

Abundance and Effects of Predators and Parasitoids on the Russian Wheat Aphid (Homoptera: Aphididae) Under Organic Farming Conditions in Colorado

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ABSTRACT *Diuraphis noxia* (Mordvilko) is an exotic, economically important pest in North American cereal crops. A survey of insect natural enemies of *D. noxia* was made from 1991 to 1994 on a farm using organic farming methods. Crested wheatgrass, *Agropyron cristatum* L., had fewer *D. noxia* and natural enemies than barley, *Hordeum vulgare* L., or wheat, *Triticum aestivum* L., but on all plants *D. noxia* was the most abundant aphid. We observed 41 species of natural enemies: 15 carabids, 12 coccinellids, six spiders, five syrphids, two nabids, and two chrysopids. The most consistently abundant were the coccinellids and nabids. *Hippodamia convergens* (Guerin) and *Nabis alternatus* Parsh were the most common species in each family, respectively. *Diaeretiella rapae* M'Intosh was the only primary parasitoid found in the 4-yr study, and *D. noxia* parasitism rates were generally <5%. Four hyperparasitoids, found in association with *D. rapae*, combined to make a 29% average hyperparasitism rate. Predator and parasitoid exclusion studies using cages showed aphid populations to be between 2.6 and 11.2 times higher in cages compared with wheat plants exposed to natural enemies. Four predatory species were released—*Eupeodes nuda* (F.), *Hippodamia variegata* (Goeze), *Leucopis ninae* Tanasijtshuk, and *Propylea quatuordecimpunctata* (L.). Of these, only a small colony of eight *L. ninae* and only one *P. quatuordecimpunctata* were later observed. Four parasitoids species were released—*Aphelinus asychis* Walker, *Aphelinus varipes* Forester, *Aphelinus matricariae* Haliday, and *Diaeretiella rapae*. Only *A. asychis* and *D. rapae* were observed after the release date, although *D. rapae* were already present.

KEY WORDS *Diuraphis noxia*, natural enemies, survey, exclusion, release

THE RUSSIAN WHEAT APHID, *Diuraphis noxia* (Mordvilko), invaded the United States in 1986 and is estimated to have cost small grain producers in the western United States \$893.1 million from 1987 to 1993 (Morrison and Peairs 1998). Several strategies using predatory and parasitic insects have been used in an attempt to reduce these production losses. One approach was to introduce a number of exotic natural enemies of *D. noxia*. A second approach was to investigate native or previously established predators and parasitoids with the goal of enhancing their effectiveness as biological control agents.

In Colorado, there are a number of native and previously established natural enemies that are known to feed on *D. noxia*. Wraight et al. (1993) found a low percentage of hymenopteran parasitism in *D. noxia* populations. They also noted that syrphids were the only predator consistently observed. Similarly, low *D. noxia* parasitism rates have been observed in Idaho (Feng et al. 1992). These results are in contrast to those from areas where *D. noxia* is native. In southern France, Chen and Hopper (1997) found *D. noxia* densities to be 40–100 times lower than in the United

States and found evidence that this was the result of the action of predatory and parasitic insects.

Approximately 85,000 individuals from 29 parasitoid and predator species have been collected and shipped to the United States for rearing and release (Hopper et al. 1998). Prokrym et al. (1998) estimated 2.5 million natural enemies have been released in Colorado by USDA-APHIS, Colorado Department of Agriculture, Colorado State University Agricultural Experiment Station, and USDA-ARS personnel from 1987 to 1994. Of these, 91.6% were hymenopteran parasitoids, 4.5% were coccinellids, and the remainder were dipteran predators in the families Syrphidae and Chamaemyiidae. Prokrym et al. (1998) noted that of all the parasitoids and predators released, only four hymenopteran species have been recovered, although the absence of other species may reflect inadequate sampling effort rather than their absence.

Biological control by introduced and native natural enemies may be influenced by cultural practices. For example, the use of herbicides, pesticides, and certain fertilizers can limit the abundance of natural enemies (e.g., Felland and Hull 1996, Walde 1996, Banken and Stark 1998). Agricultural practices such as the control of weeds, which act as refuges for aphid parasitoids, also may reduce natural enemy abundance and aphid

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biological control (Horn 1984). An assessment of the potential of natural enemies to control *D. noxia* could thus be complicated by the use of these chemicals. Therefore, examining the establishment of natural enemies and their effectiveness may be accomplished better in an area where crops are grown to meet organic certification requirements and where synthetic chemicals are not used.

Our primary goal in this study was to determine the identity, relative abundance, and population trends of the existing (indigenous and naturalized) predators and parasitoids of *D. noxia* in wheat, *Triticum aestivum* L., and barley, *Hordeum vulgare* L., grown in conditions meeting organic certification requirements. We also examined crested wheatgrass, *Agropyron cristatum* L., in the same area for aphids and their natural enemies. An additional goal was to evaluate the impact of these natural enemies on *D. noxia* populations in wheat using a cage-exclusion study. Our third goal was to determine whether released predators and parasitoids would become established in this cropping system.

Materials and Methods

Study Location. All study sites were located in 480 ha at Piedmont Farm, Larimer County, Colorado. At these sites, wheat, barley, and a variety of vegetables are grown in rotation under sprinkler irrigation and organic cropping practices. Some of this land also was devoted to perennial grass cover, dominated primarily by crested wheatgrass, which is also a host of *D. noxia*.

Survey of *D. noxia* and Natural Enemies. Aphids, aphid predators, and parasitoids were sampled at weekly intervals in fields of winter wheat (four 36–48-ha fields in May, June, and July of 1991–1994); winter barley fields (two 24–48-ha fields in May, June, and July of 1991 and 1992); and in one crested wheatgrass field (4.8-ha field in June, August, and September of 1991 and 1992). Sampling of *D. noxia* was carried out as described by Kauffman and Bell (1989). In each field, 100 tillers were cut randomly at 10 random locations (10 tillers per location). Each group of 10 tillers was placed in plastic self-sealing bags and transported to the laboratory in an ice-cooled insulated box. Using Berlese funnels, aphids in the collected tillers were extracted into 70% ethanol for 24 h. All tiller samples were processed in this manner. Identifying and counting of aphids were performed under a microscope. All density estimates are reported as the mean \pm SD with $n = 4$.

Aphid predators and parasitoids were sampled using a sweep net, pit fall traps, water pan traps, and inspection for parasitized aphids (Sunderland and Vickerman 1980, Chambers et al. 1982). Weekly sweep net samples consisted of 25 arcs (each 180°) taken along a diagonal line across each field, using a net 37.5 cm in diameter. Four yellow water pan traps (17.5 cm diameter) and four pitfall traps (8.7 cm diameter, 10 cm deep) were positioned at fixed, random locations in each field. A mixture of water, liquid detergent (surfactant), and benzoic acid (preservative) was used to

fill the traps to a depth of 5 cm. Traps were emptied weekly. The insect catches from sweep net and trap samples were preserved in 70% ethanol. Only adult stages were identified and counted. Fifty mummified *D. noxia* were collected weekly from the study sites and placed individually in gelatin capsules (no. 00). These capsules were placed at room temperature for at least 3 wk, and emerged adult parasitoids were identified.

Evaluating the Impact of Insect Natural Enemies on *D. noxia* in Wheat. An estimate of the effectiveness of the parasitoids in controlling *D. noxia* was obtained by determining the percentage of parasitism in aphid samples (Dean 1974). Twenty-five tillers of wheat with symptoms of *D. noxia* infestation were collected weekly from random locations in the field and taken to the laboratory in plastic self-sealing bags. Parasitized and nonparasitized *D. noxia* in the tillers were counted under the microscope.

To further ascertain the effects of natural enemies, experiments involving host exposure and natural enemy exclusion techniques were performed in two fields of wheat in 1992 and 1993. Wheat plants (cultivar TAM 107) were planted in plastic pots (17.5 cm diameter) at weekly intervals in the greenhouse. Fifteen seeds were sown per plot, and the pots were kept inside insect-proof cages to prevent the accidental infestation of aphids. Four weeks after germination, the plants were thinned to 10 plants or tillers per pot. In a separate room, tillers were then infested with *D. noxia* at a rate of ≈ 300 aphids per 10 plants. Last-instar aphids of similar size were obtained from pure *D. noxia* laboratory colonies maintained at $\approx 21^\circ\text{C}$ with a photoperiod of 14:10 (L:D) h. The infested plants were kept under cages for 1 wk to allow aphid establishment, and the pots were then transferred to the wheat fields. There, four randomly chosen pots were individually buried to the rim of the container inside exclusion cages. Another four pots were buried at random locations outside of the cages, exposing the aphids to natural enemies.

The exclusion cages were rectangular (1.5 by 0.5 by 0.5 m) and made from tubular metal frames with polyester screen covers (mesh size 0.4 by 0.5 mm, thread thickness 0.1 mm). One week after setting the potted plants in the field, the caged and uncaged pots were removed and replaced by new pots with infested plants. The plants from both treatments were cut, placed in self-sealing plastic bags, and transported to the laboratory in ice-cooled insulated boxes. Aphids were extracted from the plants into ethanol using Berlese funnels for 24 h, and the extracted aphids were counted and identified under a microscope. The entire procedure was repeated weekly until wheat senescence.

Recovery Surveys for Released Exotic Predators and Parasitoids. Releases of *D. noxia* parasitoids and predators were made in one field of wheat (36 ha) at Piedmont Farm by USDA-APHIS. The released species were the predators *Eupeodes nuda* (F.), *Hippodamia variegata* (Goeze), *Leucopis ninae* Tanasijtshuk, and *Propylea quatuordecimpunctata* (L.) (Table 1).

Table 1. Introduced predator and parasitoid species released in wheat in northern Colorado in 1992

Species	Origin	No. and stage	Date of release
Predators			
<i>Eupeodes nuda</i>	Iran, Kazakhstan	23,663 eggs 610 adults	25 and 29 April 7 and 14 May
<i>Hippodamia variegata</i>	Chile, Morocco	3,723 adults	29 April, 7 and 14 May
<i>Leucopis ninae</i>	China, Iran, Pakistan, Uzbekistan	13,334 eggs	24 and 29 April,
		17,946 adults	7 and 14 May
<i>Propylea quatuordecimpunctata</i>	Kirghizia, Kazakhstan	5,868 adults	29 April, 7 and 14 May
Parasitoids			
<i>Aphelinus asychis</i>	Chile, Kazakhstan, Pakistan	25,645 mummies 4,523 adults	24, 25, and 29 April 7 and 14 May
<i>Aphelinus varipes</i>	Chile, Kazakhstan, Uzbekistan, Caucassus	18,850 mummies 4,523 adults	25 and 29 April 7 and 14 May
<i>Aphidius matricariae</i>	Pakistan	2,620 mummies	24, 25, and 29 April
			7 and 14 May
<i>Diaeretiella rapae</i>	China, Iran, Pakistan	8,350 mummies	29 April and 7 and 14 May

Information is from E. J. Bernklau (personal communication).

The species of parasitoids released were *Aphelinus asychis* Walker, *Aphelinus varipes* Forester, *Aphelinus matricariae* Haliday, and *Diaeretiella rapae* (M'Intosh) (Table 1). The combined release totals of eggs and adults or mummies and adults were between 2,620 and 31,289 of these predator and parasitoid species. All releases took place in April and May of 1992 (Table 1). Field surveys were made from the time of release until the end of the summer in 1994, to examine for establishment of released natural enemies. These surveys were made at Piedmont Farm in fields of wheat, barley, volunteer wheat, grass areas, and vegetable fields including broccoli, *Brassica oleraceae* L. variety *italica* Plenck; cabbage, *B. oleraceae* L. variety *capitata* L.; and squash, *Cucurbita* spp. Surveys were conducted in wheat, barley, and grasses using sweep nets (25–50 sweeps per field per week, taken in a manner similar to that described above). In vegetables, visual observations were made (at least 2 h/wk), and some sweep net samples were taken as above. From all sites, large numbers of aphid mummies were collected. These mummies were collected by going to several random sites in the fields examined above, collecting vegetation, and taking it back for examination in the laboratory. The first 50 mummies observed were placed in geletin capsules or kept in cages in the laboratory. Emerged parasitoids were identified and counted.

Results and Discussion

Survey of *D. noxia* and Natural Enemies. *Diuraphis noxia* densities were greater than the total of all the other aphid species at all the study sites and in all the years except wheat in 1993. The mean density (\pm SD) of *D. noxia* in wheat was 356 ± 142 , 280 ± 113 , 22 ± 13 and 163 ± 67 per 100 tillers in the four successive years from 1991 to 1994. The very low *D. noxia* densities observed in 1993 were similar to the trend for other populations throughout the west in that year (Russian Wheat Aphid Task Force 1994). Barley had higher *D. noxia* populations than did wheat and

crested wheatgrass at 539 ± 399 and 478 ± 367 per 100 tillers in 1991 and 1992, respectively. Higher densities of *D. noxia* on barley than on wheat have been noted elsewhere (Hughes 1988). Mean densities in crested wheatgrass were 27 ± 17 and 20 ± 16 *D. noxia* per 100 tillers in the same years. In the 2 yr of the survey when *D. noxia* was sampled, crested wheatgrass was nearly senescent by the end of August or early September and was not suitable for supporting aphid populations. Racette (1993) also found in this area that crested wheat grass was probably not an important alternative host plant of *D. noxia*.

Other aphid species that were found to co-exist with *D. noxia* included the greenbug, *Schizaphis graminum* (Rondani); the birdcherry oat aphid, *Rhopalosiphum padi* (L.); the rice root aphid, *R. rufiabdominalis* (Sasaki); the corn leaf aphid, *R. maidis* (Fitch); and the English grain aphid, *Sitobion avenae* (F).

The predators that were encountered in all habitats during this study are listed in Table 2. These predators included six spider species, 15 carabids, 12 coccinellids, five syrphids, two nabids, and two chrysopids. The predominant species in each predator family are listed in Table 3. Although the relative abundance of predators and parasitoids differed among years and host plants, the coccinellids and nabids were most abundant in all habitats (Fig. 1). The relatively low abundance of natural enemies observed in crested wheatgrass may have reflected the low abundance of *D. noxia*. However, the high abundance of aphids in barley relative to wheat did not appear to result in a higher abundance of predators in barley (Fig. 1).

Hippodamia convergens made up over half the coccinellids sampled. This species has been found to control aphids in other crops (e.g., Dreistadt and Flint 1996) (Table 2). The other major species of coccinellids we observed was *Coccinella septempunctata*. In southern France, this species was associated with effective biological control of *D. noxia* (Hopper et al. 1995). Syrphids were the other major predators of *D. noxia* in southern France. In Colorado, Wraight et al.

Table 2. Potential predators of *D. noxia* collected at Piedmont Farm, Larimer Co., 1991–1994

Order	Family	Species	
Araneae	Lycosidae	<i>Pardosa sternalis</i> (Thorell)	
		<i>Paradosa</i> spp.	
	Tetragnathidae	<i>Schizocosa avida</i> (Wachenaer)	
		<i>Tetragnatha laboriosa</i> Hentz	
		Thomisidae	
Coleoptera	Carabidae	<i>Misumenaops asperatus</i> (Hentz)	
		Thomisidae spp.	
		<i>Agonum placida</i> (Say)	
		<i>Agonum subsericeus</i> (LeConte)	
		<i>Amara carinatus</i> (LeConte)	
		<i>Amara coelebs</i> Hayward	
		<i>Amara farcta</i> (LeConte)	
		<i>Amara littoralis</i> Mannerheim	
		<i>Amara quenseli</i> (Schöenherr)	
		<i>Anisodactylus harrisii</i> LeConte	
	<i>Bemidion nitidus</i> (Kirby)		
	<i>Harpalus amputatus</i> Say		
	<i>Harpalus pennsylvanicus</i> (De Geer)		
	<i>Loricera pilicornis pilicornis</i> (F.)		
	<i>Poecilus lucublandus</i> (Say)		
	<i>Poecilus scitulus</i> LeConte		
	<i>Selenophorus planipennis</i> LeConte		
	Coleoptera	Coccinellidae	<i>Brachyacantha</i> spp.
			<i>Coccinella septempunctata</i> L.
			<i>Coccinella transversoguttata richardsoni</i> W.J. Brown
<i>Coleomegilla maculata</i> (De Geer)			
<i>Exochomus aethiops</i> (Bland)			
<i>Hippodamia convergens</i> Guérin			
<i>Hippodamia parenthesis</i> (Say)			
<i>Hippodamia sinuata crotchii</i> Casey			
<i>Hyperaspis quadricittata</i> LeConte			
<i>Paranaemia vittigera</i> (Mannerheim)			
Diptera	Syrphidae	<i>Scymnus brullei</i> Mulsant	
		<i>Scymnus postpictus</i> Casey	
		<i>Allograpta obliqua</i> (Say)	
		<i>Eupeodes volucris</i> Osten Sacken	
		<i>Helophilus latifrons</i> Loew	
Hemiptera	Nabidae	<i>Mesogramma marginata</i> Say	
		<i>Syrphus opinator</i> Osten Sacken	
		<i>Nabis alternatus</i> Parshley	
Neuroptera	Chrysopidae	<i>Nabis americanoferus</i> Carayon	
		<i>Chrysoperla plorabunda</i> Fitch	
		<i>Eremochrysa sabulosa</i> (Banks)	

(1993) found chaemaemyiids in the genus *Leucopis* and in the family Syrphidae to be the only predatory group. They noted these dipteran predators to occur only in low densities, and suggested they probably had little impact on aphid populations. We identified five syrphid species from the adult stages collected (Table 2). Approximately two-thirds of the syrphids were *Mesogramma marginata*. We observed low numbers of adult syrphids and chaemaemyiids (Fig. 1), though the number of adults sampled may not be a good indicator of larval densities. Some syrphid species have the ability to control aphid populations (e.g., Tenhumberg 1995).

Similarly, Messina et al. (1997) showed the chrysopid species *C. plorabunda* to be a voracious predator of *D. noxia* in laboratory experiments. Although this predator was found in our study, it was of low in abundance (Fig. 1).

A high relative abundance of nabid predators was observed in all years and crops, with the species *Nabis alternatus* making up two-thirds of the individuals sampled (Fig. 1; Table 2). There is little known about the

Table 3. Numbers and percentages (of each group) of predominant predatory species from combined samples from wheat, barley and crested wheat grass, Piedmont Farm, Larimer Co., during 1991–1994

Group ^a	Species	Number	Percentage
Araneae (319)	<i>T. laboriosa</i>	107	33.5
	Thomisidae spp.	93	29.2
	Others	119	37.3
Carabidae (690)	<i>B. nitidus</i>	260	37.7
	<i>A. placida</i>	147	21.3
	<i>P. lucublanda</i>	95	13.8
Coccinellidae (1,725)	Others	188	27.3
	<i>H. convergens</i>	911	52.
	<i>C. septempunctata</i>	542	31.4
Syrphidae (243)	Others	273	15.8
	<i>M. marginata</i>	159	65.4
	<i>A. obliqua</i> ^a	65	26.8
Nabidae (1,310)	Others	19	7.8
	<i>N. alternatus</i>	878	67
	<i>N. americanoferus</i>	432	33
Chrysopidae (84)	<i>C. plorabunda</i>	78	92.9
	Others	6	7.1

^aNumbers in brackets indicate total number observed in each family.

effects of nabids on aphid populations, but they have been regarded as effective in the control of aphids in other crops (Carroll and Hoyt 1984).

Carabid beetles also were abundant in most years in wheat and barley (Fig. 1). The predominant species we found, *Bemidion nitidus* (Kirby), has been observed in other wheat fields and is probably a generalist predatory species (Frank 1971, Doane 1981). Carabid beetles alone probably play a minor role in aphid population regulation (Boiteau 1986). However, a recent study has shown the presence of some carabids to have multiplicative effects on aphid mortality in multiple predator systems (Losey and Denno 1998). When predators such as chrysopids attack aphids, aphids will fall off the plant stem often as an escape behavior. Once on the ground they were more susceptible to carabid predation, and the observed mortality of aphids was found to be greater than the sum of the two predators alone (Losey and Denno 1998). Spiders may influence aphid mortality in a similar manner. However, although some spiders can significantly reduce aphid population growth rates (Mansour and Heimbach 1993), they also can negatively effect parasitoid searching behavior and abundance (Voelkl and Kraus 1996).

Four hymenopteran parasitoids were found to be associated with *D. noxia*. The only primary parasitoid we sampled was *Diaeretiella rapae*, which made up between 67.6 and 77.2% of all parasitoids. The three other parasitoids found were *Asaphes* sp., combining *A. suspensus* Nees and *A. californicus* (Girault), *Alloxysta megourae* (Ashmead), and *Dendrocerus* sp., all of which are obligate hyperparasitoids (Sullivan 1988). The most abundant hyperparasitoids were the *Asaphes* sp., whereas others such as *Dendrocerus* sp. were much rarer and were not found in 1994 (Fig. 2). Of these parasitoids, *A. megourae* is endoparasitic and the others are ectoparasitoids (Sullivan 1988).

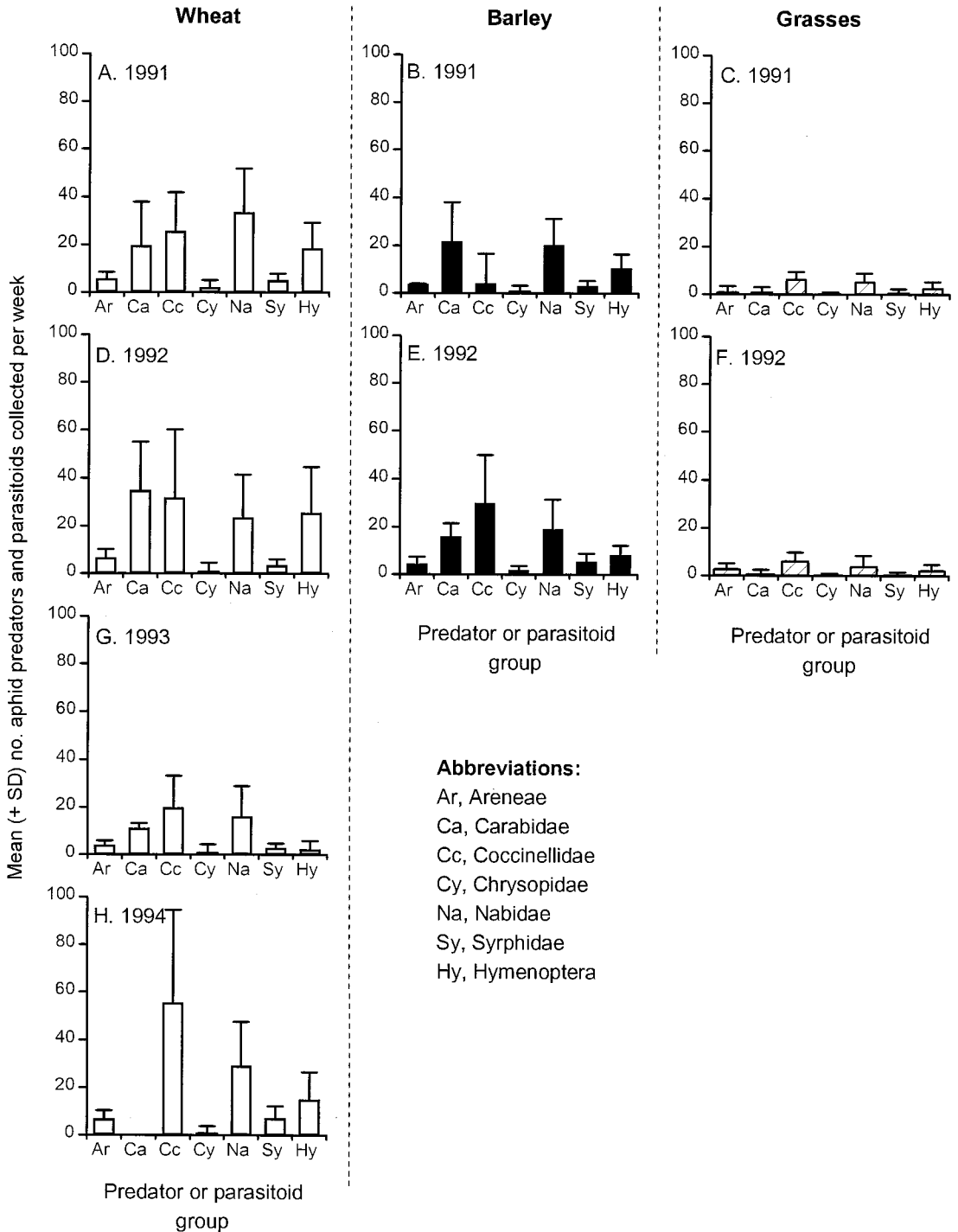


Fig. 1. Mean \pm SD number of aphid predators and parasitoids ($n = 4$) collected per week per 25 sweep net samples from the three *D. noxia* habitats sampled (wheat: A, D, G, H; barley: B, E; grasses: C, F) for 1991 (A, B, C), 1992 (D, E, F), 1993 (G), and 1994 (H). For Carabidae, the means represent the mean number caught per four pitfall traps per week.

Feng et al. (1992) found six primary parasitoids attacking *D. noxia*, but considered only *D. rapae* and *Aphelinus varipes* (Foster) to be relevant for biological

control. These two species have been shown to be important for *D. noxia* biological control in Europe (Hopper et al. 1995) and South Africa (Aalbersberg et

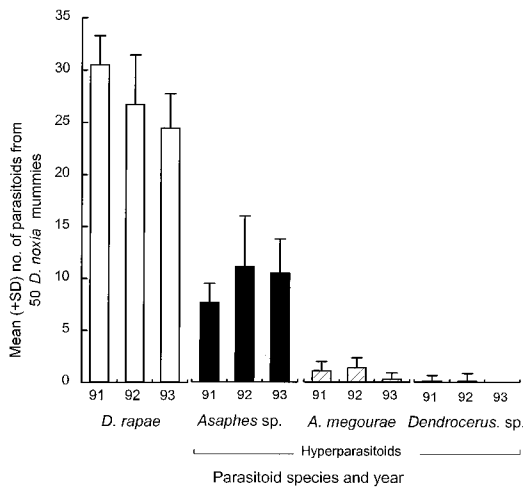


Fig. 2. Parasitoid guild structure of *D. noxia* in wheat. Data are from 50 *D. noxia* mummies collected at weekly intervals for 5–8 wk. Error bars are ± 1 SD, $n = 4$.

al. 1988). Low numbers of *A. varipes* were observed in Colorado by Wraight et al. (1993), but were not found in our study.

The high number of hyperparasitoids per primary parasitoid is of concern. The average hyperparasitism rate over our entire study was 29% of all mummified aphids. Similarly, Wraight et al. (1993) observed a hyperparasitism rate of 37% in their Colorado study, with a similar range of hyperparasitoid species. A much lower *D. noxia* hyperparasitism rate of 8% was noted in irrigated wheat fields in Idaho (Feng et al. 1992). It seems likely that the high hyperparasitism rate in the fields that we sampled influenced the abundance and efficacy of *D. rapae* control of *D. noxia* populations.

Evaluating the Impact of Insect Natural Enemies on *D. noxia* in Wheat. Parasitism rates ranged between 0.6 and 5.4% (Fig. 3). In 1991, 1992, and 1994, the mean parasitism rates in the *D. noxia* populations were 2.1 ± 1.7 , 2.5 ± 1.1 , and $1.7 \pm 0.9\%$. The only primary parasitoid observed was *D. rapae*, but the four hyperparasitoid taxa described previously also were sampled.

Low rates of parasitism appear typical for this region. Parasitism rates of $<0.5\%$ (Meyer and Peairs 1989) and $<5\%$ (Wraight et al. 1993) have been noted previously in northern Colorado. In southwestern Idaho, the percentage of *D. noxia* parasitism was generally $<5\%$ except when *D. noxia* populations were declining (Feng et al. 1992). All of these studies in North America concluded that the role of parasitoids in the biological control of *D. noxia* was limited. The same conclusion must be reached from the parasitism rate in this study. Studies in Europe have observed much higher parasitism rates ranging up to 24% (Hopper et al. 1995), and these authors considered this rate of parasitism by species including *D. rapae*, *A. varipes*, and *A. asychis* to limit *D. noxia* populations.

Large differences were noted between treatments in the cage exclusion experiment (Fig. 4). Densities of

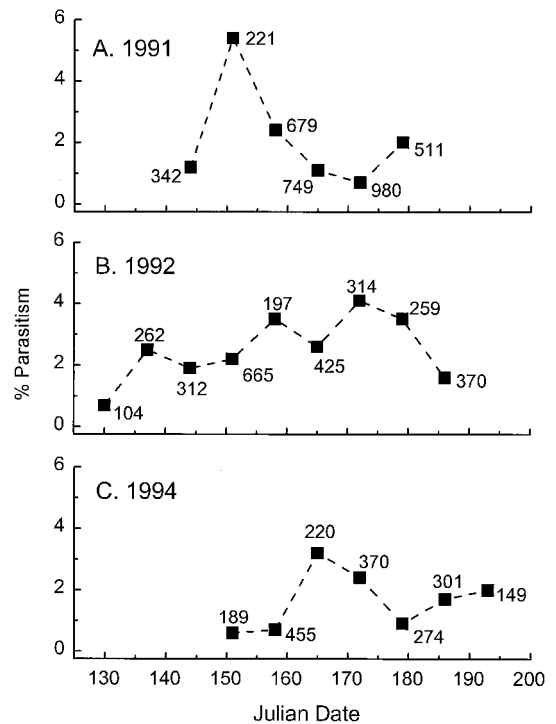


Fig. 3. Parasitism rates in *D. noxia* populations in wheat during 1991 (A), 1992 (B), and 1994 (C). Number at each data point represents the number of *D. noxia* in the sample collected from 25 damaged tillers.

D. noxia inside the cages in 1992 ranged between $1,196 \pm 209$ and $2,187 \pm 405$ aphids per 10 tillers. These densities were between 3.7 and 11.2 times higher than on wheat plants outside of cages (Fig. 4A). Similar results were observed in 1993, when densities of *D. noxia* within cages were between 2.6 and 9.5 times higher than on plants outside of the cages (Fig. 4B). Thus, the insect natural enemies in the study area did appear to reduce *D. noxia* populations. However, the reduction in the aphid populations did not prevent the

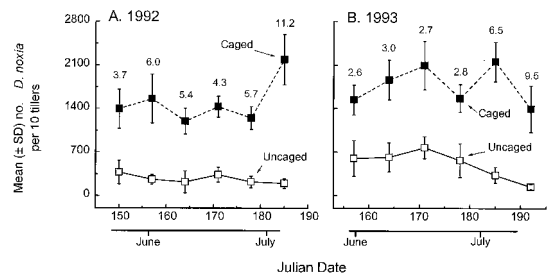


Fig. 4. Evaluation of the impact of insect natural enemies on *D. noxia* in 1992 (A) and 1993 (B), using caged populations which excluded natural enemies and uncaged populations. Every sample date (week), a new set of infested plants was used. Assessment samples comprised 10 tillers. Numbers above the data points represent the ratio of *D. noxia* in cages compared with those outside cages. Error bars are ± 1 SD, $n = 4$.

pest from reaching its economic threshold level (>20% damaged and infested tillers after the flowering stage of the plants).

Another cage exclusion experiment in Colorado showed *D. noxia* populations to be 12 times higher in cages than on uncaged wheat (Hopper et al. 1994). Comparatively, in southern France, caged *D. noxia* were 10–18 times those on uncaged plants (Hopper et al. 1995). These studies used an experimental design examining trophic interactions for a number of weeks, whereas in ours the duration for each replicate was a week, so comparisons between studies are difficult. Complicating the matter further, recent work has indicated that there are problems in assessing the impact of natural enemies on *D. noxia* using cage exclusion methods (Nechols and Harvey 1998). However, natural enemies did appear to be controlling *D. noxia* to some extent at Piedmont farm. The ratio of the number of caged/uncaged aphids did not vary greatly within the duration of the experiment in each year, but the density of aphids did appear to be declining on uncaged plants with replicates later in the experiment (Fig. 4). This result is likely to be caused by natural enemies and aphid emigration from uncaged plants.

Recovery of Released Exotic Predators and Parasitoids. For releases of natural enemies made on 24 and 25 April 1992, densities of *D. noxia* were ≈ 26 per 100 tillers, and the number of infested plants did not exceed 6%. Other releases were made on 29 April and 7 and 14 May. Populations of 132, 184, and 260 *D. noxia* per 100 tillers were recorded on 3, 10, and 17 May, and the number of infested plants reached 20% on 17 May.

Of the four predator species that were released, only two species were recovered later. A single specimen of *P. quatuordecimpunctata* was observed at the release site in July 1992 on ripe wheat. No *H. variegata* were caught after release. Since this time, both these coccinellid species have become established in North America (Wheeler 1993, Michels et al. 1997), and laboratory experiments indicate that they have potential for the biological control of *D. Noxia* (Randolph et al. 1994, Messina et al. 1997). Eight specimens of *L. ninae* were collected from cabbage (*B. oleraceae* variety *capitata*) which were infested with cabbage aphid, *Brevicoryne brassicae* L., in August 1993 and from wheat with *D. noxia* in June and July 1994. Some of the flies were collected as larvae and were reared to the adult stage in the laboratory. There is a possibility that these *L. ninae* may have originated from releases of this species that were made in northern Colorado in June 1993 (Hopper et al. 1994). This species also appears to have become established elsewhere in North America and may be useful for *D. noxia* biological control (Gaimari and Turner 1997).

Of the four species of parasitoids that were released, *A. matricariae* and *A. varipes* were not recovered in survey studies conducted from the time of release until the end of the 1994 summer. Elliott et al. (1995) released *A. asychis*, *A. varipes*, *A. matricariae*, and *D. rapae* in Colorado in 1994. They did not find any establishment by *A. matricariae* and *A. varipes* but did report finding establishment of *A. asychis* and *D. rapae*.

In mid-October 1992, we observed *A. asychis* in a *D. noxia* population on volunteer wheat plants. This parasitoid occurred in a very localized patch and in great abundance, but only a few of the black mummies were taken for identification of the wasp and no density estimates were obtained. Unfortunately, the volunteer wheat was grazed and plowed before additional specimens could be recovered. This was the only instance in which *A. asychis* was sampled at our study site. This species has been reported to be established in Texas (Michels and Whitaker-Deerberg 1993), and we cannot exclude the possibility that the *A. asychis* in our plots were from releases in other areas.

Populations of *D. rapae* were present before the release, thus it was not possible to distinguish between the indigenous populations and released insects by morphological examination. However, genetic analysis using RAPD-polymerase chain reaction techniques indicated that genes from released *D. rapae* individuals were incorporated into the local *D. rapae* population (Mohamed 1995).

In a review of release experiments, Beirne (1975) found evidence that the number of released individuals was a major factor in the success or failure of each release, as well as a lack of suitability for the environmental conditions. From our releases and those in the surrounding area, it appears that *L. ninae*, *A. Asychis*, *D. Rapae*, and possibly *P. quatuordecimpunctata* are able to withstand the environmental conditions in Colorado. Larger releases of these species may result in sufficient establishment to help control *D. noxia*. Larger releases of the other species examined here may also help determine if they would establish in Colorado.

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