Journal of Applied Ecology (1988), **25**, 1089–1095

EFFECT OF INTRODUCED BIOLOGICAL CONTROL ORGANISMS ON THE DENSITY OF *CHONDRILLA JUNCEA* IN CALIFORNIA

BY D. M. SUPKOFF,* D. B. JOLEY* AND J. J. MAROIS†

**Biological Control Services Program, California Department of Food and Agriculture, 3288 Meadowview Road, Sacramento, CA 95832, U.S.A. and*
†Department of Plant Patholology, University of California, Davis, CA 95616, U.S.A.

SUMMARY

(1) Following the intentional introduction of the exotic biological control organisms *Puccinia chondrillina*, *Cystiphora schmidti* and *Aceria chondrillae* into northern California, reductions in the density of *Chondrilla juncea* (rush skeletonweed) at three monitoring locations varied from 56·3% to 87·2%.

(2) The best correlation between change in plant density and the number of plants attacked by control agents was between the incidence of *P. chondrillina* on rosettes in early spring and change in rosette number the following year. As in Europe and Australia, *P. chondrillina* appears to be the organism most damaging to populations of *C. juncea* in California.

(3) While *C. schmidti* may have local impact on plant density, there were no significant correlations between attack by *A. chondrillae* and plant decline.

INTRODUCTION

Chondrilla juncea L. (rush skeletonweed) is a herbaceous perennial which originated in Eurasia and is now naturalized on sandy and disturbed soils in Mediterranean Europe, northern Africa and southern Russia (Moore & Robertson 1964), where it is rarely an agricultural pest. After its introduction into Australia at the beginning of this century, *C. juncea* became a serious problem throughout the south-eastern cereal-growing areas (McVean 1966). *C. juncea* was established as early as the 1870s in the eastern United States (Schirman & Robocker 1967) and by 1938 in the Pacific north-west (Pryor 1967). The first report of *C. juncea* in California was in the contiguous counties of Placer and El Dorado in 1965 (Schirman & Robocker 1967). Presently, these counties contain approximately 80 000 ha of infested rangeland each and are the primary centre of *C. juncea* establishment. Because the climate and soils of many regions in the western United States are similar to those in Europe and Asia where *C. juncea* is native, and in Australia where it has caused serious economic loss, there is potential for this invasive weed to become an important pest in the western States.

Establishment of a complex of natural enemies of *C. juncea* in south-eastern Australia, beginning in 1971, created a situation more nearly resembling that in the western Mediterranean (Cullen & Groves 1977). After the introduction of *Cystiphora schmidti* Rubsaamen (skeletonweed gall midge), *Aceria chondrillae* Canestrini (skeletonweed gall mite) and *Puccinia chondrillina* Bubak and Syl. (skeletonweed rust), plant density declined dramatically (Cullen 1978) and in many areas now approaches the normal density (10 plants m^{-2}) found in western Europe (Wapshere *et al.* 1974). The rust fungus, *Puccinia* *chondrillina*, appears to be more damaging in Western Europe to populations of *C. juncea* than the eriophyid gall mite, *A. chondrillae*. In Australia, *P. chondrillina* appears to be the most damaging of the introduced natural enemies (Wapshere 1978).

Three organisms were released and established in California for the biological control of *C. juncea*. The Biological Control Services Program of the California Department of Food and Agriculture (CDFA), in co-operation with the United States Department of Agriculture (USDA), Biological Control of Weeds Laboratory, Albany, California, made the first releases of *Cystiphora schmidti* and *Aceria chondrillae* in Placer County in October 1975 and April 1977, respectively.

The CDFA Biological Control Services Program in cooperation with the USDA Plant Disease Research Laboratory, Frederick, Maryland, made the first releases of *Puccinia chondrillina* in October 1976 in Placer and El Dorado Counties. The intentional introduction of *P. chondrillina* appears to be the first use of an exotic plant pathogen in North America for the biological control of weeds (Emge & Kingsolver 1977).

In the north-western and eastern U.S., reduced seed set, seed germinability, plant biomass and bolt height have been correlated with attack by *P. chondrillina* (Emge, Melching & Kingsolver 1981; Adams & Line 1984). However, the ability of the complex of natural enemies established for the control of *C. juncea* to reduce the density of this weed in the western U.S. has been uncertain. The present study was initiated to assess the impact of the three biological control agents on the density of *C. juncea* in California.

MATERIALS AND METHODS

During August and September 1975, a field study was initiated at two locations in Placer County, California, to monitor long-term changes in density of *C. juncea*. At the outset, both sites contained relatively uniform stands of *C. juncea* at least 1 ha in area. At Newcastle, 72 points were located and permanently marked on a paced grid with 6·10 m between points. At Rocklin, 62 points were permanently positioned in a $9{\cdot}14 \times 6{\cdot}10$ m grid pattern.

Data were collected at Newcastle during 1976–84 and at Rocklin during 1976–82. For both sites, *C. juncea* density data was collected during the flowering stage each year from 26 May to 21 June. The centre of a 1-m^2 quadrat frame was placed over each point and the number of *C. juncea* plants in each quadrat recorded. Biological control agent establishment and dispersal records were kept for both sites.

In May 1979, four sites were selected on one property in Loomis, Placer County, California, and an additional site was selected in November 1981. These five sites represented different environmental conditions typical of the *Chondrillina juncea* infestations in Placer County. *Cystiphora schmidti*, *Aceria chondrillae* and *Puccinia chondrillina* were released in 1976, 1977 and 1978, respectively, and were established at all sites by May 1979. For each site, a 15×15 m area containing a uniform dense patch of *C. juncea* was selected. Twenty-five quadrats, each 0·25 m^2, were randomly located and permanently marked at each site. The number of *C. juncea* plants, along with a record of the number of plants attacked by the three biological control agents was kept for each quadrat at each reading. A plant was considered attacked if it had at least one rust pustule, or one stem or leaf gall. Separate records were kept of plants attacked by more than one biological control agent. The first reading was made in May 1979. From 1980 to 1984, there were two readings for each year, one in early spring (15 March–1 April), and one in late spring (7 May–1 June), except in 1980 when only one early spring count was made.

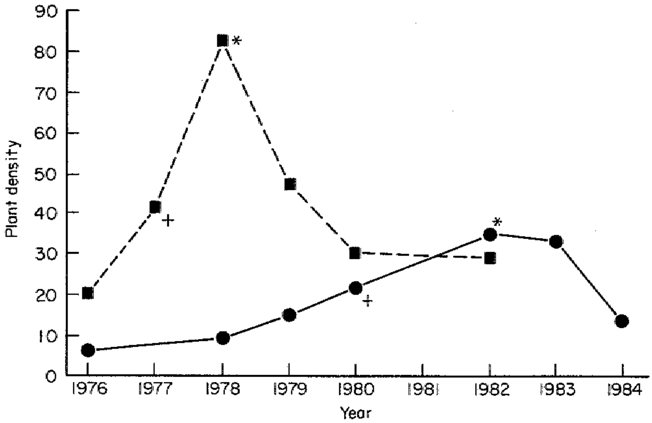

FIG. 1. Average number of *Chondrilla juncea* bolts m^{-2} at Rocklin (- - - -) and Newcastle (———), California, in years before and after establishment (+) and wide dispersal (*) of *Puccinia chondrillina*.

Early spring readings were made when most plants were in the rosette stage, before or just after the onset of *C. juncea* stem elongation. Late spring readings were made during the flowering stage after stems were much elongated following the loss by most plants of rosette leaves.

RESULTS

Control agent establishment

Puccinia chondrillina was released and established at the Rocklin site in August 1977. By spring 1978, it was widespread throughout the site. In April 1978, *P. chondrillina* was released and established 400 m from the Newcastle site. *P. chondrillina* was not found at Newcastle until May 1980, when, although it had established, relatively few plants were infected. By spring 1982, *P. chondrillina* was widespread at the Newcastle site. Galls of *Cystiphora schmidti* were first found at Newcastle in September 1976 and at Rocklin in October 1977. *C. schmidti* was well dispersed at both sites one year after establishment. *Aceria chondrillae* was established at Newcastle by November 1979 and at Rocklin by August 1977.

Changes in density of Chondrilla juncea

At both the Newcastle and Rocklin sites, the density of *C. juncea* increased until *Puccinia chondrillina* was established and widely dispersed (Fig. 1). Four years after the rust establishment, plant density remained above initial levels found in 1976 at both sites. After wide dispersal of *P. chondrillina*, plant density decreased 64·3% at Rocklin over a 3-year period and 62·4% at Newcastle over a 2-year period. At Loomis, the density of *C. juncea* at all five sites decreased significantly over the period of observation (Fig. 2). Plant density decreased 56·3% at the Orchard site, 60·7% at the East site, 84·3% at the West site and 87·2% at the Hill site from May 1979 to May 1984. At the Ridge site, the density of *C. juncea* decreased 85·1% from May 1982 to May 1984.

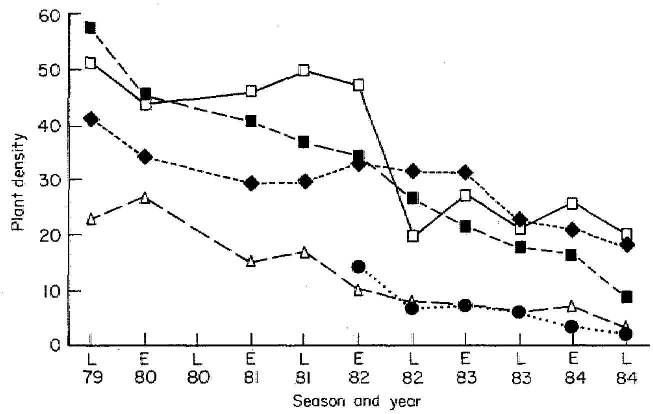

FIG. 2. Average number of *Chondrilla juncea* plants at East (□), West (■), Orchard (♦), Hill (△) and Ridge (●) sites, in early (E) and late (L) spring at Loomis, California, during 1979–84. Values estimated from twenty-five 0·25 m^2 quadrats per season per site.

Effect of biological control agents on the density of Chondrilla juncea

At Loomis, the best correlation between plant density change and the number of plants attacked by control agents was between the incidence of *P. chondrillina* on rosettes and change in rosette number. For each of the five Loomis sites, the regression equation $N = a + bI$ was estimated where N = the change in rosette number per quadrat from year x to year $x+1$, I = the number of infected rosettes per quadrat in year x, and a and b are constants. The estimated regression equations were:

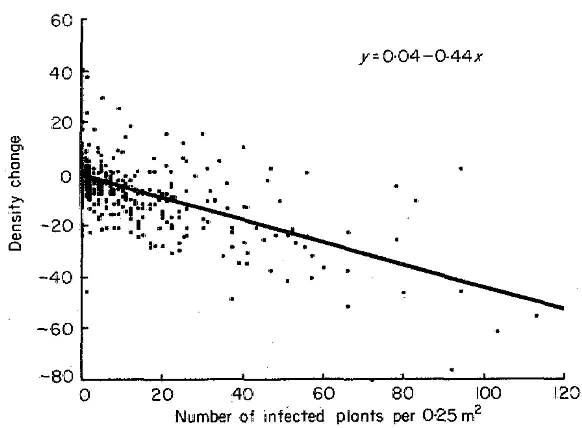

FIG. 3. Regression of the number per 0·25 m^2 quadrat of *Chondrilla juncea* rosettes in year x infected with *Puccinia chondrillina* against the change in number of rosettes in that quadrat from year x to year $x+1$, at five sites in Loomis, California, during 1980–84 ($n = 436$).

Hill site	$N = -0{\cdot}22 - 0{\cdot}54\,I\,(r = -0{\cdot}777, P < 0{\cdot}0001)$
East site,	$N = 3{\cdot}02 - 0{\cdot}60\,I\,(r = -0{\cdot}744, P < 0{\cdot}0001)$
Ridge site,	$N = -2{\cdot}5 - 0{\cdot}62\,I\,(r = -0{\cdot}707, P < 0{\cdot}0001)$
Orchard site,	$N = 1{\cdot}2 - 0{\cdot}38\,I\,(r = -0{\cdot}54, P < 0{\cdot}0001)$
West site,	$N = -2{\cdot}49 - 0{\cdot}34\,I\,(r = -0{\cdot}54, P < 0{\cdot}0001)$

Analysis of variance showed no significant difference for slope so the five data sets were combined. New estimates of a and b calculated from the combined data were $-0{\cdot}05$ and $-0{\cdot}44$, respectively ($r = 0{\cdot}619$, $P < 0{\cdot}0001$) (Fig. 3).

A significant correlation between change in number of *C. juncea* flowering plants (late spring) and the number of flowering plants infected with *P. chondrillina* was obtained for the Hill ($r = -0{\cdot}43$, $P < 0{\cdot}0002$), East ($r = -0{\cdot}32$, $P < 0{\cdot}0079$), Orchard ($r = -0{\cdot}58$, $P < 0{\cdot}001$), and West ($r = -0{\cdot}40$, $P < 0{\cdot}0004$) sites. However, except for the Orchard site, variation in plant density was better explained by the relationship between plant density change and the number of diseased rosettes (early spring), than the relationship with number of diseased flowering plants (late spring).

At Loomis, *Cystiphora schmidti* and *Aceria chondrillae* were less widely dispersed in space and time during the years of observation. In general, of the three biological control organisms, *P. chondrillina* was associated with the highest incidence of plant attack, and *A. chondrillae* with the lowest, regardless of season or year (Figs 4 and 5). It was not uncommon for *C. schmidti* and *A. chondrillae* to be absent or found in very low numbers in the early spring depending upon the location and year. *C. schmidti* was virtually absent during the early spring from the north-east site through the entire period of study. A significant correlation between change in number of *C. juncea* rosettes and the number of rosettes attacked by *C. schmidti* was obtained for the East ($r = -0{\cdot}39$, $P < 0{\cdot}0001$), Ridge ($r = -0{\cdot}26$, $P < 0{\cdot}0001$) and West ($r = -0{\cdot}21$, $P < 0{\cdot}05$) sites, although the correlation coefficients associated with this relationship were lower than those for rosettes attacked by *P. chondrillina*. There was a consistent increase from spring to summer at all sites in the

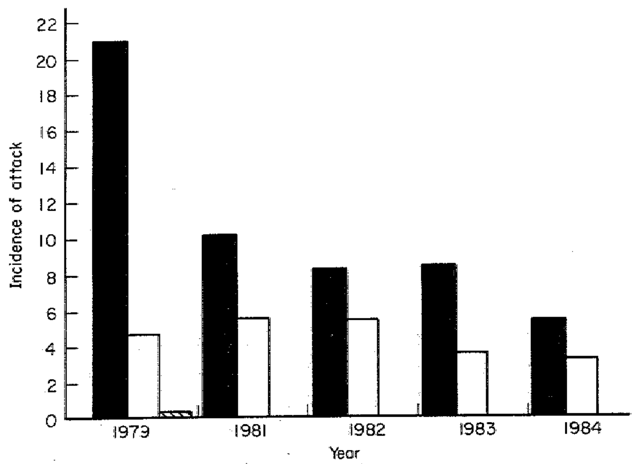

FIG. 4. Average yearly incidence over five sites in Loomis, California, of attack of *Chondrilla juncea* per $0{\cdot}25$ m^2 quadrat by *Puccinia chondrillina* (■), *Cystiphora schmidt* (□) and *Aceria chondrillae* (▧) in late spring during 1979–84.

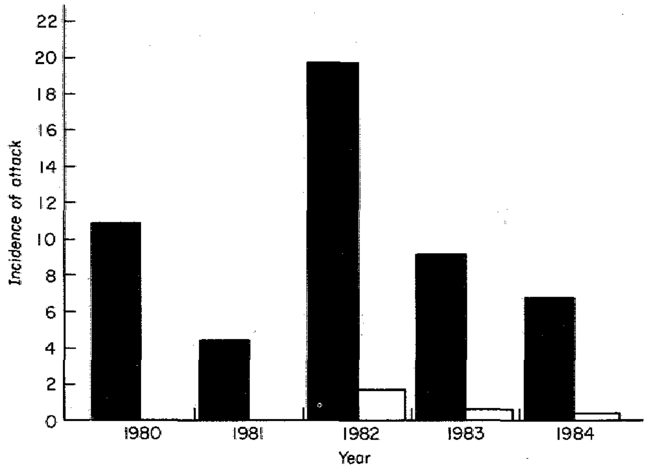

FIG. 5. Average yearly incidence over five sites in Loomis, California, of attack of *Chondrilla juncea* per 0·25 m^2 quadrat by *Puccinia chondrillina* (■) and *Cystiphora schmidti* (□) in early spring during 1980–84.

number of *C. juncea* plants galled by *C. schmidti*, but only at the West site was there a significant correlation between bolt attack and a decline in the number of flowering plants the following year ($r = -0{\cdot}55$, $P < 0{\cdot}0001$). The correlation coefficient for this relationship was just slightly lower than that for incidence of rosette attack by *P. chondrillina* and decline in rosette density. There were no significant correlations between the number of flowering plants galled by *A. chondrillae* and the change in density of *C. juncea.*

DISCUSSION

At all three monitoring locations in Placer County, there was a considerable reduction in the density of *C. juncea* following the introduction of three biological control organisms. At Loomis, plant numbers at the Ridge site have been reduced to 10 plants m^{-2}, within the range of normal density for *C. juncea* found in Mediterranean Europe. At Newcastle and Loomis (Hill site) *C. juncea* density is below 19 plants m^{-2} and is now approaching the normal density found in Europe. Despite dramatic reductions in plant numbers, three sites at Loomis are still heavily infested with *C. juncea*, with densities varying from 39 to 84 plants m^{-2}. These heavily infested sites had higher densities of *C. juncea* at the outset. It may be several years before it can be determined whether plant numbers will yet be brought below 10 plants m^{-2} at these sites.

While plant competition, environmentally-induced stress and cultural practices are known to have an impact on the abundance of *C. juncea* (McVean 1966; Wells 1971), the damage caused by introduced biological control agents appears to be the determining factor in the density reduction of this weed in the Loomis Basin. *C. juncea*, a rangeland weed, is not regularly managed through cultural practices in California as it often is in Australia. Density change occurred at Newcastle, Rocklin and Loomis in the absence of cultural manipulation. The density of *C. juncea* was increasing at Rocklin and Newcastle, areas with similar weather conditions, before the introduction of biological control agents. While the density of *C. juncea* increased at Rocklin until *P. chondrillina* was well dispersed in 1978, the density of this weed continued to increase at Newcastle. Only after *P. chondrillina* was well dispersed at Newcastle in 1982 did density there begin to decline.

In California, as in Europe and Australia, *P. chondrillina* appears to be the most important biological control agent for control of *C. juncea*. As in Europe, *P. chondrillina* is more widely dispersed in space and time than either *C. schmidti* or *A. chondrillae*. Of the three introduced biological control organisms, incidence of attack by *P. chondrillina* correlates best with density changes of *C. juncea*. Despite differences in the environmental conditions at five Loomis sites, the incidence of disease had a similar effect on plant density change regardless of site. The y intercept of the estimated regression equation for this relationship was close to 0, suggesting that, at Loomis, in the absence of disease the plant population would have remained at equilibrium.

The effect of *C. schmidti* on density change of *C. juncea* appears to be greatly dependent upon site. *C. schmidti* either does not overwinter well or emerges late at the north-east site and this may help to explain both the lower levels of *C. schmidti* during the late spring and the lack of significant correlation between incidence of midge attack and density change at this site. At the West site, incidence of midge attack correlates as well with density decline as rust attack. While *P. chondrillina* appears to be the most important biological control organism in the Loomis Basin, *C. schmidti* may be locally important depending upon site.

ACKNOWLEDGMENTS

We wish to thank K. Casanave, H. Yee and G. Hanisch for their technical assistance.

REFERENCES

Adams, E. B. & Line, R. F. (1984). Epidemiology and host morphology in the parasitism of rush skeletonweed by *Puccinia chondrillina*. *Phytopathology*, **74**, 743–748.

Cullen, J. M. & Groves R. H. (1977). The population biology of *Chondrilla juncea* in Australia. *Proceedings of the Ecological Society, Australia*, **10**, 121–134.

Cullen, J. M. (1978). Evaluating the success of the program for the biological control of *Chondrilla juncea* L. *Proceedings of the IV International Symposium on the Biological Control of Weeds* (Ed. T.E. Freeman), pp. 117–121. University of Florida, Gainesville, Florida, 1976.

Emge, R. G. & Kingsolver, C. H. (1977). Biological control of rush skeletonweed with *Puccinia chondrillina*. *Proceedings of the American Phytopathology Society*, **4**, 215.

Emge, R. G., Melching, J. S. & Kingsolver, C. H. (1981). Epidemiology of *Puccinia chondrillina*, a rust pathogen for the biological control of rush skeletonweed in the United States. *Phytopathology*, **71**, 839–843.

McVean, D. N. (1966). Ecology of *Chondrilla juncea* L. in southeastern Australia. *Journal of Ecology*, **54**, 345–365.

Moore, R. M. & Robertson, J. A. (1964). *Studies on skeletonweed. Competition from pasture plants.* CSIRO, Division of Plant Industry, Field Station Record No. 3, pp. 69–73.

Pryor, M. R. (1967). Skeletonweed control. *Proceedings of the 19th Annual California Weed Conference*, pp. 27–30. California Weed Conference, Sacramento, California.

Schirman, R. & Robocker, W. C. (1967). Rush skeletonweed—threat to dryland agriculture. *Weeds*, **15**, 310–312.

Wapshere, A. J., Hasan, A. Wahba W. K. & Caresche, L. (1974). Ecology of *Chondrilla juncea* in the western Mediterranean. *Journal of Applied Ecology*, **11**, 783–800.

Wapshere, A. J. (1978). Effectiveness: A comparison of prediction and results during the biological control of *Chondrilla*. *Proceedings of the IV International Symposium of the Biological Control of Weeds* (Ed. T.E. Freeman), pp. 124–127. University of Florida, Gainesville, Florida, 1976.

Wells, G. J. (1971). The ecology and control of skeletonweed (*Chondrilla juncea*) in Australia. *Journal of the Australian Institute of Agricultural Sciences*, **37**, 122–137.

(Received 24 April 1987; revision received 16 March 1988)