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Classical Biological Control of Nodding and Plumeless Thistles

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Nodding (musk) thistle (*Carduus thoermeri* Weinmann in the *Carduus nutans* L. group) and plumeless thistle (*Carduus acanthoides* L.) are introduced noxious weeds of Eurasian origin. Both weeds are problematic in pastures, rangelands, and croplands and along state highways in many parts of the United States. The success of both species of thistles is largely due to their prolific seed production, seed longevity, competitive ability, and lack of natural enemies. Classical biological control of nodding thistle in Virginia has been achieved with three exotic thistle herbivores, *Rhinocyllus conicus* Froelich (Coleoptera: Curculionidae), *Trichosirocalus horridus* (Panzer) (Coleoptera: Curculionidae), and *Cassida rubiginosa* Müller (Coleoptera: Chrysomelidae). *T. horridus* also effectively controls plumeless thistle. These insect herbivores complement each other. Nodding thistle biological control is achieved in about 5–6 years in Virginia, Missouri, and Montana. In addition, a rust fungus (*Puccinia carduorum* Jacky) (Uredinales: Pucciniaceae) has been introduced and established for control of nodding thistle in Virginia. Development and reproduction of the three thistle herbivores are not adversely affected by the rust. The rust hastens plant senescence and reduces seed production. Control of plumeless thistle with *R. conicus* and *T. horridus* takes approximately twice as long as control of nodding thistle.

Key Words: **classical biological control of weeds; nodding thistle; musk thistle; *Carduus thoermeri; Carduus acanthoides;* plumeless thistle; *Rhinocyllus conicus; Trichosirocalus horridus;* Curculionidae; *Cassida rubiginosa;* Chrysomelidae.**

INTRODUCTION

Carduus thistles are introduced Eurasian weeds in North America. McCarty (1978) indicated that seven species occur in the United States. Two of the most important species are the nodding or musk thistle (*Carduus thoermeri* Weinmann = *Carduus nutans* L. subsp. *leiophyllus* (Petrovic) Stoj. & Stef.), which has large capitula, and the plumeless thistle (*Carduus acanthoides* L.), which belongs to the small-sized capitula group. Both thistles are winter annuals or biennials. Seeds produced in summer form rosettes which overwinter. The rosettes resume development in spring, followed by stem elongation and flowering. Nodding thistle was first recorded in 1853 at Harrisburg, Pennsylvania (Stuckey and Forsyth, 1971) and has been reported in 40 of the 48 contiguous states (Frick, 1978). Plumeless thistle first appeared in 1878 at Camden, New Jersey and in Ohio (Batra, 1978) and is found in 19 states (Frick, 1978). The two thistle species often occupy the same habitats in the northeast, such as overgrazed pastures and disturbed roadsides, sometimes occurring in mixed stands (Batra, 1978). Both thistles have become persistent, major weeds of pastures, rangelands, and croplands and along highways despite repeated attempts to control them with herbicides. The question then arises as to why the *Carduus* thistles have been so successful as invasive weeds of disturbed habitats. This report summarizes the results of the use of natural enemies for biological control of nodding and plumeless thistles.

SUCCESS OF THISTLES

Several factors contribute to the success of nodding and plumeless thistles as weeds. Introduced without their natural enemies, both thistles have been able to dominate infested areas because of their prolific reproductive capacity and seed longevity. With multiple flowering heads, each plant can produce an average of 11,000 seeds (Feldman *et al.*, 1968) and up to 20,000 seeds (Kok, 1978a) that remain viable for approximately 20 years. Seeds are dispersed by wind. Less than 1% of seeds are blown farther than 100 m and most seeds are deposited within 50 m of the release point (Smith and Kok, 1984). This concentration of large numbers of seeds in a small area and an ability to grow in poor soil make these thistles extremely competitive. Although pastures are frequently overgrazed, thistles are avoided by grazing animals because of their numerous spines. As thistles are not subjected to grazing or other stress, they easily outcompete forage grasses to become the dominant vegetation. In time, thistles can spread to dominate entire fields. Mowing

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TABLE 1

Biological Control Agents Established for Nodding (Musk) Thistle Control in the United States

Species	Year introduced	Origin	Reference
Insects			
Rhinocyllus conicus Froelich (Coleoptera: Curculionidae)	1969	Rhine Valley, France	Surles *et al.*, 1974
Trichosirocalus horridus (Panzer) (Coleoptera: Curculionidae)	1974	Rome, Italy	Kok and Trumble, 1979
Cassida rubiginosa Müller (Coleoptera: Chrysomelidae)	1901 (accidental, via Canada)	Europe	Barber, 1916
Fungus			
Puccinia carduorum Jacky (Uredinales: Pucciniaceae)	1989	29 km South of Ankara, Turkey[a]	Baudoin *et al.*, 1993

[a] Dr. W. L. Bruckart, USDA-ARS, Fort Detrick, MD, personal communication.

helps to disperse the seeds, and herbicidal sprays for thistle control also kill competing vegetation, creating bare ground ideal for thistle seed germination in the following season. Hence, repeated herbicidal sprays provide only short-term suppression of the thistles and promote thistle colonization and spread.

Very few herbivores native to the United States cause serious stress to exotic thistles (Kok, 1978a). Consequently, in the absence of their natural enemies, reproduction and spread of the thistles have not been impeded. Thus, thistle control has become a multimillion dollar program in several states since the late 1960s.

BIOLOGICAL CONTROL

Biological control efforts for nodding thistle and plumeless thistle in the United States began with a search for natural enemies in Europe in 1963 (Andres and Kok, 1981). Through the joint efforts of the USDA, Agriculture Canada, and the International Institute of Biological Control, several species of insects with potential for thistle control were considered for introduction into the United States. Among potential candidates were the weevils *Rhinocyllus conicus* Froelich (Coleoptera: Curculionidae), *Trichosirocalus horridus* (Panzer) (Coleoptera: Curculionidae), and *Ceutorhynchus trimaculatus* (F.) (Coleoptera: Curculionidae) and the flea beetle *Psylliodes chalcomera* (Illiger) (Coleoptera: Chrysomelidae). The first two candidates were subsequently released and their impact will be discussed here. *C. trimaculatus* was not approved for release after extensive testing because it fed on several *Cirsium* species and artichoke (Kok *et al.*, 1979, 1982; Kok and McAvoy, 1983). *P. chalcomera* was initially rejected after tests showed that it fed on artichoke under caged conditions (Boldt, 1978), but it has recently been approved for release in the United States. *P. chalcomera* has not been released in Virginia because of the success achieved with *R. conicus* and *T. horridus.*

Four biological control agents have become well established for nodding thistle control in Virginia and many mainland states in the United States (Table 1). The thistle-head weevil, *R. conicus*, was the first insect to be released and established in North America for thistle control (Surles *et al.*, 1974). It was collected from the Rhine Valley in France and released in Canada in 1968. In 1969, it was introduced into California, Virginia, and Montana and became successfully established (Goeden, 1978; Rees, 1977; Kok and Surles, 1975). Subsequently, it was relocated to other states in the United States and has become established in many other states, including Missouri (Puttler *et al.*, 1978), Tennessee (Lambdin and Grant, 1992), and Georgia (Buntin *et al.*, 1993). *R. conicus* is a native of southern and central Europe, northern Africa, and western Asia between latitudes 30° and 52° north. Adults are dark brown in color and 10 to 15 mm long. *R. conicus* overwinters in the adult stage and becomes active in mid- to late-April, depending on temperature. Oviposition is well synchronized with nodding thistle phenology and occurs as flower buds develop. Oviposition is, however, less well synchronized with plumeless thistle development (Surles and Kok, 1977). The oviposition period lasts for 5 to 6 weeks from mid-April through May (Surles and Kok, 1977). Each female lays from 100 to 200 eggs on the bracts of different thistle heads. Eggs hatch in 6 to 9 days. Newly eclosed larvae chew through the bracts into the receptacles. Developing larvae feed on the receptacle and young achenes, preventing the production of viable seeds. Four larval instars complete development in 4 to 6 weeks and larvae change into pupae within thistle heads (Rowe and Kok, 1985). Pupation occurs in ovoid cells and the pupal stage lasts 7 to 10 days before new teneral adults emerge. New adults begin to emerge in July through early August and feed slightly on leaves. These adults estivate through late summer and diapause over winter. Overwintered adults reemerge in spring to oviposit and die 1–2 weeks after completion of oviposition. Emergence in spring is well synchronized with thistle

TABLE 2

Biological Attributes of Insects Established for Biological Control of Nodding (Musk) Thistle

Attribute (mean/stage)	*Rhynocyllus conicus*[a]	*Trichosirocalus horridus*[b]	*Cassida rubiginosa*[c]
No. generations/year	Univoltine; partial second generation	Univoltine	Univoltine
No. eggs/female	100.5	807.2	815.0
% Egghatch	67.0	69.0	74.1
Egg stage (days)	6.5	13.5	5.9
No. larval instars	4	3	5
Larval stage (days)	25.0	65.0	14.9
Pupal stage (days)	11.0	18.7	6.5
% Mortality from 1st instar to adult	9.7	83.0	79.0
Adult longevity (weeks)	40	31.5	37.7
% Overwintering adult mortality	52.0	27.7	78.7
Overwintering stage	Adult	Egg, larva, adult	Adult
Damaging stage	Larva in buds	Larva in crown tissue	Larva, adult on leaves

[a] Surles *et al.*, 1975; Kok, 1976, 1979; Rowe, 1981.
[b] Kok *et al.*, 1975; Sieburth, 1981.
[c] Ward and Pienkowski, 1978a; Ang and Kok, 1995; Spring and Kok, 1997, 1999.

stem elongation (Surles and Kok, 1977; Smith and Kok, 1987) and there is usually one generation of *R. conicus* per year in Virginia. A partial second generation occurs when weevil emergence occurs early in the season. The first success in biological control of nodding thistle by *R. conicus* was documented soon after the weevils became established in Virginia, with typical thistle density reduction of 80–95% in infested pastures (Kok and Surles, 1975). However, *R. conicus* provided only partial control of plumeless thistle, which prompted research on *T. horridus* and its impact on nodding and plumeless thistles.

The rosette feeder, *T. horridus*, was the second insect released for thistle control in North America (Kok, 1978b). It is native to south and central Europe and the first batch was imported from Rome, Italy into the United States in 1970–1972 for quarantine testing. Host specificity tests (Ward *et al.*, 1974; Kok, 1975) revealed that it would not be a threat to nontarget plants and it was approved for field release in the United States in 1974. Following its release in the fall of 1974 in Virginia, *T. horridus* became established by 1977 (Kok and Trumble, 1979) and its impact on musk and plumeless thistles was evident 5–6 years later (Kok, 1986). It has recently been established in North Carolina (McDonald *et al.*, 1994), Missouri (B. Puttler, USDA, personal commun.), and Tennessee (P. L. Lambdin, University of Tennessee, personal commun.). *T. horridus* is univoltine and overwinters in the adult, egg, and larval stages (Kok and Mays, 1989). Overwintering in three different life stages (Table 2) confers an advantage to *T. horridus* over *R. conicus* by allowing it to survive unusually prolonged winters. The adult is about 10 mm long and emerges in late winter and early spring. The eggs are laid in clusters of 2 or 3 and oviposition occurs in the midribs on the underside of young rosettes. Each female lays an average of 807 eggs, although over 2000 eggs from several individual females reared in the laboratory have been recorded (Kok *et al.*, 1975). The eggs hatch in 13.5 days at day:night temperatures of 21:10°C, and young larvae feed within midribs and move toward the central growth point of rosettes. Larvae reach the thistle crown in about 7 days and continue feeding within this vicinity, causing necrosis of crown tissue. On completion of feeding in 6 to 8 weeks, full-grown larvae leave the plant and pupate in the soil in a pupation chamber consisting of soil particles and organic material. The pupal stage lasts for 14 to 25 days. Newly emerged or teneral adult weevils are reddish, changing to dark brown to black in about 3 weeks. The new generation of adults appears in May and June and enters estivation from July until fall, when they reemerge to feed on leaves and oviposit. Females may oviposit until the first frost of winter (Kok, 1992). *T. horridus* typically has one generation per year. Biological attributes of the three established insect biological control agents are summarized in Table 2.

PROGRAM RESULTS AND IMPACT

With field establishment of *T. horridus* and *R. conicus*, thistle reduction exceeding 90% of initial thistle density was achieved in Virginia. As the two weevils attack different thistle growth stages, they have had a complementary role in the suppression of the thistles. The typical long-term trend of nodding thistle density in relation to weevil infestation is shown in Fig. 1. The decline in thistle populations is clearly depicted despite some occasional spikes due to resurgence of the weeds. Conditions that cause resurgence include dumping of soil with thistle seeds, exposure of soil during excavating in fields, and overgrazing by lifestock. Also, frequent sharp temperature fluctuations in winter cause

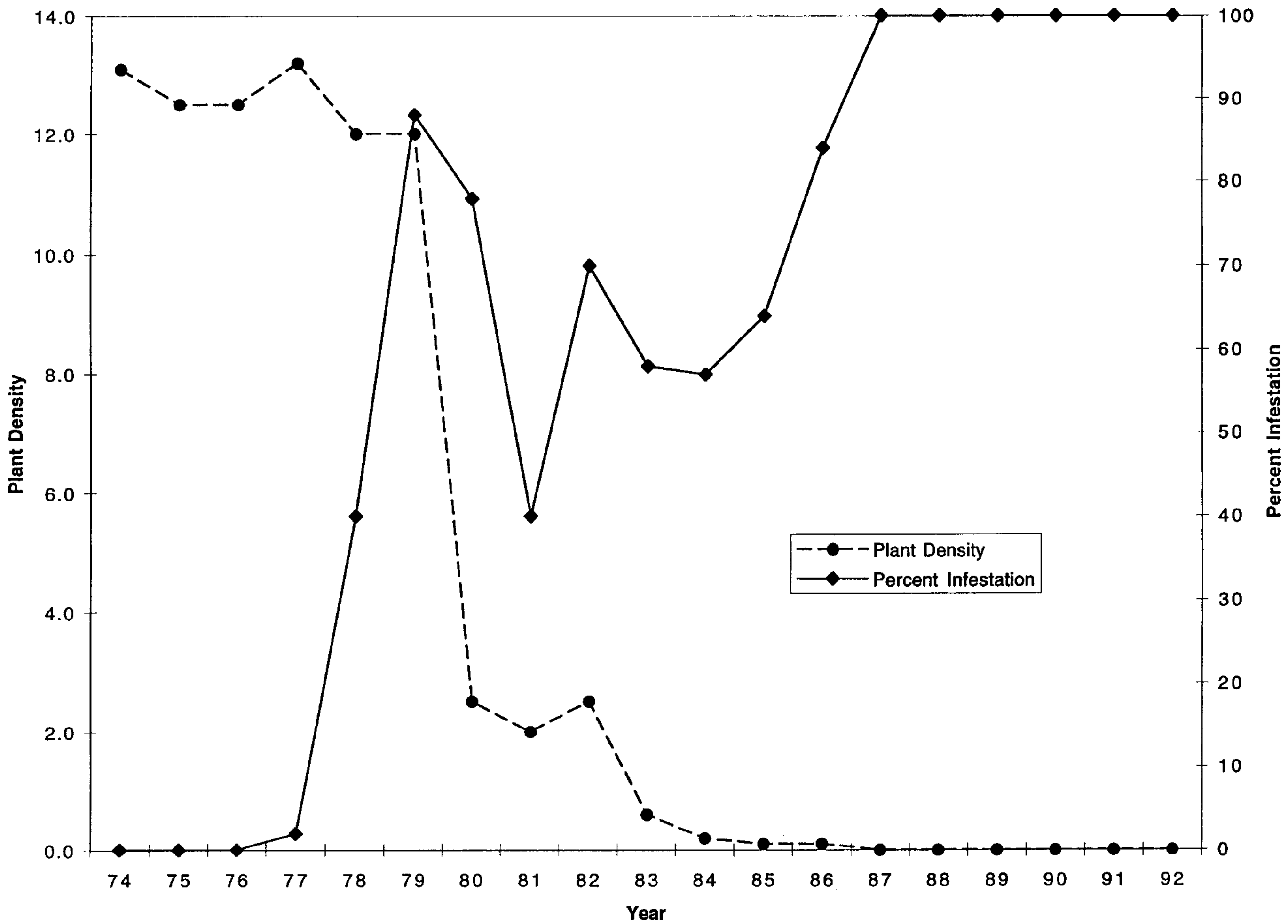

FIG. 1. Relationship of nodding thistle density (No. plants per m^2) and percentage infestation by *R. conicus* and *T. horridus* at the Radford site, Montgomery County, Virginia.

high overwintering mortality of the weevils and reduced thistle control in spring. Despite such occurrences that cause temporary resurgence of thistles, these two weevils eventually resuppress thistles. Thus, both weevils have been highly successful in controlling nodding thistle.

In addition, *T. horridus* is also effective in plumeless thistle control (Fig. 2), although it takes a longer period for suppression to become apparent. Biological control is evident after 5 to 6 years for nodding thistle (*T. horridus* or *R. conicus*) and 10 to 12 years for plumeless thistle (*T. horridus*) (Kok and Mays, 1991). *T. horridus* and *R. conicus* are excellent examples of successful classical control of terrestrial weeds in the United States. Much of the success of these natural enemies is the result of good synchronization of plant phenology and insect activity and the low incidence of parasitism and predation (Table 3) of the two weevils. Our studies have revealed no parasitism of *T. horridus* but some predation by ants. Several parasitoids were found attacking *R. conicus*. These include a tachinid adult parasitoid (Smith and Kok, 1983) and several larval parasitoids (Dowd and Kok, 1982) (Table 3). None is host specific and overall parasitization rates were low. Similar low rates (<15%) of parasitization of *R. conicus* were reported by other researchers in the United States: Rees (1977) in Montana, Puttler *et al.* (1978) in Missouri, and Goeden and Ricker (1977, 1978) in California. Dowd and Kok (1981) found several insects and spiders to be opportunistic predators of *R. conicus*. Several species of bacteria were isolated from larvae and adults of *R. conicus*, the most common being *Bacillus cereus* Frankland and Frankland and *Bacillus megatherium* DeBary (Dowd and Kok, 1983) (Table 3). Adults of *R. conicus* were occasionally attacked by the fungus *Beauveria bassiana* (Balsamo) Vuillemin (Dowd and Kok, 1983), and a protozoan, *Nosema* sp., was detected in some eggs and first instars of *T. horridus* that were reared in the laboratory. None of the field-collected eggs or larvae had infections of this protozoan. We attribute this to a laboratory-induced problem and it is not a major mortality factor in the field.

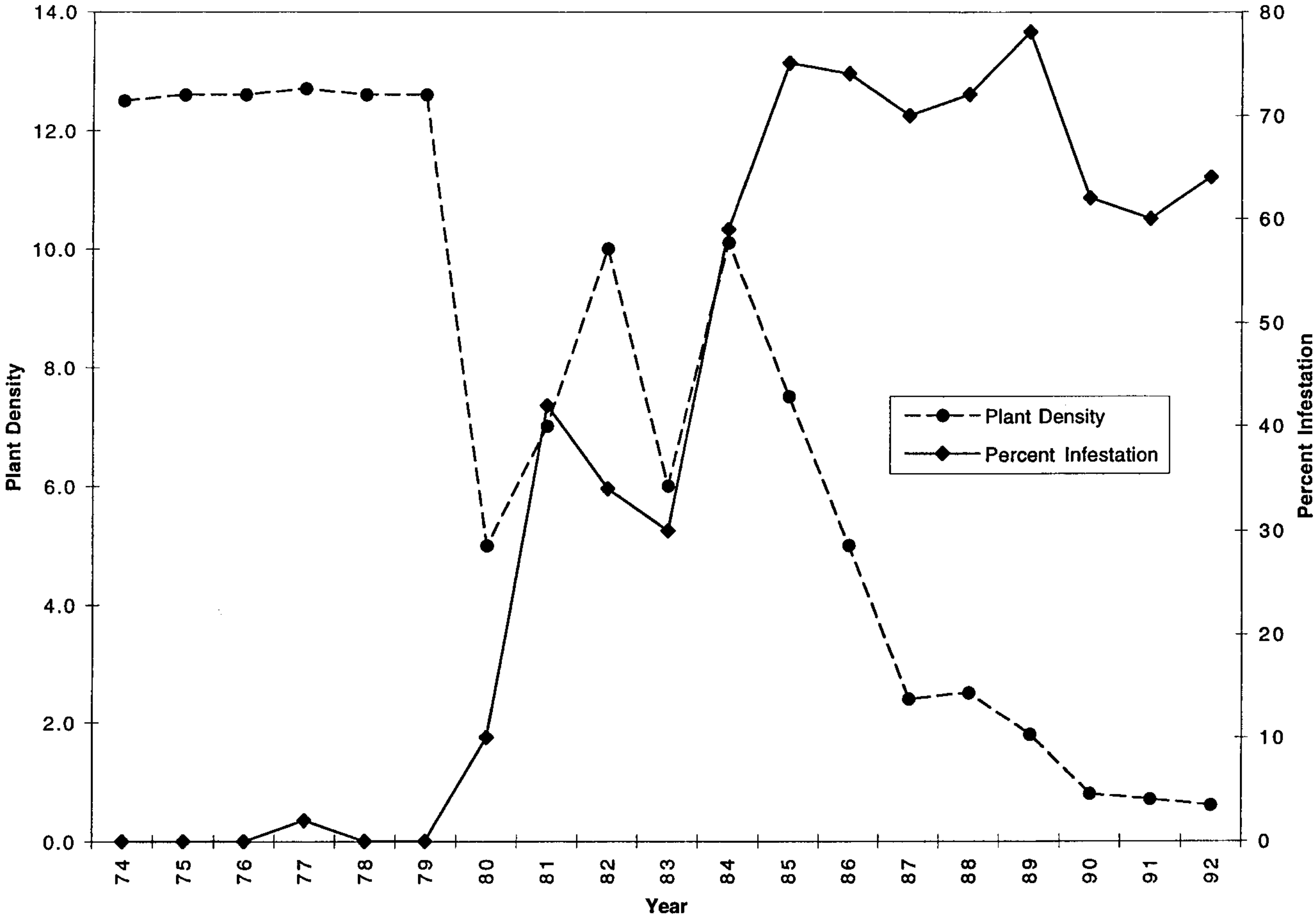

FIG. 2. Relationship of plumeless thistle density (No. plants per m^2) and percentage infestation by *T. horridus* at the Lester Site, Giles County, Virginia.

A third beetle, *Cassida rubiginosa* Müller (Chrysomelidae), accidentally entered eastern North America and was first reported in Quebec in 1901 (Barber, 1916). This beetle spread south and was recovered in northern Virginia in 1973 (Ward and Pienkowski, 1978a). *C. rubiginosa* is a thistle foliage-feeding beetle native to the Palearctic region (Zwölfer and Eichhorn, 1966). Its host range is limited to the Carduinae and includes the economically important thistles of the genus *Carduus*. It is univoltine, with overwintering adults first appearing on host plants in late February and early March (Ward and Pienkowski, 1978a). Oviposition begins in March and continues through early July. The larval stage, with 5 instars, occurs from April through early August. Adult emergence occurs from mid June through August. Both the adults and the larvae feed on thistle leaves. Females from a field population of *C. rubiginosa* maintained in the laboratory laid an average of 815 eggs (Ward and Pienkowski, 1978a). Field-collected, overwintered females produced 61 oothecae per individual over a 15-week period. They showed no preference between nodding and Canada thistle (*Cirsium arvense* (Linnaeus) Scopoli) for oviposition, and development from egg to adult was 27.4 and 28.5 days, respectively, on Canada and nodding thistle. Survival from egg to adult was 18.3 to 26.7% (Spring and Kok, 1997). Defoliation studies indicated that *C. rubiginosa* inflicted damage on nodding thistles that resembled 50 to 75% of damage caused by multiple mechanical defoliations (Cartwright and Kok, 1990). Mortality of thistles was highest with 75% defoliation at the rosette stage. Defoliation of thistles after the plant bolted had little effect on thistle growth and reproduction. *C. rubiginosa* leaf consumption increased as larvae matured, and feeding rates are temperature dependent (Cartwright and Kok, 1990). Thus, heavy feeding by this beetle greatly stresses thistle growth and contributes to the overall mortality on thistles. The principal host of this beetle, however, is Canada thistle. A high rate of parasitism prevented *C. rubiginosa* from effective thistle control in Canada (Harris and Zwölfer, 1971). Ward and Pienkowski (1978b) reported five parasitoid species causing 14.6 and 23.8% in 1974 and 1973, respectively, in Virginia. Parasitization rate was lower in Maryland than in Virginia (Tipping, 1993). Mortality of *C. rubiginosa*

TABLE 3

Predators, Parasites, and Pathogens of *Rhinocyllus conicus* and *Trichosirocalus horridus* in Virginia

Mortality factor	Life stage of weevil attacked	
	R. conicus[a]	*T. horridus*[c]
Predators[a]		
Orius insidiosus (Say) [Anthoridae]	Larva (0.1)	None
Monomorium minimum (Buckley) [Formicidae]	Larva (1)	Larva (1)
Arilus cristatus (L.) [Reduviidae]	Adult (0.1)	None
Phidippus audax (Hentz) [Salticidae]	Larva, adult (1)	None
Xysticus ferox (Hentz) [Thomisidae]	Larva, adult (1)	None
Xysticus funestus Keyserling [Thomisidae]	Larva, adult (1)	None
Parasites[a]		
Bracon mellitor (Say) [Braconidae]	Larva (11.2)	None
Nealiolus curculionis (Fitch) [Braconidae]	Larva (2)	None
Zatropis sp. [Pteromalidae]	Larva (2.8)	None
Neocatolaccus sp. [Pteromalidae]	Larva (45.4)	None
Campoplex polychrosidis Viereck [Ichneumonidae]	Larva (0.1)	None
Hyalomyodes triangulifer (Loew) [Tachinidae][b]	Adult (5.1)	None
Pathogens		
Nosema sp. [Nosematidae][c]	None	Egg, larva (1)
Beauveria bassiana (Balsamo) Vuillemin[a] [Fungi Imperfecti]	Adult (5.9)	Adult (1)
Fusarium sp.	Larva (4.7)	None
Bacillus megatherium DeBary	Larva (12.5)	None
Bacillus cereus Frankland and Frankland	Larva (20.3)	None
	Adult (3.1)	None
Serratia sp.	Larva (6.3)	None
Streptococcus sp.	Larva (3.1)	None
Micrococcus sp.	Larva (3.1)	None
	Adult (6.3)	None

Note. Maximum percentage of stage attacked in parentheses; overall parasitization rates were low.
[a] Dowd and Kok, 1981, 1982, 1983.
[b] Smith and Kok, 1983.
[c] Unpublished data.

due to parasitoids was relatively low (<20%) early in the season, but increased to 98% in late June and early July (Ang and Kok, 1995). Although *Aprostocetus* sp., the most important parasitoid of pupae of *C. rubiginosa*, can reach a high level (Table 4), overall parasitization rates were much lower than the maximum rates recorded.

Puccinia carduorum Jacky was the first plant pathogen introduced into North America for biological control of nodding thistle. This is an autoecious rust fungus from the Mediterranean area that produces urediniospores and teliospores on nodding thistle. In greenhouse tests under quarantine, nodding thistle was the only host that became severely diseased (Politis *et al.*, 1984). Nodding thistle biomass was reduced significantly by inoculations of the rust in the plant (Politis and Bruckart, 1986). Based on these results, approval was granted by the USDA Animal and Plant Health Inspection Service for limited field tests in Virginia in 1987. A 3-year field test conducted in Blacksburg, Virginia revealed that it posed no threat to non-

TABLE 4

Parasitoids of Larvae and Pupae of *Cassida nubiginosa*

Parasitoids	Host stage	Maximum mortality (%) (a)	(b)
Eucelatoriopsis dimmocki (Aldrich)	Larva	2	41
(Diptera: Tachinidae)	Pupa	2	
Aprostocetus sp. (Eulophidae)	Larva	9	9.9
	Pupa	96	78.4
Itoplectis conquisitor (Say)	Larva	2	1
(Ichneumonidae)	Pupa	2	
Conura torvina (Walsh)	Larva	0	
(Chalcididae)	Pupa	8	10.8
Eupelmella vesicularis Ratzeburg (Eupelmidae)	Larva	0	3.1

Note. Overall mortality rates were lower than maximum mortality rates. No egg or adult parasitoids were recovered.
[a] Ang and Kok, 1995.
[b] Ward and Pienkowski, 1978b.

target plants (Baudoin *et al.*, 1993). The rust reduced seed production and hastened plant senescence. In 1994, it was found west of the Mississippi River in north central Missouri (Baudoin and Bruckart, 1996). Heavy exposure of the above biological control agents to the rust did not reveal any apparent adverse effects on the beetles. All three beetles transmitted the rust with most of the urediniospores observed on setae of the legs of adults (Kok and Abad, 1994). Further tests revealed that the rust does not interfere with the development of the three thistle herbivores (Kok *et al.*, 1996). *P. carduorum* has only a slight impact on the feeding behavior of the adults and larvae of *C. rubiginosa* and the adults of *T. horridus*. They avoided feeding on rust-infected foliage. The thistle insects attack areas on the plant not infected by the rust, thereby increasing damage to the thistle. Thus, the three thistle herbivores and the rust appear to be highly compatible and together play an important role in the biological control of target thistles.

CONCLUSION

The four biological control agents *R. conicus, T. horridus, C. rubiginosa,* and *P. carduorum* used for nodding thistle control complement each other and increased the overall stress on the nodding thistle. *T. horridus* is the only insect that controls plumeless thistle, but it takes twice as long to control plumeless thistle than to control nodding thistle. Thus, an additional biological control agent that complements *T. horridus* might hasten the rate of control of plumeless thistle. *C. rubiginosa* is an efficient defoliator of nodding thistle and Canada thistle, but as it feeds only sparingly on plumeless thistle, it is not useful for control of this weed. Considering these results, I feel that no further biological control agents need be introduced into the United States for nodding thistle control. In the case of plumeless thistle, a root-feeding insect or host-specific pathogen that would complement the activity of *T. horridus* would be useful for biological control of this weed. However, to the best of my knowledge, there has been no active search to fill this need.

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