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Introduction and Establishment of the Biological Control Agent *Apion ulicis* (Forster) (Coleoptera: Apionidae) for Control of the Weed Gorse (*Ulex europaeus* L.) in Hawai'i

G.P. MARKIN
Research Entomologist, USDA Forest Service, Forestry Sciences Laboratory, Intermountain Research Station, 1648 South 7th Avenue, Bozeman, Montana 59717-0278

and

E.R. YOSHIOKA
Plant Pest Control Branch, Hawai'i Dept. of Agriculture, 16 East Lanikaula St., Hilo, HI 96720

ABSTRACT. In 1984, 10,000 adults of the gorse seed weevil, *Apion ulicis* (Forster), were collected on the island of Maui and released at 10 sites on the southern slope of Mauna Kea, Hawai'i Island. Monitoring showed that the weevils were successfully established at eight release sites. They gradually built up their populations for three years, after which they spread out from their release points. Establishment failure at two sites was attributed to poor synchronization of the biology of the weevils with the phenology of the gorse. By 1993, the final year of this survey, weevils had reached every point sampled throughout the 15,000-ha range of gorse and attacked 59.4% of the pods sampled.

Estimates of the weevil populations, based on the number of adults in beating samples, indicated that the initial 10,000 weevils had multiplied to approximately 350 million, a 3.22 fold increase each year. On the neighboring island of Maui, where the insect has been established since 1955, a comparable population in Haleakalā National Park has remained relatively stable for the last 10 years with about 90% of the pods being infested. It is estimated that if the weevils on Mauna Kea continue the present rate of population increase, they will reach this level in four to five years. Unfortunately, a chemical control program being conducted by the land manager may interfere with this prediction.

Gorse, a spiny, woody shrub introduced from Europe, is established between 1000 and 2300 m elevation on the islands of Hawai'i (15,000 ha) and Maui (6,000 ha) (Markin *et al.*, 1988). Introduced to Hawai'i sometime around the turn of the century, its aggressive rate of spread and dense impenetrable stands soon resulted in it being identified as a serious weed. As early as 1926 it was targeted for biological control, but the first effort was unsuccessful. After several additional attempts, the seed-feeding weevil, *Apion ulicis*, was successfully established in 1955 on the island of Maui and introduced in 1962 to the island of Hawai'i (Markin & Yoshioka 1989). On the island of Hawai'i, it was found at its release site and declared established by the Hawai'i Department of Agriculture in 1965. The original release site on Hawai'i was a small patch of gorse (< 1 ha in size) centered on a *kipuka* between mile posts 25 and 26 and adjacent to Saddle Road. At that time the site was separated from the main infestation at Mauna Kea by approximately 5 km.

In 1983, during a routine survey of weed biological control agents on the island of Hawai'i, we failed to detect this weevil at either this kipuka or in the main gorse area. A new, more intensive survey, conducted in 1984 during peak flowering and pod set between January and April, again failed to detect the presence of the insect which had last been seen in 1972. At the same time, a survey of gorse on Maui showed this weevil was very abundant throughout the plant's range. Further investigation indicated that the kipuka had been the target of a control program and that all gorse plants had been sprayed with herbicide and burned. It was our conclusion that the population established in the kipuka never reached the main gorse infestation and subsequently died when its food source was exterminated during the gorse chemical control program.

Since gorse was still spreading aggressively on the island of Hawai'i, reintroduction of the weevil was planned for 1984. This report describes the successful introduction of *Apion ulicis* from Maui and its establishment and population build-up on Hawai'i Island between 1984 and 1993.

MATERIALS AND METHODS

Origin of Insects Released

The gorse infestation on Maui ranges in elevation from 750 m to over 2300 m. The two main areas where the weed is most abundant are at 2100 m in Haleakalā National Park and from 900 to 1050 m in the Olinda area above the town of Makawao. Two collection sites were selected at the higher elevation park area and 3 at the lower elevation area at Olinda. At each site, branches were beat into 30 × 45 × 10 cm plastic pans and the weevils collected by aspiration until approximately 1,000 had been obtained (estimated by volume, 1 cc = ±100 weevils).

The weevils from each site were kept separate and shipped to the island of Hawai'i, where each collection was released in a sleeve cage with a bouquet of locally collected gorse foliage and observed for 1 week. During this period, the first 5 weevils that died in each cage were removed and submitted for pathological examination (Consultant Diagnostic Service, Berkeley, California). Any additional weevils that died, plus enough live adults that were randomly selected and killed to give a total of 20 per cage, were examined microscopically to determine whether they contained mites, internal parasites, nematodes, or other signs of parasitism. When the pathology report came back negative and all observations for parasitism were negative (about 10 days after the collection on Maui), the beetles were transported to the field for release.

Each population representing a different collection site on Maui was released at a different location on Mauna Kea. Releases were made by shaking half of the total number of weevils in each batch on a single gorse bush approximately 1 m tall and then covering the top of the plant with a 1 m^2 piece of plastic tied at its corners to form a rain shield. The remaining weevils were randomly scattered on bushes within a 3 m radius of the covered plant.

According to Cowley (1983), Davies (1928), and Miller (1970), *A. ulicis* has 1 generation a year, with larvae developing in the new pods in spring and adults escaping during pod dehiscence in summer. The first collection made in May was at peak pod abundance and it was expected that the weevils collected were mostly new emergents, which had come from the 1984 spring flower season. According to Cowley (1983), after emerging, the weevils remain sexually inactive during the summer, fall, and early winter until the next flowering season begins. At this time, mating and feeding occur. Therefore, from their May release, the weevils would have had to survive for at least 6 months until pods again became available. Thus, a second collection was made in November 1984, just as the new flush of flowers appeared. It was expected that these would be sexually mature adults ready to mate and attack the new pods as soon as they began to form. Weevils for this second release were collected from the same 5 sites in Maui, processed in the same way, and, when found free of parasitoids and pathogens, released at 5 additional sites on Mauna Kea in November 1984.

The main gorse area on Mauna Kea is a band, centered on the 2000 m elevation line (Markin *et al.*, 1988), that stretches along the southeast and south side of the mountain. The main portion of the infestation is transected by a four-wheel drive road that goes from near the Saddle junction on Highway 200 (Saddle Road) to the Keanakolu Ranger Station and eventually reaches Waimea. In 1984, gorse infestations stretched for 11.7 km along

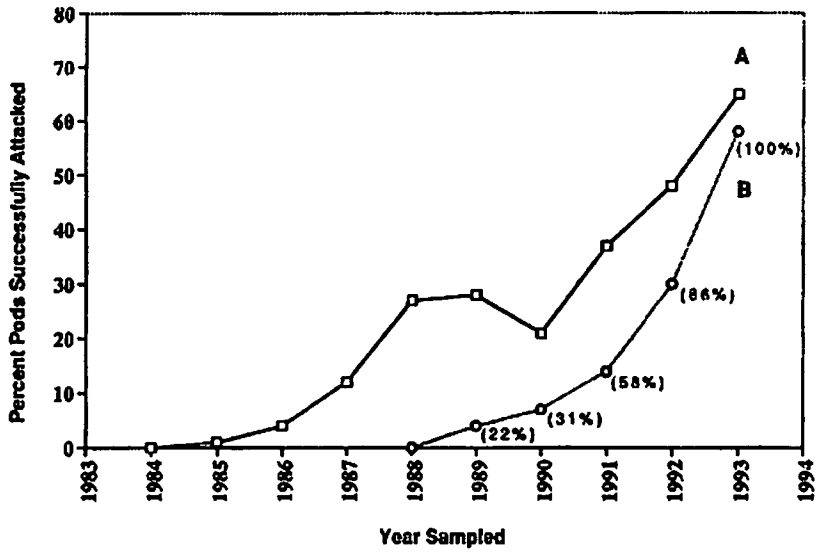

Fig. 1. Line A. Mean population of *A. ulicis* at nine release points expressed as percent of gorse pods successfully attacked. Line B. Percent of gorse pods attacked at 50 additional random collection sites. Figures in parentheses indicate the percentage of these sites at which *A. ulicis* attack was found.

this road, where 8 release sites were chosen at approximately 1.7 km intervals. Each release site was approximately 100 m off the road and centered in the nearest stand of gorse. The May releases were made at 5 sites randomly selected from the 8 chosen along the road. The November releases were made at the remaining 3 locations and 2 additional sites, one at the original *kipuka* on Saddle Road and a second at the 1,500 m elevation level at the transect between grazing land and the forest boundary. The tenth site was the lowest elevation at which a dense stand of gorse was discovered on the island of Hawaii. Both sites were isolated from the main body of gorse by approximately 5 km.

Redistribution

By November 1987, when *A. ulicis* populations had been confirmed as established and reasonable populations had built up at some release sites, further redistribution of the insect was initiated. Thirty thousand adults were collected at Site 6 (*kipuka* by Saddle Road) by beating the gorse branches to collect the weevils into plastic pans. They were immediately released at intervals halfway between the original eight release sites along the road in the main gorse area, with approximately 2,000 of them being released 30 m below the road and another 2,000 released 100 m above the road. During both the original release and the redistribution, all weevils released were in a line approximately 0.83 km apart, but within 100 m of the Keanakolu Road.

Surveys.

Annual seed weevil surveys were conducted in May by collecting 100 fully formed pods, opening them, and determining if they contained live eggs, larvae, or pupae. At each sampling site which corresponded to the 10 original release sites, 2 pods were removed from each of 5 branches on 10 randomly selected plants within an area of 10 m^2. During

Table 1. Establishment of gorse seed weevil *Apion ulicis* on the island of Hawai'i, 1984 through 1991. Percentage of 100 (or 50 after 1987) pods opened and found successfully attacked.

Release Site and Date of Release	Sample Location	Percentage of Pods Successfully Attacked									
		Pre-release 1984	Year 1 1985	Year 2 1986	Year 3 1987	Year 4 1988	Year 5 1989	Year 6 1990	Year 7 1991	Year 8 1992	Year 9 1993
Site 1-May 1984	PR[1]	0.0	8.0	23.0	25.0	38.0					
	10 m		0.0	19.0	31.2	50.0	46.5	3.0	40.4	46.5	56.0
	100 m				0.25	28.0	43.5	15.2	42.5	48.0	58.7
Site 2-May 1984	PR[1]	0.0	9.0	29.0	30.0	.53.0	—			—	—
	10 m		0.0	3.1	26.0	64.0	43.0	21.0	37.6	49.6	84.0
	100 m				0.5	9.2	37.0	29.5	39.5	47.3	80.7
Site 3-May 1984	PR[1]	0.0	0.0	0.0	0.0	0.0	—	—	—	—	—
	10 m		0.0	0.0	0.0	0.0	0.0	0.0	19.0	64.5	80.0
	100 m				0.0	0.0	0.0	3.0	32.0	67.3	72.7
Site 4-May 1984	PR[1]	0.0	1.0	6.0	3.0	18.0	—	—	—		
	10 m		0.0	6.0	2.0	10.3	23.2	21.5	33.6	61.5	67.7
	100 m				0.0	1.0	4.0	12.0	33.0	60.0	70.5
Site 5-May 1984	PR[1]	0.0	0.0	0.0	0.0	0.0	—	—	—		
	10 m		0.0	0.0	0.0	0.2	0.0	0.0	1.8	22.0	—
	100 m				0.0	0.0	0.0	0.0	0.25	15.7	—
Site 62-Nov. 1984	PR[1]	0.0	7.0	2.0	52.0	39.0	—	—	—		
	10 m		0.0	0.0	56.7	42.0	51.3	35.0	42.5	43.5	44.0
	±100 m				1.7	39.0	51.0	47.3	44.0	38.0	46.5
Site 7-Nov. 1984	PR[1]	0.0	6.0	5.0	48.0	52.0	—	—	—		
	10 m		0.2	43.0	56.0	28.2	35.5	44.0	45.5	40.2	
	±100 m				2.2	7.0	22.3	26.5	49.1	40.6	45.0

Table 1. Establishment of gorse seed weevil *Apion ulicis* on the island of Hawai'i, 1984 through 1991. Percentage of 100 (or 50 after 1987) pods opened and found successfully attacked (continued).

Release Site and Date of Release	Sample Location	Pre-release 1984	Percentage of Pods Successfully Attacked Year 1 1985	Year 2 1986	Year 3 1987	Year 4 1988	Year 5 1989	Year 6 1990	Year 7 1991	Year 8 1992	Year 9 1993
Site 8-Nov. 1984	PR[1]	0.0	0.0	6.0	4.0	60.0	—	—	—		
	10 m		0.0	3.5	10.7	62.0	40.8	57.2	55.4	62.6	77.0
	100 m				0.0	2.0	10.7	8.2	39.0	50.0	76.2
Site 9-Nov. 1984	PR[1]	0.0	0.0	6.0	15.0	27.0	—	—	—		
	10 m		0.0	7.0	21.5	26.0	45.0	18.5	47.1	57.0	70.4
	100 m				0.0	2.0	10.7	8.2	39.0	50.0	76.2
Site 10[3]-Nov. 1984	PR[1]	0.0	0.0	8.3	NS[4]						
	10 m			7.6							
Mean		0.0	0.62	5.2	11.9	25.4	27.1	21.2	36.6	49.2	65.0

1 PR = Point of Release, 100 pods collected from same gorse bush or where *A. ulicis* had been released.
2 *Kipuka* by Saddle Road, separated by 5 km from main infestation.
3 Lowest release site, separated from main gorse infestation by 500 m elevation and 5 km.
4 Sampling discontinued, land ownership changed and access lost.
5 Mean of release site and 50 random sample points.

the first 3 years while the weevil populations were spreading, 5 samples (100 pods each) were taken at each release site: 1 sample at the central release point, and 4 additional samples at cardinal points 10 m from the release site. By 1987, when populations were well-established and increasing, the number of samples was increased by 4 additional sample sites, each located at the 4 cardinal points 100 m from the release point. At this time, sampling at the original release points was discontinued since gorse growth was hindering access. Therefore, from 1987 on, each release point was sampled at 8 different locations, four at 10 m out and 4 more at 100 m.

All release and sample collection sites were located along the road transecting the gorse infestation. By 1987, the weevils had begun to migrate above and below the road into the remaining gorse area; therefore, additional samples were collected. Fifty randomly selected sites at least 500 m from the road (above or below it) were chosen so they represented the remaining main gorse infestation. In addition, 5 isolated patches of gorse 1000 m or more beyond the periphery of the main infestation were chosen. The large number of samples collected in 1987 (132 sites and 13,200 pods), and the tedious process of dissecting and counting pods in the laboratory prompted a change in procedure; dissecting fewer pods. One hundred pods were still collected for each sample, but initially only 50 pods were examined. If the number found infested was greater than 25%, no more pods were opened. However, if less than 25% of the pods were infested, the remaining 50 pods were examined and insects were counted. All surveys for 9 years were made in mid- to late May. Opening pods to determine weevil activity was usually completed in 2 to 3 weeks.

Termination of Study

The gorse infestation in the main core area on Mauna Kea had been sprayed and burned as part of the 1976/77 control program. When this program began in winter 1983, the gorse was just regenerating and the majority of plants were only 1 m tall and sparsely distributed. At that time, it was estimated that < 1% of the ground area was covered by gorse in the core of the weed infestation. As the study progressed, gorse rapidly regenerated from the seed bank in the soil or from existing plants. By 1993, it was estimated that at least 50% of the core of the gorse area was covered by a solid mass of the weed. Access to many sites had been severely restricted and would have been lost had the landowner not bulldozed trails. By 1993, the gorse problem had become so severe that land managers decided to initiate a new control program. In fall 1993 and through 1994, they planned to spray and then burn all established gorse sites. However, they agreed to leave approximately 5% of the area untreated in scattered patches as reservoirs to harbor the gorse weevil and other established biological control agents. This control program terminated the study. Final samples were collected in 1993.

RESULTS AND DISCUSSION

In 1985, one year after the weevils were initially released, infested pods were found at the point of release at 4 of the 10 sites (Table 1). By the second year, 1986, they had become established at 8 sites, with weevils being found 10 m out from the original release site for the first time. The first attack at 100 m from the release site was found in 1987. In 1988, the populations increased very rapidly, but then seemed to peak and remain constant or even drop during the next 3 years. After 1990, the populations again increased to reach a peak of 65% in 1993.

Figure 1 shows the average overall infestation plotted as it built up in the gorse area on Mauna Kea over the 10 years of the study. Line A represents the mean population at

the nine release areas. Line B represents the average of 50 randomly selected points located at least 0.5 km from any release point.

During this time, an unusual occurrence was the failure of the insect to establish at 2sites (3 and 5), where almost no infested pods were found until 1990. After this, a rapid build up occurred at both sites. It is suspected that these sites had been invaded by weevils migrating from neighboring successful release sites where *A. ulicis* was well-established, since this corresponds with the first time weevils were collected in large numbers at the sites located at least 0.5 km from the release points.

This lack of establishment could not be associated with either their origin on Maui, weather conditions, or any observable difference in the stands of gorse. Since both failures were from the May release, but the 5 releases in November 1984 and the 14 redistribution releases in November 1987 succeeded, it is suspected the problem was poor timing. The adults released in May would have had to survive for over 6 months before the next period of flowering, and it is possible they were destroyed by predators such as spiders, which were very abundant. Also, since mating does not occur until the following winter, the adults could have dispersed so greatly that they could not locate mates. While this latter explanation is tentative, it supports the need to fully understand the biology of a new biological control agent and the phenology of its target weed, and to synchronize the two in planning a release.

At the 8 sites where establishment took place, population build-up varied greatly (Table 1), but, generally speaking, it rose steadily until 1988 (Fig. 1). At that time, it appeared to peak and then remained steady or declined for the next 3 years before continuing to increase again after 1990. It is suspected that during the first period, when an increase occurred, the populations remained relatively sedentary. By 1988, however, populations had reached a critical threshold that triggered emigration, and during the next 3 years, this excess population began dispersing. This corresponds with the first recovery of weevils at points 500 m and further beyond the release sites (Fig. 1, Line B). By 1993, the 50 random samples collected over the remaining gorse indicated *A. ulicis* had reached all parts of the gorse infestation. By 1993, the populations at the original release sites and at the 50 outlying sites were almost the same (Fig. 1), indicating that dispersal had been completed.

Since the gorse seed weevil is reported to have 1 generation annually, this would mean that from its time of release in 1984 until the final sample in 1993, the bio-agent underwent 9 generations as it spread from the 8 initial release points to all points within the 15000-ha gorse infestation on Mauna Kea (Markin *et al.* 1988). Gorse did not completely cover the entire 15000 ha; over most of this area, its density was less than 0.5 plant per ha. The core of the gorse infestation at Humuula was approximately 2,100 ha, of which an estimated 1,250 ha appeared to be completely covered by the weed. In 1993, an effort was made to estimate the total weevil population in this area.

During sampling, plants with a horizontal branch that projected out far enough that a 30 × 45 × 10 cm plastic pan could be placed under it were selected and beaten to dislodge and collect adult weevils. From this crude sampling method, it was estimated that each m^2 of gorse canopy contained 30.6 adults. Extrapolating this to the estimated 1,250 ha of gorse cover, we found that the initial 10,000 weevils had increased to 350 million individuals in nine generations. While this 35,000 fold population increase seems high, it only represents a 3.22 fold yearly increase.

From 1990 through 1993, the overall population appeared to increase by 10–20% per year, but in the final sampling period in 1993, slightly less than 60% of the pods were attacked. By comparison, the same weevils established on Maui since 1955 at Haleakalā

National Park—a comparable elevation—showed a pod-attack rate of around 90% during yearly surveys in May since 1984. This was interpreted to mean that the Hawai'i population needed at least 3–5 more years of growth before it would reach a level of equilibrium similar to that on Maui. Unfortunately, the chemical control efforts will probably interrupt this population build up, although it will be interesting to see how rapidly the weevils will move from the reservoirs to invade the new gorse as it regenerates.

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