401′S 22°45.415′E	350
24 May 2007	ditto	ditto	400
04 Jun. 2007	Joubertina	33°48.524′S 23°41.908′E	450
04 Jun. 2007	Kareedouw 1	33°57.714′S 24°23.412′E	450
25 Jun. 2008	Kareedouw 2	33°54.237′S 24°09.022′E	245
25 Jun. 2008	Kareedouw 3	33°56.370′S 24°16.123′E	245
25 Jun. 2008	Kareedouw 4	33°57.229′S 24°16.220′E	245
05 Jun. 2007	Grahamstown 1	33°21.231′S 26°29.797′E	450
05 Jun. 2007	Grahamstown 2	33°17.159′S 26°40.617′E	490
05 Jun. 2007	Grahamstown 3	33°20.006′S 26°35.457′E	450
18 Jun. 2008	Stettynskloof 1	33°43.598′S 19°19.379′E	500
18 Jun. 2008	Stettynskloof 2	33°48.351′S 19°18.056′E	500
18 Jun. 2008	Stettynskloof 3	33°49.018′S 19°17.150′E	500
18 Jun. 2008	Stettynskloof 4	33°50.058′S 19°15.437′E	500
19 Jun. 2008	Waaihoek	33°34.022′S 19°20.009′E	585

sites in the Western and Eastern Cape (Table 3). Twenty-six of the release sites were visited during October and November 2009 to record whether or not the weevils had established. Of the 26 sites, five had been cleared, two destroyed by fire, and one was destroyed by a landslide. *Dicomada rufa* adults were found at 10 (56 %) of the remaining release sites and no weevils were found at eight of the sites (A.J. Gordon, unpubl.). It is not known whether or not the weevils had dispersed away from the release sites.

EVALUATION OF AGENTS ON *H. SERICEA*

Evaluating the effectiveness of the agents that are already well established on *H. sericea* is complicated because the three insect species and the fungus all interact with each other and their combined impact is superimposed on manual clearing interventions. It is therefore not possible to determine independently what each of the agents is doing to the extent and abundance of the weed. Nevertheless, measurements have been made of the abundance of the agents and the levels of damage they cause. Some of these measurements have been used to populate a model of the effects of the agents on the dispersal patterns of their host plant (Le Maitre *et al.* 2008).

Erytenna consputa is the most widespread of the agents. Its impact was initially evaluated by Kluge (1983) who showed that it was destroying up to 72 % of the developing fruits annually, with natural abortion of fruits accounting for an additional 22 % of the annual fruit loss (Kluge & Siebert 1985). More-recent surveys between 1998 and 2003 at six sites (Slanghoek, 33°36.0′S 19°13.7′E; Stettynskloof, 33°52.0′S 19°21.2′E; Welverdiend, 33°39.9′S 19°12.5′E; Goudini, 32°40.0′S 19°13.9′E; Grahamstown, 33°19.9′S 26°34.8′E; Kareedouw, 33°56.2′S 24°15.8′E) showed that *E. consputa* and, to a lesser extent, *C. autologa,* continue to destroy most of the seeds produced by *H. sericiea.* In most situations the damage is not resulting in declines in the density of the weed in areas where fire has destroyed the original infestations (Le Maitre *et al.* 2008).

After the initial research on the use of *C. acutatum* as a mycoherbicide (Morris 1982b, 1983, 1989, 1991; Morris *et al.* 1999), more time has been spent in recent years assessing the natural occurrence of the fungus and its impact on the weed in South Africa. Spot-sampling at 32 sites throughout the range of the weed in the Western Cape Province during 2008, showed that the fungus was present at 23 (72 %) sites and that on average, 40 % (range 10–97 %) of the hakea trees showed disease symptoms, with an average mortality rate of 15 % (range 5–75 %) (A. Fourie, unpubl.). In a number of areas, *e.g.* Genadendal-1 (34°03.309′S 19°33.383′E), Slanghoek (33°36.032′S 19°13.414′E) and Goudini (33°38.061′S 19°15.569′E), there was a particularly high occurrence of the gummosis disease with an average of 97 %, 87 % and 90 % of the trees infected, respectively, accompanied by extensive dieback (average 28.7 %). These three areas all received early rains followed by regular rainfall during the winter of 2008, conditions which favour the development and spread of *C. acutatum.* By contrast, the fungus was scarce (<10 % infection rate) at Stettynskloof (33°43.520′S 19°20.446′E) where it may be worth using the mycoherbicide formulation at regular intervals, especially following fires or after exceptionally dry summers, to increase inoculum loads and promote natural spread of the disease.

In 2008 and 2009, five sites were selected to evaluate *C. acutatum.* The results showed that at Genadendal-1 which receives rain at regular intervals throughout the year, almost 100 % of the hakea trees showed disease symptoms and nearly one third of the trees had already died when the site was first visited in 2008. By 2009 mortality had increased to 55 %. At Genadendal-2 (34°03.436′S 19°32.554′E), also a mesic site, the proportion of dead plants doubled from 13 % in 2008 to 26 % in2009. At Slanghoek, another mesic area, an incidence of 87 %, and resultant mortality of 19 % were recorded in 2008, rising to an incidence of 99 % and a mortality of 44 % in 2009. At Waboomskraal (33°50.138′S 22°21.114′E) which is in a drier area, there was a low incidence (5 %) of disease and no mortality of hakea trees. Following inoculation of the hakea trees at this site at the end of 2008, the incidence of the disease increased to 36 % in 2009, a level which typically marks the threshold for the start of an epidemic (A. Fourie, unpubl.) although whether or not this will happen needs to be monitored. Unexpectedly, at Krakeelrivier (33°51.151′S 23°43.580′E), also in a dry area, 95 % of the trees showed disease symptoms in 2008. This apparent paradox is explained because the hakea trees at that site had received repeated applications of the fungus as a mycoherbicide over several years (A. Fourie, unpubl.)

Almost no hakea seedlings were found within any of the five study sites, confirming the findings of Richardson & Manders (1985) that, under favourable conditions, *C. acutatum* infection induces premature release of seeds which are then depleted by rodents before they can germinate.

BIOLOGICAL CONTROL OF *HAKEA GIBBOSA*

Hakea gibbosa has a much more restricted distribution than *H. sericea,* occurring in the mountain areas around Franschhoek (33°55.00′S 19°08.00′E) the northern and southern slopes of the Klein River Mountains between Caledon (34°13.54′S 19°25.26′E) and Hermanus (34°25.04′S 19°14.29′E), and on the Cape Peninsula (Neser 1978).

Although *H. gibbosa* was considered a weed of minor importance, its potential to proliferate prompted biological control efforts against it in 1979. Five hundred *E. consputa* adults, collected from *H. gibbosa* in Australia, were released into ten infestations in the south western Cape. The establishment and impact of the weevils at these sites

Table 4. The number and source of *Erytenna consputa* adults imported into South Africa from Australia in 2003 and 2004 for the biological control of *Hakea gibbosa.*

Date	Locality	Coordinates	Number collected
Sept. 2003	Gosford/Kulnura	33°18.960′S 151°15.808′E	301
Sept. 2003	Peats Ridge/Kulnura	33°17.990′S 151°14.098′E	189
Sept. 2003	Pacific Hwy, Brooklyn	33°27.021′S 151°12.763′E	124
May 2004	Pacific Hwy, Brooklyn	33°27.021′S 151°12.763′E	57
May 2004	Gosford/Kulnura	33°18.960′S 151°15.808′E	109
May 2004	Peats Ridge/Kulnura	33°17.990′S 151°14.098′E	45
May 2004	Central Mangrove/Somersby	33°19.040′S 151°15.830′E	152

was never monitored, the assumption being that the insects had not survived. Renewed interest in *H. gibbosa* resulted in 614 and 363 weevils being collected around Gosford, New South Wales, Australia in September 2003 and May 2004, respectively (Table 4) for releases at Stanford (34°24.492′S 19°34.979′E), Hermanus (34°24.462′S 19°25.365′E) and Paardenkloof (34°18.637′S 19°13.338′E) (Table 5) (A.J. Gordon, unpubl.)

The Hermanus release site was mechanically cleared and the Paardenkloof site was destroyed by a wild fire shortly after the releases. At Stanford, the only remaining release site, where 200 weevils were released in 2003 counts of mature fruits, developing healthy fruits and attacked fruits, on 41 sample trees showed that percentage annual fruit loss due to *E. consputa* larval damage over a four-year study period had increased steadily to 15.4 %. Over the same period the mean number of mature fruits recorded, per plant, had increased three-fold (A.J. Gordon, unpubl.). These initial results indicate that the negative impact of *E. consputa* on seed production by *H. gibbosa* is not going to be as pronounced as that on *H. sericea.*

Hakea gibbosa is also a host for *A. australe* in Australia (Neser 1978). During September 2003, 45 *H. gibbosa* stumps containing mature larvae or pupae were collected near Gosford and shipped to South Africa. The 48 *A. australe* adults that emerged from the stumps were released onto *H. gibbosa* at Paardenkloof and Stanford. Establishment has not been confirmed and is unlikely because the Paardenkloof site burnt down and the Stanford site was chopped out by the landowner (A.J. Gordon, unpubl.). It is recommended that *A. australe* should be reintroduced for biological control of *H. gibbosa.*

DISCUSSION

Seed-attacking agents were initially selected for biological control because of the copious quantities of seed that *H. sericea* produces in South Africa. It was anticipated that *E. consputa* and *C. autologa* would complement one another by destroying fruits in different stages of development. The most obvious limitation with both agents is that they are slow to colonize regenerating hakea populations and populations of *C. autologa* increase very slowly (Dennill *et al.* 1987, Gordon 1993b), allowing the plants to set fruits before the agents have taken full effect. This is less problematic in areas where fires

Table 5. The number of *Erytenna consputa* adults released in South Africa for the biological control in *Hakea gibbosa* in 2003 and 2004.

Date	Locality	Coordinates	Number released
Oct. 2003	Paardenkloof	34°18.303′S 19°13.594′E	100
Oct. 2003	Paardenkloof	34°18.761′S 19°13.197′E	100
Oct. 2003	Hermanus	34°19.389′S 19°23.762′E	100
Oct. 2003	Stanford	34°24.492′S 19°34.979′E	200
Oct. 2003	Stanford	34°24.757′S 19°25.539′E	112
May 2004	Paardenkloof	34°18.761′S 19°13.197′E	200
May 2004	Stanford	34°24.757′S 19°25.539′E	100
Jun. 2004	Stanford	34°24.459′S 19°35.030′E	57

are patchy, or are confined to small areas, and where there are *H. sericea* plants nearby, because *E. consputa* can rapidly re-colonize burnt areas and the newly-recruited plants set very few fruits (A.J. Gordon, unpubl.).

A simulation model developed to assess the impacts of the two seed-destroying biological control agents on *H. sericea* indicates that the combination of both agents has had an effect on the dispersal of the weed, making it less invasive (Le Maitre *et al.* 2008). However, field studies also show that regenerating seedlings still exceed the parent population in existing stands in most cases (Le Maitre *et al.* 2008; A.J. Gordon & J.H. Hoffmann, unpubl.). In terms of affecting density of their hosts, seed-destroying agents such as *E. consputa* and *C. autologa* are likely to have most effect when combined with measures that destroy the parent plants. For example Hoffmann (1990) and Hoffmann & Moran (1998, 1999) showed that the impact of two seed-reducing weevil species introduced for the biological control of *Sesbania punicea* (Cav.) Benth. (Papilionaceae) in South Africa were most effective when used in combination with a third species which bores in the trunk and stems and kills the plants. The deployment of three seed-reducing agents together with a stem-boring beetle and a fungal pathogen on *H. sericea* is an analogous situation which it is hoped will prove to be effective.

The distribution of *H. sericea* in South Africa has been reduced by an estimated 64 %, from a land area of about 530 000 ha in 1979 to about 190 000 ha in 2001 (Esler *et al.* 2010). During the same period the density of hakea decreased, over about 230 000 ha, from either high or moderate levels of infestation to low levels of infestation, or absence (Esler *et al.* 2010). The reduced range and density decline can only be attributed to the combined effect of the biological control agents together with manual clearing operations. There is no doubt that the hakea fungus, *C. acutatum,* is making a substantial contribution to this trend, especially in the high rainfall areas of the Western Cape where it is killing plants in large numbers without any outside intervention. Establishment of *C. acutatum* in the field is, however, dependent on having sufficient inoculum available, as well as suitable environmental conditions. In dry areas, and in high rainfall areas after dry periods or fires, applications of the fungus may be needed to bolster inoculum loads. The successful employment of *C. acutatum* as a biological control agent of *H. sericea* can be enhanced if it is used as a mycoherbicide where necessary (Morris 1982b, 1983, 1989, 1991; Morris *et al.* 1999).

In conclusion, an integrated approach has been used to great effect to limit the impact of *H. sericea* in South Africa over many years. This approach should continue while the new biological control agents are given an opportunity to show their worth, in the hope that, with time, there can be increasing reliance on biological control and less on laborious manual clearing operations. There is much evidence to indicate that this goal can be achieved by persevering with the new agents in the system.

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