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Aerial Application of the Pyrethroid Deltamethrin for Grasshopper (Orthoptera: Acrididae) Control

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ABSTRACT Field trials were conducted to determine deposition of deltamethrin applied to pastures by aircraft, and resulting effectiveness in controlling grasshoppers. Residue analysis indicated that 73% of 7.2 g (AI)/ha deltamethrin applied was deposited on vegetation and litter. Sampling via sweep net indicated considerably higher rates of control than did estimates of density based on trap catches 1 day after application, although both methods indicated a 65% reduction in grasshopper density after 4 days. The bias in sweep-net samples is due to reduced activity just after spraying. Contrary to earlier reports, efficacy of deltamethrin was unrelated to age distribution, species composition, or grasshopper movement. Estimates of mortality based on independent toxicological experiments in the laboratory agreed with field results, given the deposition measured at time of spraying.

GRASSHOPPERS ARE THE most serious pests of grassland in western North America. Economic injury is effected through removal of forage that would otherwise be available to grazing livestock. The resulting loss is a function of plant growth, grasshopper species composition, and weather, but in general one grasshopper per square meter can be expected to cause a forage loss of at least 13 kg/ha per month (Hewitt and Onsager 1982, 1983).

Recently, pyrethroids have been licensed in Canada for control of grasshoppers on a variety of crops. Deltamethrin is one that has generated interest because of its high toxicity to arthropods and the consequent small quantities required for insect control (Lhoste 1982). Deltamethrin is presently registered for application via ground-sprayer to forage and cereal crops in western Canada at rates of 5.0–7.5 g (AI)/ha for grasshopper control. However, application of deltamethrin to grassland would necessitate aerial spraying owing to the large areas and rough terrain requiring treatment. Generally, results of ground application trials are poor predictors of the effectiveness of aerial applications. Blickenstaff and Skoog (1974) found poor agreement between results of ground and aerial application of insecticides to rangeland and pasture for grasshopper control. In the case of deltamethrin, aerial application may present serious problems of achieving adequate deposition, coverage, and crop canopy penetration with the small amounts of pesticide used. These problems may be especially acute in the case of insecticides such as deltamethrin that act mainly by contact and not by ingestion. In addition, pyrethroids, including deltamethrin, have been shown to result in initial knockdown and subsequent recovery of grasshoppers and locusts under laboratory conditions (MacCuaig 1980, Ewen et al. 1984).

Because of the potential of this new pyrethroid and the general lack of information regarding its effects on grasshoppers, we examined its potential for aerial application in a study combining toxicological experiments, insecticide residue analysis, and determination of field efficacy as a function of grasshopper species composition and age distribution. We paid particular attention to the methods of population sampling because of the possibility of recovery of grasshoppers that received sublethal quantities of deltamethrin.

Materials and Methods

Deltamethrin, formulated as Decis 5.0 emulsifiable concentrate (EC) (Hoechst Canada), was tested as a grasshopper insecticide applied by aircraft to crested wheatgrass, *Agropyron cristatum* (L.) Gaertn., pasture.

Test Area. The field trial was carried out in June and July 1983 in southern Canada on pastures near Claresholm, Alberta (NW sec. 21 and SW sec. 22, T13, R24, W of 4th Meridian). The two pastures (blocks) used in the experiment were relatively uniform stands of crested wheatgrass (standing crop dry weight = 173 g/m^2, SE = 11.6 g/m^2) with interspersed alfalfa (7.8 g/m^2, SE = 2.9 g/m^2). The pastures were about 1 km apart in an area infested with 10–20 grasshoppers/m^2.

Experimental Design and Spray Parameters. Each block was divided into a treated and an untreated area. The treated plots were ca. 400 by 500 m (20 ha) and the adjacent untreated check plots were ca. 100 by 500 m (5 ha). Deltamethrin was applied to the treated plots at a rate of 7.2 g (AI)/ha in 8.9 liters of water/ha (0.95 U.S. gal/ha) at a pressure of 138 kPa (20 psi). Both blocks

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were treated the same day (0900–0950 hours, 23 June 1983) using an aircraft (Grumman Ag Cat 164) equipped with nozzles (T-Jet 4664) (no. 5 tips, no. 25 cores) tilted 157° to the rear. The airplane maintained a ground speed of 145 km/ha at a height of 3 m during the application. From the spray parameters, the volume median diameter of drops was estimated to be about 250 μm. At the time of spraying, wind speed and direction were 13–18 km/h from NNW. Relative humidity at 2 m was measured at 71%, and temperatures at 0.01, 0.1, 1.0, and 3.0 m were 18.1, 18.2, 15.5, and 14.5°C, respectively (slight lapse condition).

Insecticide Deposition. An 8-by-8 grid (70 m between grid lines) was laid out on a sampling area (210 by 210 m) within each treated plot. Residue samples from 16 sites, chosen in a stratified random design, were combined to form one composite sample per plot. Two such composite samples were collected from each plot. At each sampling location, the forage and litter from a quadrat (25 by 25 cm) were collected separately. Sampling commenced 3 h after spraying and was completed within 3 h. Samples were placed on dry ice as they were collected and were then stored at −40°C. Before analysis, any soil collected with the litter samples was removed by sieving through a 20-mesh screen. The concentration of deltamethrin on the forage and litter samples was determined using a previously reported residue analysis procedure (Hill et al. 1982). Briefly, the samples were chopped, extracted in a blender (Waring) with acetone/hexane (1:1), cleaned up by liquid–liquid partitioning and adsorption column chromatography, and the deltamethrin was determined by ^{63}Ni-electron capture gas chromatography.

The average density (g/m^2) of forage was estimated from clipped vegetation from 11 quadrats (50 by 50 cm) per plot located at random intervals along transects. The average litter density was estimated from the composite samples collected for residue analysis.

To confirm the application rate, samples were taken from the aircraft tank and analyzed for deltamethrin content.

Population Assessment. Grasshopper numbers were sampled from a 4-ha area within each of the treated and untreated plots in each block, 1 day before application and 1, 4, 8, and 15 days after. There was a minimum of 80 m of deltamethrin-treated border surrounding the sampled areas within each of the sprayed plots. Density estimates were made by counting the number of grasshoppers in each of 25 samples (0.25 m^2) randomly selected within strata in each plot (i.e., 100 0.25-m^2 counts per sampling date). The grasshoppers in these samples were trapped by tosses of a bottomless cage modified from Smith and Stewart (1946). In addition, on each sampling date, two samples of 100 sweeps (180°, 38-cm sweep net through the vegetation at a height of 5–15 cm) were collected from each plot. All sweep-net samples were taken between 1000 and 1500 hours. The grasshoppers from the sweep-net samples were stored at −20°C for later counting and identification of species, sex, and instar with a dissecting microscope. Species identifications were based on reference to taxonomic keys (Criddle 1926, Handford 1946, Brooks 1958), and on comparison with specimens in the insect collection of the Lethbridge Research Station.

Toxicity of Deltamethrin to Grasshoppers. The effects of dose and water volume on mortality were established independently of the field trials to provide a basis for interpretation of field efficacy.

Experiment 1. Concentration regressions were estimated by spraying groups of 100 second-instar nymphs of the nondiapause strain of *Melanoplus sanguinipes* (F.) (Pickford and Randell 1969) on filter paper with the equivalent concentrations of 1.75, 3.50, 7.00, 14.0, and 28.0 g (AI)/ha, at each of 16, 21, or 27°C. The nymphs were anesthesized with CO_2 just before treatment. Prior experiments confirmed that the response to pyrethroids is unaffected by CO_2 anesthesia just before spraying (C.F.H., unpublished data). The insecticide was applied by a Track Sprayer (Thompson et al. 1969) equipped with nozzles (T-Jet 650067) at a volume equivalent to 33 liters/ha. Mortality was assessed 3 days after spraying. The experiment was replicated three times (i.e., a total of 4,500 nymphs was treated).

Experiment 2. The effects of water volume on mortality were examined in a concentration/mortality experiment in which groups of 100 second-instar *M. sanguinipes* nymphs were sprayed with 1.64, 3.28, 6.56, 13.1, or 26.3 g (AI)/ha in 14, 28, or 56 liters/ha water-volume equivalent. Nozzles (T-Jet TX1) were used on the Track Sprayer and the water volume was varied by diluting the spray solution and making extra passes with the sprayer. This technique was used to avoid changing spray droplet size. The water-volume experiment was repeated with a lower range of insecticide concentrations: 0.41, 0.83, 1.64, 3.28, and 6.56 g (AI)/ha, in 14, 28, or 56 liters/ha water volume equivalent, providing replication of the experiment at 1.64, 3.28, and 6.56 g (AI)/ha.

Statistical Analyses. Hypotheses involving insecticide concentrations and grasshopper densities were tested using linear models available on the Statistical Analysis System (SAS Institute 1982). Hypotheses requiring discrete multivariate analysis (e.g., effects of treatments on sex ratios and species composition) were analyzed with BMDP4F log-linear models for multi-way frequency tables (Dixon 1983). Probit analyses were done with Agriculture Canada Program No. S103.

Adjusted percent mortality (and SE) in the sprayed plots was calculated from the modified Abbott's formula (modified by Henderson and Tilton [1955] from Abbott [1925]) in which the proportion of the insect population reduced by the insecticide treatment is:

$$1 - (T_2C_1)/(T_1C_2),$$

where T_1, C_1, T_2, C_2 are the numbers of living insects in the treated and check groups before (1) and after (2) application of the treatment. Assuming approximately Poisson samples (justified by the results of Onsager [1977]) and uniformity of plots, the standard error is given by

$$\alpha \sqrt{1/T_1 + 1/C_1 + 1/T_2 + 1/C_2}$$

where $\alpha = (T_1C_2)/(T_2C_1)$, the cross-product ratio (Bishop et al. 1980). Estimates of the common mortality over blocks were computed using the Mantel–Haenszel formula (Breslow and Liang 1982) for combining cross-product ratios. Associated tests of homogeneity of these ratios were carried out to test for differences between blocks and between sampling methods.

Results and Discussion

Insecticide Deposition. Residue analysis indicated that 73% of the applied deltamethrin was deposited on the forage and litter (Table 1). There was no significant difference ($P > 0.10$) in the mean deposition between blocks. These estimates of deposition are not corrected for losses during residue sampling and analysis (5–10%), and do not include the amount of deltamethrin deposited on bare soil. We estimated that 5% of the sampled area was bare soil.

Deltamethrin residues on vegetation from the control plots were determined to be 1.3 and 1.1% of the applied deltamethrin, after correction by background levels of 3.4 µg (AI)/m². These low values indicate that no appreciable insecticide drift was deposited on the control plots.

The amount of deltamethrin deposited in this aerially applied experiment is within the 5.0–7.5 g (AI)/ha recommended to control grasshoppers using ground equipment (Hoechst Canada 1983). Also, the amount of applied deltamethrin reaching the litter (20%, Table 1) indicated that there was good penetration of the forage canopy.

Population Responses to Deltamethrin. The species composition and age distribution of the grasshoppers collected in the pretreatment sweep-net samples are shown in Table 2. Deltamethrin is recommended for instars 1–4, when applied using ground equipment (Hoechst Canada 1983). Of the grasshoppers collected the day before spraying, 81.5% were in these age classes, or 96.8% if *Aeropedellus clavatus* (Thomas) is excluded (n = 1,262 and 1,032, respectively). *A. clavatus* is a rangeland species that hatches as early as April and attains maturity in early June. Determination of optimum spray timing is usually made on the basis of the age structure of *Melanoplus* spp., composing 77.2% of the community represented by our samples.

The effect of the insecticide application on changes in grasshopper numbers was determined by the analysis of variance of Smith-trap counts per 0.25 m² as a split-plot over collection date. The variable analyzed was response = $\log_e$(posttreatment count) − $\log_e$(pretreatment count). Grasshopper densities, as evidenced by the Smith-trap

Table 1. Deltamethrin deposition estimated from residues on forage and litter

Block	Composite sample	Substrate	Residue[a] (ppm)	Dry wt[b] (g/m²)	Total residue (µg/m²)	Deposition[c] (% of applied)
1	1	Forage	2.19	180.0	394	54.5
	1	Litter	0.78	205.5	161	22.3
					Total	76.8
	2	Forage	2.44	180.0	440	60.9
	2	Litter	0.56	250.8	140	19.4
					Total	80.3
			Block 1 mean deposition			78.6
2	1	Forage	1.98	184.8	367	50.8
	1	Litter	0.49	307.6	149	20.7
					Total	71.5
	2	Forage	1.74	184.8	321	44.5
	2	Litter	0.44	319.6	142	19.6
					Total	64.1
			Block 2 mean deposition			67.8

[a] µg residue/g dry wt of substrate. Moisture contents were forage, 32–37%; litter, 5–6%.

[b] Forage dry wt estimated from 11 samples (50 by 50 cm) per block; litter dry wt estimated from 16 samples (25 by 25 cm) per composite.

[c] Deltamethrin applied was 722 µg (AI)/m².

Table 2. Age and species distribution of grasshoppers the day before spraying[a]

	Instar					Adult	n	Species (%)
	1	2	3	4	5			
M. infantilis Scudder	11.9	11.1	46.2	29.9	0.9	0	561	44.5
A. clavatus	0	0	2.2	10.4	15.7	71.7	230	18.2
M. packardii Scudder	27.0	18.5	19.8	28.8	5.9	0	222	17.6
M. sanguinipes	43.6	11.2	24.6	16.2	4.5	0	179	14.2
Camnula pellucida (Scudder)	3.8	5.8	28.8	51.9	9.6	0	52	1.4
Other[b]	33.3	11.1	16.7	27.8	11.1	0	18	4.1
All species	16.9	10.1	29.3	25.1	5.5	13.1	1,262	100.0
Excluding *A. clavatus*	20.6	12.4	35.4	28.4	3.2	0	1,032	81.8

[a] Percentages in each class are based on the total counts from sweep samples (four plots × two samples × 100 sweeps).

[b] Includes *Ageneotettix deorum* (Scudder), *Arphia conspersa* Scudder, *M. bivittatus* and *M. dawsoni* (Scudder).

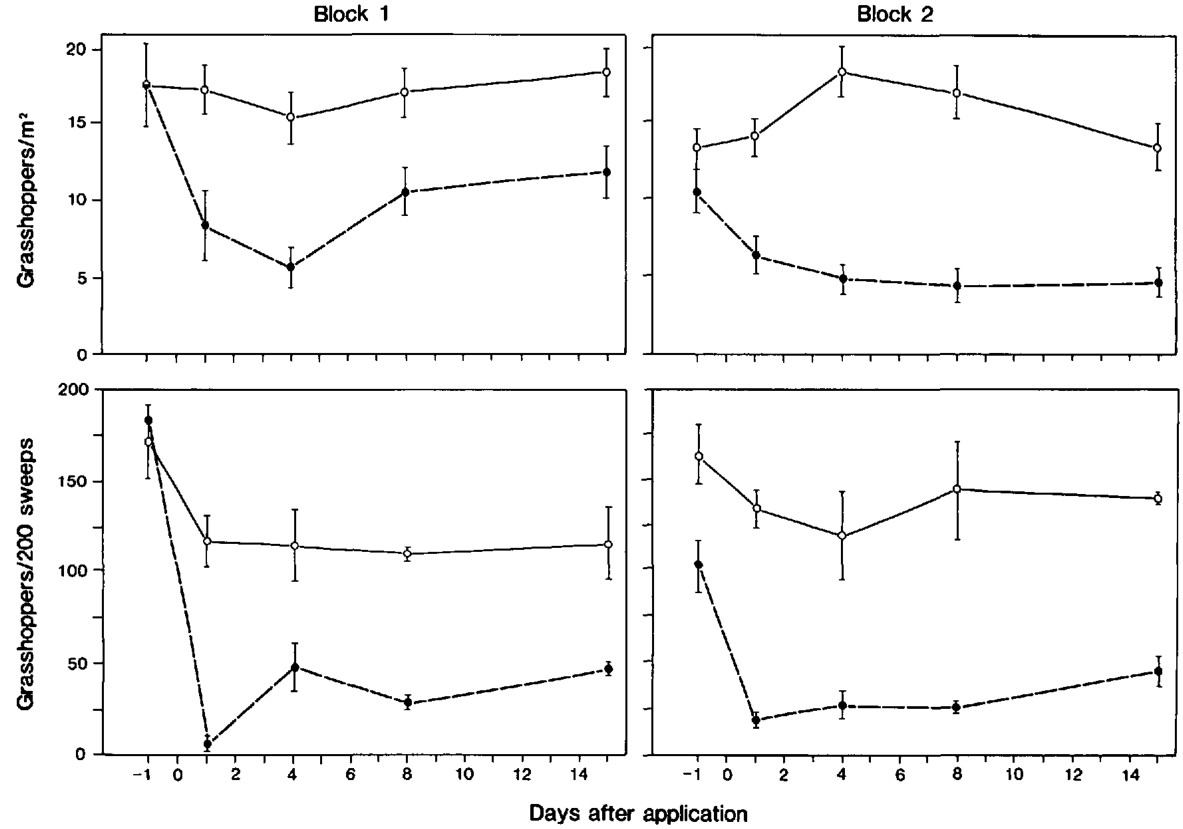

Fig. 1. Numbers of grasshoppers before and after application of the deltamethrin on day 0. Means (±SE) are shown for the treated (●) and untreated (○) plots. Estimates of the numbers of grasshoppers per m² were based on Smith-trap sampling.

counts of 25 randomly chosen 0.25-m² quadrats per plot, differed significantly ($P = 0.012$) between the sprayed and unsprayed areas during the 4 days following insecticide application. Over the 8 days following application, the treatment effect was maintained but was not as strong ($P = 0.073$). Blocks differed slightly over the first 4 days ($P = 0.037$), but the effect did not last over the 8-day period ($P = 0.32$).

The numbers of grasshoppers of all species collected in the sweep-net samples (2 × 100 sweeps per plot per sampling date) and the densities calculated from Smith-trap samples are shown in Fig. 1. Sweep-net samples are often considered to be relative measures of population size that can be used for comparative purposes. However, interpretation of results of grasshopper insecticide trials should not be based entirely on sweep-net counts because of the effects of insect behavior on efficiency of sweep sampling. Efficiency may vary with the treatment if the insecticide affects the activity and vertical position of survivors on vegetation. To avoid this bias, we have based our analysis of gross population change on direct density estimates from the Smith-trap capture data. In both blocks, the density derived from Smith-trap captures dropped rapidly during the day following spraying, and continued to decline at a lower rate (Fig. 1, grasshoppers per m²). The sweep-net samples showed more dramatic declines on the first sampling date after spraying, but exhibited partial recovery of the population by the fourth day after insecticide application. Given the large size of the plots, the 80-m treated borders, the immature stage of most of the grasshoppers and the absence of such an effect in the density estimates based on Smith traps, it is unlikely that this apparent recovery was due to immigration into the sprayed areas. Considerable immigration into the plots from surrounding areas was not evident until after 15 days, at which time counts and variances increased. Although not included here, counts were made up to 27 days after application of the insecticide. The apparent recovery on day 4, particularly in block 1 (Fig. 1), was probably due to the nature of pyrethroid toxicity: those insects that received a sublethal dose were either repelled or temporarily incapacitated. Consequently, they were not available for capture in a sweep net until they recovered and resumed activity in the crop. In the case of grasshoppers, we suspect that a behavioral reaction in response to the deltamethrin drives them into the litter and the bases of the crested wheatgrass. Extensive searches for dead, dying, or living grass-

Table 3. Percent mortality (SE) adjusted via the modified Abbott's formula[a]

Site	Sampling method	Days after application			
		1	4	8	15
Block 1	Sweep nets	96 (1.4)	64 (5.1)	79 (3.6)	66 (5.0)
	Smith traps	52 (10)	64 (8.7)	39 (13)	36 (13)
	Test of equality[b]	$P < 0.0001$	$P = 0.95$	$P = 0.006$	$P = 0.10$
Block 2	Sweep nets	77 (4.4)	65 (6.3)	73 (4.9)	50 (7.6)
	Smith traps	43 (14)	67 (8.6)	68 (8.7)	58 (12)
	Test of equality[b]	$P = 0.036$	$P = 0.88$	$P = 0.72$	$P = 0.72$
Common Abbott's (combined blocks):	Sweep nets	88.0	64.5	75.9	59.1
	Smith traps	48.2	65.2	52.0	44.7

[a] The common Abbot's adjusted mortality is calculated as: $1 - \frac{\Sigma T_{2i} C_{1i}/N}{\Sigma T_{1i} C_{2i}/N}$ $i = 1, Z$ in this case.

[b] P values of χ^2 statistics calculated from the Mantel–Haenszel test of the hypothesis of common cross-product ratios (Breslow and Liang 1982).

hoppers in the grass and litter within 3–5 h after spraying were unsuccessful. Only a few individuals could be found by four searchers in 20 min, even though the sprayed plots averaged 11–18 grasshoppers per m^2 before treatment. Cannibalism and predation may remove dead grasshoppers (Putnam 1947), but cannot account for their disappearance in this case, owing to the short time interval and the absence of active arthropods just after spraying. The day following application, living grasshoppers showing some disorientation could be found on the ground where they were available for sampling by the bottomless cages, but not by sweeping an insect net through the vegetation.

Percent Control. Total numbers of grasshoppers in the 25 Smith-trap samples (0.25–m^2) and in the 200 sweep-net samples per plot per sampling date were used to estimate mortality (adjusted via Abbott's formula and compared via the Mantel–Haenszel test). The apparent percent of control resulting from the application of 7.2 g (AI) deltamethrin/ha was similar on most dates, other than the day immediately following application (Table 3). The sweep-net sample data collected the day following the spraying indicate spurious high rates of control (77 and 96% in the two replications of the experiment), followed by a decline to about 65% control. The Smith-trap data, on the other hand, indicate control of 48% the day after treatment, increasing to about 65% after 4 days. Mortality estimates from the two sampling methods differed significantly on the day following spray application, but converged by day 4. Percent mortality estimates based on Smith traps were not distinguishable between the blocks on any date, while the estimates based on sweep-net samples differed between blocks on day 1 only ($P < 0.0001$). The estimates based on the two sampling methods differed on the first sampling date ($P < 0.0001$), at which time both estimates were significantly higher than later estimates.

The difference in the estimates of insecticide efficacy calculated from the two methods of sampling illustrates the response to sublethal effects previously discussed. This evidence suggests that sweep-net sample data collected in pyrethroid efficacy trials, and perhaps in other insecticide trials as well, should be interpreted with caution. The Smith traps provide a more unbiased measure of efficacy, a reduction of 65% in the grasshopper populations by the fourth day after insecticide application. Although initially overestimated, efficacy as measured by sweep-net samples agrees very well with the Smith-trap estimate by the fourth day. Sweep-net sampling may be usefully employed as a method of comparing plots in properly replicated and randomized grasshopper control trials as long as the following minimum requirements are met: 1) sweep samples are collected more than 1 day after insecticide application, 2) sweeping is done under similar weather conditions and with similar techniques on each sampling date. In the remainder of this paper, we restrict the use of sweep-net data to inferences regarding species composition and age structure.

Effect of Species Composition on Mortality Estimates. Since deltamethrin is intended by the manufacturer for use in controlling nymphs of grasshoppers, it may be suggested that the presence of *A. clavatus*, the only species found as adults at application time, may have reduced the efficacy of the insecticide. This hypothesis was tested by calculating the percent mortality excluding this species. Since the sweep-net samples provided apparently unbiased estimates of percent mortality after the first posttreatment sampling date, we used

Table 4. Abbott's adjusted percent mortality (SE) from the sweep-net samples, calculated with and without *A. clavatus*

Site	Method	Days after application			
		1	4	8	15
Block 1	With	96 (1.4)	64 (5.1)	79 (3.6)	66 (5.0)
	Without	97 (1.1)	64 (5.2)	89 (2.4)	71 (4.7)
Block 2	With	77 (4.4)	65 (6.3)	73 (4.9)	50 (7.6)
	Without	80 (4.9)	70 (6.1)	82 (4.0)	62 (6.8)

Table 5. Adjusted mortality (SE)[a] of the common species in the deltamethrin-treated areas

Species	Block 1				Block 2			
	Days after spraying				Days after spraying			
	1	4	8	15	1	4	8	15
A. clavatus	82 (9.1)	81 (15)	0	18 (30)	70 (9.8)	48 (20)	27 (23)	0
M. infantilis	98 (1.2)	78 (4.4)	90 (3.1)	82 (18)	74 (8.8)	72 (8.7)	80 (6.6)	51 (14)
M. packardii	96 (4.4)	76 (10)	89 (6.0)	65 (14)	88 (6.6)	93 (4.6)	84 (7.1)	44 (2.1)
M. sanguinipes	99 (0.3)	0[b]	91 (5.2)	49 (17)	82 (14)	28 (30)	79 (12)	41 (59)

[a] Percent mortality of each species has been adjusted by the modified Abbott's formula, against the counts of the same species in the untreated areas.

[b] Unexplained low count in the sample (for this date and species only).

the later samples to make the comparison. Table 4 shows that the estimates of mortality calculated after *A. clavatus* is excluded from the data are not very different from estimates based on all species. Although this species does appear to be slightly less susceptible than others (see also Table 5), the presence of *A. clavatus* cannot explain the lower than expected control obtained with 7.2 g (AI) deltamethrin/ha.

Grasshopper Movement. Earlier trials of deltamethrin applied to rangeland and pastures have exhibited the knockdown and recovery effects apparent in the sweep-net results (Fig. 1). However, this effect has been attributed to immigration into the treated plots. For example, Wise and Blouw applied deltamethrin at 4, 5, or 6 g (AI)/ha via ground-sprayer (1981a) and by aircraft (1981b) to 6-ha plots on rangeland in grasshopper control trials. In both experiments, "excellent initial control" was observed 1–2 h after insecticide application, followed by the reappearance of grasshoppers in the sweep-net samples on the second sampling date, 2 days after application. Kitson and Blouw (1981) performed a similar experiment on 2-ha plots using 4, 5, 6, or 7 g (AI) deltamethrin with similar results: excellent control was observed after 24 h, but after 7 days the numbers collected in the sprayed plots increased. In all three experiments, the numbers of grasshoppers in the sweep-net samples on the second sampling date were negatively correlated with the rate applied. Kitson and Blouw attributed the change in percent of control to immigration into the treated plots. It is more likely, given the large size of the plots and the negative correlation of the putative migration with deltamethrin rate, that those experiments illustrate the change in sweep-net sampling efficiency caused by sublethal dose effects.

In our experiment, most of the grasshoppers present at the time of insecticide application were immature and consequently wingless. There is published evidence (Table 6) that directional

Table 6. Rate of movement of grasshoppers

Author	Species	Stage	Food source	Rate of movement
Riegert et al. (1954)	*Camnula pellucida*	Nymphs	No: bare fields	Up to 82 m in 8 days
	Melanoplus sanguinipes	Mixed	No: bare fields	Up to 220 m in 6 days
Baldwin et al. (1958)	*M. sanguinipes*	Mixed	Yes: alfalfa and grass	28 m in 3 weeks
Edwards (1961)	*M. sanguinipes*	Adults	Yes: mixed grass and forbs	"Very little" in 10 days
Putnam (1963)	*C. pellucida*	Nymphs	Yes: native grassland	Averaged 5.5 m per day; increased to over 18 m per day
Smith et al. (1964)	*Aeropedellus clavatus*	Nymphs	Yes: short-grass prairie	"Very slight" over 2 days
	Aulocara elliotti (Thomas)	Nymphs	Yes: short-grass prairie	
Aikman and Hewitt (1972)	*Myrmeleotettix maculatus* (Thunberg)	Nymphs	Yes: grass golf course	<20 m in a lifetime of 8 weeks
Barton and Hewitt (1982)	*Podisma pedestris* (flightless)	Adults	Yes: short grass	Averaged 5.1 m in 3 days (variance 128.4 m^2)
Joern (1983)	*Cordillacris cenulata* (Bruner) *Dactylotum variegatum* (Scudder) *Trachyrhachys kiowa* (Stål) *Trimerotropis pallidipennis* (Burmeister)	Adults	Yes: sparse grass	Averaged 4.9 to 8.1 m/day

Table 7. Percentage (SD) of males in the sampled *A. clavatus* populations[a]

Treatment	1 day before	Days after application			
		1	4	7	15
Unsprayed	71 (4.2)	72 (4.3)	81 (5.9)	65 (5.4)	65 (5.4)
Sprayed	79 (5.9)	79 (9.4)	75 (15)	69 (7.4)	63 (7.1)

[a] Dispersal by flight would increase this proportion in the sprayed plots. Blocks are pooled since they did not differ significantly.

movement by nymphs, and even by adults, is not sufficient to overrun large-plot experiments in a matter of a week. However, it may be hypothesized that the reappearance of grasshoppers in the treated plots was due not to recovery but to flight by adult *A. clavatus* back into the sprayed plots. *A. clavatus* made up over 18% of all grasshopper species present during the experiment, and consisted of 72% adults. This hypothesis can be tested by consideration of sex ratio. Females of this species are short-winged and are not strong fliers. Males have functional wings of normal length, extending to the posterior of the abdomen. Flight dispersal into the sprayed plots would be primarily by males and would increase the male proportion of the population. The statistics shown in Table 7 indicate that this hypothesis can be rejected: there is no evidence for a change in *A. clavatus* adult sex ratio after spraying. A three-way log-linear model (Bishop et al. 1980) fit to *A. clavatus* counts, with insecticide treatment and date as terms, indicates that date and insecticide treatment interact ($P < 0.001$), but sex ratio is independent of treatment ($P = 0.70$) and date ($P = 0.14$) effects.

Laboratory Toxicity Tests. Probit regression equations were fitted to the mortality observed at the five rates of deltamethrin sprayed onto second-instar nymphs. The field-equivalent rates required to achieve probabilities of death of 50 and 90% are shown in Table 8. Conversion to μg (AI)/g body weight (ppm), on the basis of average live weight of 16.5 mg and planar body area of 15 mm^2, indicates LD_{50} and LD_{90} values of 0.231 and 1.42 μg/g, respectively, at 21°C. These values are somewhat lower than the values of 0.38 and 5.72 μg/g reported by McDonald (1982) from topical application of deltamethrin in acetone and olive oil to fifth-instar *Melanoplus bivittatus* (Say) nymphs at 26°C.

LD_{90}'s in Table 8 are lower than indications in laboratory toxicity tests by Javadi and Knutson (1979). Their results indicate 90% mortality after treatment with 22.4 g (AI)/ha.

It is clear that there is little effect of temperature over the 16–27°C range. The following interpretation is based on the 21°C probit line, but applies as well to the others within the range examined. The observed rate of mortality estimated from field population sampling was compared with the toxicological data by reference to the results of the insecticide residue trials. The treated areas of blocks 1 and 2 received 78.6 and 67.8% of the potential 7.2 g (AI)/ha insecticide deposit, respectively (see Table 1). The predicted estimates of mortality from the probit regression equation,

$$\phi = 4.341 + 1.629 \log_{10}(\text{dose in g [AI]/ha})$$

$$\%\ \text{mortality} = 100\ (z_{(\phi\text{-}5)} + 0.5)$$

where z is the standard normal deviate, are 71.5 and 67.5% in blocks 1 and 2, respectively. These estimates correspond well to the observed efficacy of ca. 65% reduction of the grasshopper population in both blocks (Table 3). This further indicates that the deltamethrin reached the target and effected the degree of mortality that could be expected, given the inherent toxicity of the compound to grasshoppers.

Effects of Water Volume. There was no apparent effect of spray volume on percent of mortality at the seven rates of application in the Track Sprayer trials. Analysis of variance of the mortalities observed at rates of 1.64, 3.30, and 6.40 g/ha equivalent indicated a strong rate effect ($P < 0.0001$) but no significant effects of volume ($P = 0.87$) or rate × volume interaction ($P = 0.76$). Mortalities at 14, 28, and 56 liters/ha were 71, 77, and 74% in the first run of the experiment and 69, 67, and 65% in the second run.

Although the water volume used in the field experiment was 5 liters/ha less than the lowest volume used in the laboratory experiment, there is no compelling reason to conclude that moderate increases in water volume would greatly improve efficacy.

Our field results indicate that although aerial application of deltamethrin is capable of providing adequate deposition and crop penetration, the subsequent reduction in the grasshopper populations is not as great as would be desired in control programs on rangeland and pasture. The lower than expected mortality in our field experiment was not due to the presence of relatively resistant species or age classes, or to migration into the treated areas after application. The temporary disappearance and apparent recovery of treated

Table 8. Toxicity of deltamethrin to second-instar *M. sanguinipes*

Temp (°C)	Probit slope (SE)	LD_{50} (g [AI]/ha)	95% CL (g [AI]/ha)	LD_{90} (g [AI]/ha)	95% CL (g [AI]/ha)
16	1.678 (0.211)	2.50	$1.72 < x < 3.25$	14.49	$10.59 < x < 23.51$
21	1.629 (0.165)	2.54	$1.90 < x < 3.16$	15.56	$11.90 < x < 22.74$
27	1.998 (0.164)	2.66	$2.19 < x < 3.13$	11.65	$9.58 < x < 15.05$

grasshoppers indicate that a significant number received sublethal doses of deltamethrin, a conclusion supported by our toxicological experiments.

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