SETAC PRESS

Environmental Toxicology and Chemistry, Vol. 19, No. 12, pp. 2987–2996, 2000

Printed in the USA
0730-7268/00 $9.00 + .00

EFFECTS OF TWO GRASSHOPPER CONTROL INSECTICIDES ON FOOD RESOURCES AND REPRODUCTIVE SUCCESS OF TWO SPECIES OF GRASSLAND SONGBIRDS

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(*Received* 27 *October* 1999; *Accepted* 1 *May* 2000)

Abstract—We conducted a field experiment to determine the direct and indirect effects of spraying two broad-spectrum insecticides with widely differing avian toxicities in grassland habitat on the survival and reproductive success of nesting songbirds. Three 56-ha plots were sprayed with Decis 5F™, three plots were sprayed with Furadan 480F™, and three plots were left unsprayed. Insecticides were applied at rates recommended for grasshopper control. Grasshopper (Orthoptera: Acrididae) density was measured throughout the spring and summer. Nests of chestnut-collared longspurs (*Calcarius ornatus*) were monitored to determine survival rates and nestling growth. Food habits of nestlings and parental foraging parameters were measured using esophageal ligatures and observations of parental foraging flights. Applications of both insecticides decreased grasshopper populations by more than 90%. Nevertheless, the number of grasshoppers in nestling diets was significantly decreased only in nests in Decis-sprayed plots. Total arthropod biomass delivered to the nestlings did not decrease in plots sprayed with either insecticide. Nestling weight and size were unaffected by insecticide spraying. Rate of prey delivery also did not change; however, by two weeks after spraying with Decis, parent longspurs were foraging almost twice as far from their nests as were birds in control plots ($p < 0.05$) to maintain prey delivery rates. Clutch size and egg and nestling success were similar among treated and control plots within specific two-week periods during the season. Age-corrected brain acetylcholinesterase activities of longspur nestlings in plots sprayed with Furadan were significantly depressed compared to controls; a single case of insecticide-induced mortality was detected in a nestling that was severely infested with blowfly larvae. Nevertheless, success of nests with Furadan-exposed nestlings ($n = 20$) was greater than that in control plots during the two-week period following spray ($n = 19$, $p = 0.03$). The Baird's sparrow (*Ammodramus bairdii*), an uncommon prairie species of conservation concern, was monitored using an index of productivity. The number of 3.14-ha census circles having productive Baird's sparrow territories was significantly lower in Furadan-sprayed plots than in unsprayed and Decis-sprayed plots; a larger number of sparrow territories were abandoned in Furadan plots.

Keywords—Deltamethrin Carbofuran Grassland songbirds Reproductive success Acetylcholinesterase

INTRODUCTION

Large areas of the prairie provinces in Canada are sprayed to control grasshoppers during infestation years. Although crops are the primary target, grazing land is also sprayed in an effort to reduce insect damage on pasture vegetation and also in response to the concerns of farmers producing crops on adjacent land. Grazing land represents important remnant grassland habitat for many prairie birds, including a number of endemic species of conservation concern. Grasshopper densities exceeded the economic threshold (8–13 grasshoppers/m^2 [1]) at which they cause significant reductions in grazing capacity, on 4 to 19% of grasslands surveyed annually in Alberta, Canada, between 1984 and 1995 (D.L. Johnson, unpublished data). Thus, a substantial proportion of quality wildlife habitat is at risk of exposure to insecticides used for grasshopper control.

The insecticides most commonly used in grasshopper control programs, the organophosphorus and carbamate compounds, are cholinesterase inhibitors; many have acute toxic effects on avian wildlife. The alternative pyrethroid insecticides, although low in mammalian and avian toxicity, are highly toxic to a broad spectrum of arthropods and may negatively impact avian populations through reduction of this crucial food source. During the most recent prairie-wide grasshopper infestations of 1985 and 1986, Furadan (a carbamate: active ingredient carbofuran; FMC, Philadelphia, PA, USA) and Decis (a pyrethroid: active ingredient deltamethrin; Roussel-Uclaf, Paris, France) were two of the three most commonly used insecticides. Furadan accounted for 57% (440,600 ha) and 65% (468,700 ha) and Decis for 22% (168,000 ha) and 15% (104,000 ha) of the total area sprayed in Alberta for the two years, respectively [2]. Furadan has caused large die-offs of waterfowl feeding in sprayed vegetation on the wintering grounds [3], and gulls (*Larus sp.*) died after gorging on grasshoppers in sprayed fields in Saskatchewan [4]. Nevertheless, adult clay-colored sparrows (*Spizella pallida*) fed grasshoppers sprayed with Furadan at grasshopper control rates were unaffected [5]. Day-old mallard (*Anas platyrhynchos*) ducklings walking 200 m through Furadan-sprayed grasslands were minimally impacted [6], although a small proportion of pheasant chicks living and foraging in similarly sprayed vegetation showed signs of severe intoxication [7].

Decis is highly toxic to terrestrial invertebrates, and its efficacy in the control of grasshopper populations makes it a popular choice for this application. Aerial application of the flowable formulation, Decis 5F, at rates below the highest current rate recommended for grasshopper control (6.25 g active ingredient [a.i.]/ha), reduced grasshopper populations by 91 to 98% [8]. Effects on nontarget arthropods are not well documented, but the great diversity of registered uses of Decis [9] suggests that effects would be wide ranging.

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The nestlings of most songbirds rely entirely on invertebrates for food [10–13]. Grasshoppers appear to be a preferred food item in all grassland nestling songbird diets, and the proportion that they contributed to the diet increased at a greater rate than their increase in availability to the foraging parents [10]. Prey diversity was greatest in seven species of grassland songbird when grasshopper numbers were lowest ($<1/m^2$), whereas an increase in grasshopper numbers ($3–5/m^2$) brought about a reduction in prey diversity as all seven species switched to a heavy reliance on grasshoppers [10]. Thus, even at population levels below economically significant densities ($10/m^2$), grasshoppers provide a superabundant food source to birds, such that segregation of prey sizes and types among species was not necessary [14]. Applications of broad-spectrum insecticides in breeding habitat could not only knock out this superabundant food item but may also severely reduce populations of other terrestrial arthropods, thereby depleting food supply with potential effects on the growth and survival of nestlings of all competing species. In a previous study [15], Decis applied for grasshopper control resulted in >95% reductions in grasshopper numbers but caused an abundance of moribund cutworm larva for 6 of 10 d after spraying during which the songbird population was monitored. No effects on nestling growth or survival were noted; the unusual appearance of lepidopteran larvae appeared to compensate for the disappearance of grasshoppers in the diet of the birds. Decis, but not Furadan, had previously been observed to cause this behavior in the otherwise subterranean cutworm larva in applications to grass pasture [16].

The purpose of the current study was to assess the affects of these two broad-spectrum grasshopper control insecticides on the reproductive success of grassland songbirds through the mechanisms of food removal (both Decis and Furadan) and direct avian toxicity (Furadan only).

METHODS

Study site

The study was conducted on the property of the Purple Springs Grazing Association (49°48′N, 112°18′W, elevation 790 m above sea level) located approx. 12 km east of Taber, Alberta, Canada. The land was moderately grazed, dry mixed-grass prairie (*Bouteloua gracilis*, *Stipa comata*, and *Koeleria cristata*), with some patches of *Melilotus officinalis* and *Agropyron cristatum*. The plots were undisturbed by cattle throughout the study period. The property contained several wetlands (seasonal and semipermanent) as well as irrigation canals throughout.

Study design

The study was conducted on three experimental blocks (termed east, west, and south). Within each block we delineated three 56-ha study plots (750 × 750 m), at least 200 m apart, and conducted intensive monitoring of insects and birds within the central 36 ha (600 by 600 m). Plots within a block were randomly assigned to one of three treatments.

Plots were marked with 1-m white wooden stakes placed at 100-m intervals and unpainted stakes at 50-m intervals in a grid pattern and numbered for orientation, for ease of location of insect sampling sites, and as an aid in estimating distance and location in avian foraging observations.

Pesticide application

A single aerial application of either Decis 5F or Furadan 480F was made to the designated plots between June 24 and 29, 1994, by a commercial applicator. Decis and Furadan were applied at rates of 6.25 and 132 g active ingredient per hectare, respectively, the highest rates recommended for control of grasshoppers. Spraying was conducted between 0500 and 0800 h at wind speeds of <15 km/h from a height of 3 to 5 m. Spray deposit was validated using gas chromatography analysis of residues collected on silica gel collection plates and examination of spray droplet cards [17,18] placed on stakes at vegetation height in a diagonal line across each sprayed plot. Samples of tank mix were also collected and returned for residue analyses at the Agriculture and Agri-Food Canada Research Centre, Lethbridge, Alberta, using methods similar to those described by Hill and Johnson [19]. We did not specifically assess the possibility of spray drift among plots but were confident that they were spaced sufficiently far apart to avoid unwanted contamination.

Nest monitoring

The nine plots were intensively searched for nests four times between May 25 and July 6 by rope dragging. This technique involved dragging a weighted rope (30 m long) on the ground between two people walking about 25 m apart. Many nests were also located by chance in the course of other sampling tasks. Locations of flushed birds were searched for nests that were then marked with flagged stakes placed 2 m on either side of the nest. Nests were checked on alternate days after discovery, so that date of hatch and survival could be determined to within a day. If a clutch of eggs was partially hatched at one visit, that day was considered to be date of hatch (day 0). If the entire clutch had hatched and nestlings were dry and fluffy, the previous day was considered to be the date of hatch, and thus the nestlings were 1 d old on the day of the visit. Active nests found depredated on a visit were assumed to have been destroyed on the day between visits. Body weight (to 0.1 g) and tarsus length (to 1 mm) of nestlings were measured at 7 d of age; we stopped nest visits after this age, as further disturbance could have forced nestlings to fledge prematurely. Although undisturbed nestlings might not leave the nest until 8 to 10 d old [20], we considered nestlings surviving in the nest at the time of the final visit to be successfully fledged. Egg success was calculated as the number of hatched nestlings divided by number of eggs laid in a given nest. Nestling success was calculated as the number of fledged nestlings divided by the number of hatched nestlings. Overall nest success was defined as number of fledged nestlings divided by number of eggs laid in a given nest.

Foraging and food habits

We conducted observations of adult foraging and nestling food habits in approx. 16 nests per plot over the entire breeding season. Nests were sampled when nestlings were 7 d old, between 0630 and 1230 h. Esophageal ligatures were fastened on each nestling, which were then returned to the nest. Ligatures were made of thin, solid copper wire coated with plastic and looped firmly around the nestlings' necks. The ligatures prevented them from swallowing food received from parents yet did not hinder their safety or ability to beg for food. Nests were observed for a period of 10 min from a distance of about 50 m immediately before fastening ligatures on nestlings to ensure that adults were actively attending the nest and that our presence was not disturbing activity [15]. After ligatures were attached, nests were observed for 30 min. If three feedings had occurred during the first 15 min, nestlings were checked, and food was removed from their throats at that point; they were then returned to their nest for a further 15 min of observation. Otherwise, nestlings were undisturbed for the full 30-min observation period, after which they were checked for food, the ligatures were removed, and they were returned to their nests. Prey items were removed from the throats of nestlings using forceps and placed in vials of 70% ethanol, where they were stored until they could be sorted, identified to appropriate taxonomic level, and weighed. Samples were removed from ethanol, blotted dry, and weighed to an accuracy of 0.1 mg. No correction was made to convert from preserved mass to fresh mass. Throughout the 30-min observation period, the total number of feedings and the number, distance, and location of parental foraging flights were recorded on maps and data sheets. Although adult birds were not color marked for individual identification, the gentle topography and extreme openness of the landscape allowed us to have confidence in the movements of parent birds. Distance estimates were based on the flight path from the nest to the point at which the parent bird alighted on the ground. Movements while on the ground could not be seen and were not measured, but birds invariably flew up from the ground within 10 m of where they had alighted.

Cholinesterase activity

To assess the occurrence of exposure of nestlings to carbofuran during the day of application, we collected nestlings for brain acetylcholinesterase (AChE) activity from Furadan-sprayed plots. Nests known to contain nestlings were checked approx. 1 h prior to spraying to ensure their presence at spray time. They were revisited 2 to 4 h after spray application, and one or two nestlings were taken from the nest. An assessment of behavior of the parents was also made at that time as well as at a second visit in the evening (approx. 12 h after spraying). The age of nestlings collected from Furadan-sprayed plots ranged from 1 to 11 d. To account for the increase of AChE activity with age known to occur in altricial birds, we also collected nestlings from control plots within the same age range for comparison. Nestlings were killed by cervical dislocation and decapitated; whole heads were wrapped in foil and put on ice and returned to the laboratory for storage in liquid nitrogen. Samples were shipped on dry ice to the National Wildlife Research Centre in Hull, Quebec, Canada, where whole brains were analyzed for enzyme activity using the methods of Ellman et al. [21] modified according to Hill and Fleming [22].

Productivity index: Baird's sparrow

Our study area was known to contain numerous Baird's sparrow (*Ammodramus bairdii*) territories. Although we were interested in assessing pesticide impacts on this species, its conservation status (listed as threatened until 1996 when delisted [23]) prompted us to use a behavioral index rather than invasive nest monitoring to determine their reproductive success [24,25]. Productivity of territories was scored within four census circles (100 m in radius, 3.14 ha in area) per treatment plot, 200 m apart and 75 m in from the plot edge. Six standardized productivity assessments were conducted at 10- to 14-d intervals from early June to early August. During each 30-min assessment, the plot was traversed along a set route (1,100 m in length) at a constant rate of travel; all evidence of avian productivity was indicated on a plot map. The presence of a male and a female on a territory, call note changes, adults carrying food, discovery of a nest, and observation of fledged young were criteria used in assigning increasing scores of productivity. The scoring system, which was on a territory basis, was as follows: 1—territorial male, 2—mated pair, 3—nest with eggs, 4—nest with chicks, and 5—fledged young. Scores could continue to increase through the season with evidence of a second brood or breeding attempt on a territory by adding 3, 4, or 5, as appropriate, to the highest score obtained with the first breeding attempt.

We determined number of territories, number of productive territories (productive defined as having evidence of young, either in nest or fledged), number of abandoned territories, and mean territory productivity on a per plot basis over the entire season. Comparisons were made among treatments using analysis of variance [26]. We also compared the proportion of plots having breeding territories and proportion of plots having productive territories using Fisher's exact (two-tailed) test [26].

Table 1. Grasshopper numbers and percentage reductions on unsprayed plots and before and after spraying on plots with either Decis™ or Furadan™ for grasshopper control

	Unsprayed	Decis		Furadan	
	No./m²	No./m²	% Reduction[a]	No./m²	% Reduction
Prespray	4.27	3.53	—	5.47	—
Postspray weeks					
1	11.75	0.78	92.0	0.62	95.9
2	18.90	0.63	96.0	1.29	94.7
3	21.11	1.01	94.2	2.64	90.3
4	19.78	1.42	91.3	3.53	86.1
5	16.48	1.54	88.7	3.65	82.7

[a] Based on Abbott's formula [28,29].

Grasshopper abundance

Each plot had 64 permanent stations (grid of 8 × 8 stations, 100 m apart) at which grasshoppers were counted in 0.25 m² quadrats (method tested and described by Johnson [27]) on a weekly basis throughout the field season. The proportion reduction in grasshopper population resulting from pesticide application was expressed using Abbott's formula (Abbott [28] as modified by Henderson and Tilton [29]; see Table 1), mathematically equivalent to one minus the cross-product ratio of a table of before- and after-treatment counts of insects from all treated and untreated plots [30].

Statistical analysis of longspur data

We divided the nest monitoring season into four approximately equal periods. Periods were based on approx. two-week intervals, with day of spray application as the central point. The early period was prior to June 12, prespray period was between June 13 and the day of spraying for each individual plot (last week of June), the postspray period was from spray day until July 12, and the late period was from July 13 onward. For the calculations of clutch size and egg and nest success, periods were based on clutch completion dates; for nestling number, fledging number, and nestling success, periods were based on hatching dates. All statistical analyses were con-

Table 2. Number and density of chestnut-collared longspur nests in which clutches were completed during three two-week periods

	Control		Decis™		Furadan™		Total	
Period	No.	No./100 ha	No.	No./100 ha	No.	No./100 ha	No.	No./100 ha
Early (May 30–June 12)	61	56	61	56	86	80	208	64
Prespray (June 13–spray day)	30	28	26	24	26	24	82	25
Postspray (spray day–July 12)	8	7.4	19	18	12	11	39	12

ducted using the General Linear Model procedure (PROC GLM) or the Regression procedure (PROC REG) in SAS [26]. Egg, nestling, and overall nest success as well as clutch size and nestling and fledgling number were compared among treatment groups at each time period using analyses of variance with a blocking factor. As plots and not individual nests were the true replicates, the significance of the effect of treatment was calculated using the treatment × block interaction mean square as the error term in determining the F statistic rather than the model error mean square. We also tested differences in reproductive parameters among periods, pooled across treatments using analyses of variance. Day 7 measurements were analyzed using a similar model, except that nestling age was included as a covariate (because of hatching asynchrony in some nests, some nestlings were measured at 6 or 8 d of age). Foraging parameters of adult longspurs and esophageal contents were analyzed similarly using number of nestlings in the nest as a covariate.

Brain AChE of control and Furadan-exposed nestlings were separately fitted to least-squares regressions on nestling age. The effect of treatment was tested using nestling age as a covariate.

RESULTS

Spray deposit

Residue analysis of silica gel spray deposit plates in the three experimental plots for each compound showed that 82, 57, and 73% of the target rate of 6.25 g a.i./ha of Decis and 76, 118, and 96% of the target rate of 132 g a.i./ha of Furadan reached the vegetation. These deposition rates were typical or slightly higher than other published values [31,32].

Insect control

In unsprayed plots, grasshopper numbers increased from 12 individuals/m^2 measured during the week of spraying in late June to approx. 20 individuals/m^2 over the next three weeks, then subsided slightly in August (Table 1). Initial reductions in grasshopper populations exceeded 90% in all treated plots. By five weeks after spraying, populations in Decis-sprayed plots had recovered to 12% of those predicted by trends in unsprayed plots, whereas those in Furadan plots had increased slightly more, to 18% of those predicted.

Reproductive success of monitored nests

A total of 487 nests were found and monitored over the course of the summer. Chestnut-collared longspurs (*Calcarius ornatus*) were by far the most numerous species (349 nests), followed by horned larks (*Eremophila alpestris,* 28 nests), western meadowlarks (*Sturnella neglecta,* 26 nests), grasshopper sparrows (*Ammodramus savannarum,* 20 nests), clay-colored sparrows (17 nests), and several species of waterfowl (Genus: *Anas*), upland shorebirds, and other sparrows. Calculations and comparisons of reproductive success were made for chestnut-collared longspurs, as they were the only species for which data were sufficient for statistical analysis.

Overall, there was a seasonal decline in nesting effort. A total of 208, 82, and 39 longspur nests in which clutches were completed were located in the early, prespray, and postspray periods, respectively (Table 2); we found no nests in which clutch completion occurred during the late period (>July 13). Number of nests per plot showed no trends among treatment groups after spraying had occurred.

The proportion of successful nests were similar among

Table 3. Fate of nests of chestnut-collared longspurs on native pasture either unsprayed or treated with Decis™ or Furadan™ for grasshopper control. Values are expressed as percentages of total nests

				Destroyed by predators				
Period	Treatment	*n*[a]	Fledged	Egg stage	Nestling stage	Abandoned	Dead[b]	Unknown[c]
Early	Unsprayed	60	56.7	15.0	23.3	1.7	0	1.6
	Decis	63	73.0	6.4	14.3	3.2	1.6	2.0
	Furaden	72	62.5	6.9	25.0	1.4	4.2	0
Prespray	Unsprayed	31	67.7	3.2	29.0	0	5.3	0
	Decis	33	57.6	9.1	27.3	3.0	0	0
	Furadan	41	48.8	19.5	22.0	7.3	0	2.8
Postspray	Unsprayed	10	30.0	10	60.0	0	0	0
	Decis	21	66.7	9.5	19.1	4.8	0	2.6
	Furadan	14	42.9	14.3	35.7	7.1	0	0
Late	Unsprayed	3	0	0	100	0	0	0
	Decis	5	100	0	0	0	0	0
	Furadan	3	66.7	0	33.3	0	0	0

[a] Number of nests for which fate could be determined within that period.

[b] Chicks were found dead in nests, usually heavily infested with dipteran parasites, or incubating female was found dead on nest following hailstorm.

[c] Includes cases where nest markers were accidentally destroyed and nests could not be relocated.

Table 4. Reproductive parameters of chestnut-collared longspurs breeding on native pasture either unsprayed or treated with Decis™ or Furadan™ for grasshopper control[a]

		Reproductive parameters							
		Clutch size		Nestling no.		Egg success	Nestling success	No. fledging	Nest success
Period[c]	Treatment	n^b	$\bar{X}$ (SE)	n^c	$\bar{X}$ (SE)	$\bar{X}$ (SE)	$\bar{X}$ (SE)	$\bar{X}$ (SE)	$\bar{X}$ (SE)
Early	Unsprayed	60	3.9 (0.1)	49	2.4 (0.3)	0.71 (0.05)	0.72 (0.07)	1.61 (0.23)	0.46 (0.06)
	Decis	63	4.2 (0.1)	50	2.8 (0.3)	0.79 (0.04)	0.66 (0.07)	1.86 (0.25)	0.57 (0.05)
	Furadan	72	4.2 (0.1)	60	2.5 (0.3)	0.86 (0.03)	0.60 (0.07)	1.53 (0.25)	0.50 (0.05)
	Total	195	4.1 (0.1)A[d]	159	2.6 (0.2)A	0.79 (0.02)	0.66 (0.04)	1.7 (0.1)A	0.44 (0.03)
Prespray	Unsprayed	31	4.1 (0.2)	19	3.7 (0.2)	0.84 (0.08)	0.52 (0.11)	2.00 (0.45)	0.59 (0.08)
	Decis	33	3.9 (0.2)	24	3.9 (0.3)	0.73 (0.06)	0.80 (0.07)	3.12 (0.35)	0.52 (0.08)
	Furadan	41	4.0 (0.1)	36	3.9 (0.2)	0.61 (0.07)	0.51 (0.07)	2.11 (0.30)	0.35 (0.06)
	Total	105	4.0 (0.1)AB	79	3.9 (0.1)B	0.72 (0.04)	0.60 (0.05)	2.39 (0.21)B	0.47 (0.04)
Postspray	Unsprayed	10	4.1 (0.1)	29	3.5 (0.2)	0.75 (0.10)	0.62 (0.09)	2.17 (0.35)	0.23 (0.12)
	Decis	21	3.8 (0.2)	38	3.4 (0.2)	0.71 (0.07)	0.65 (0.08)	2.26 (0.30)	0.55 (0.10)
	Furadan	14	3.6 (0.2)	30	3.6 (0.2)	0.77 (0.11)	0.57 (0.08)	2.10 (0.34)	0.40 (0.13)
	Total	45	3.8 (0.1)B	97	3.5 (0.1)B	0.74 (0.05)	0.62 (0.05)	2.2 (0.2)B	0.43 (0.07)
Late	Unsprayed	0	—	3	4.3 (0.3)	—	0	0	—
	Decis	0	—	5	2.4 (0.6)	—	1.0	2.40 (0.60)	—
	Furadan	0	—	3	3.3 (0.7)	—	0.67	2.00 (1.16)	—
	Total	0	—	11	3.2 (0.4)AB	—	0.64 (0.15)	1.64 (0.49)A	—

[a] Mean (standard error).
[b] Sample size for calculations of clutch size and egg and nest success within periods based on clutch completion dates.
[c] Sample size for calculations of nestling number, fledging number, and nestling success within periods based on hatching dates.
[d] Period means (pooled across treatments) followed by differing uppercase letters are significantly different ($p < 0.05$; analysis of variance and Tukey's HSD [Honestly Significant Difference] test).

treatment groups in each period; typically between 50 and 75% of nests produced young; one exception was the low success (30%) in unsprayed plots in the postspray period (Table 3). Sample size during the late period was too small to make meaningful comparisons. There were no differences in clutch size, number of nestlings hatched or fledged, and egg, nestling, or overall nest success among treatment groups in any of the periods (p values > 0.05 for treatment effect; Table 4). The block effect was seldom significant. Certain reproductive parameters varied significantly by period. Clutch size was slightly but significantly greater in the early than the postspray period (by 0.3 egg; Table 4), but both number of nestlings and number of fledglings per nest were significantly lower in early period nests than in the later two periods (mid-June to mid-July; Table 4). Very little individual mortality of either eggs or chicks occurred in otherwise successful nests in any treatment or period. Survival of individual eggs in successful nests was between 83 and 98%; nestling survival in successful nests ranged from 77 to 100%.

Prefledging weight

There were no differences in the body weight or tarsus length of prefledging longspur nestlings among treatment groups in any of the periods. Age of nestling, included in the model as a covariate, was almost always highly significant, except during the postspray period. The block effect was never significant. Body weight and tarsus length differed overall among periods. Nestlings that fledged in the early and prespray periods (late May to June 12) weighed significantly less than those fledged later in the season (Table 5). Tarsus length of prespray nestlings was less than those from all other periods (Table 5).

Parental foraging and nestling diet

Esophageal ligatures and corresponding observations of parental foraging were successfully conducted on a total of 35, 42, 49, and 23 longspur nests of 7-d-old nestlings during the early, prespray, postspray, and late periods, respectively. There were no differences in the number of feedings per 30 min, average distance per foraging trip, or total distance flown by parents among treatments in the early, prespray, and postspray periods (Table 6). However, overall, there are significantly fewer feedings in the latter two versus the earlier two periods, and distance per trip is greatest during the late period (Table 6).

There is a difference among treatments during the late period, however, where the total foraging distance flown was

Table 5. Body weight and tarsus length of 7-d-old chestnut-collared longspur nestlings[a]

			Weight (g)	Tarsus (mm)
Period	Treatment	n^b	$\bar{X}$ (SE)	$\bar{X}$ (SE)
Early	Unsprayed	54	13.0 (0.2)	18.0 (0.1)
	Decis™	61	13.2 (0.3)	18.0 (0.2)
	Furadan™	56	13.5 (0.3)	18.0 (0.2)
	Total	171	13.2 (0.2)A[c]	18.0 (0.1)A
Prespray	Unsprayed	39	13.5 (0.4)	17.8 (0.3)
	Decis	73	12.6 (0.3)	17.6 (0.2)
	Furadan	72	12.2 (0.2)	17.3 (0.2)
	Total	185	12.7 (0.2)A	17.5 (0.1)B
Postspray	Unsprayed	67	15.0 (0.8)	18.6 (0.3)
	Decis	59	13.4 (0.4)	18.2 (0.2)
	Furadan	58	13.8 (0.3)	18.0 (0.2)
	Total	184	14.1 (0.3)B	18.3 (0.2)A
Late	Unsprayed	22	13.8 (0.7)	18.2 (0.3)
	Decis	64	13.6 (0.2)	17.8 (0.3)
	Furadan	23	14.7 (0.3)	18.6 (0.2)
	Total	109	13.9 (0.2)B	18.0 (0.2)A

[a] Mean (standard error).
[b] Number of nestlings.
[c] Period means (pooled across treatments) followed by differing uppercase letters are significantly different ($p < 0.05$; analysis of variance and Tukey's Honestly Significant Difference [HSD] test).

Table 6. Food consumption and foraging parameters of chestnut-collared longspurs breeding on native pasture either unsprayed or treated with Decis F™ or Furadan™ for grasshopper control[a]

		Parental foraging parameters				Prey weight, mg wet weight	
		Feedings per 30 min		Distance per trip, m	Total distance per 30 min, m	Per nest	Per chick
Period	Treatment	n[b]	$\bar{X}$ (SE)	$\bar{X}$ (SE)	$\bar{X}$ (SE)	$\bar{X}$ (SE)	$\bar{X}$ (SE)
Early	Unsprayed	14	3.76 (0.66)	32.6 (3.5)	137 (31)	304 (77)	116 (20)
	Decis	10	5.88 (0.84)	38.3 (6.3)	191 (23)	392 (72)	114 (18)
	Furadan	11	5.84 (0.80)	28.5 (5.6)	154 (30)	294 (66)	104 (23)
	Total	35	5.02 (0.46)A[c]	32.9 (2.4)A	158 (17)	326 (42)	112 (12)
Prespray	Unsprayed	8	6.23 (1.24)	42.2 (7.5)	203 (45)	453 (101)	136 (33)
	Decis	17	4.09 (0.60)	30.8 (3.6)	139 (24)	523 (87)	179 (27)
	Furadan	17	5.48 (0.72)	40.5 (3.9)	223 (35)	498 (71)	140 (19)
	Total	42	5.06 (0.45)A	36.9 (2.6)A	185 (20)	499 (48)	154 (15)
Postspray	Unsprayed	17	3.01 (0.39)	35.1 (5.9)	113 (17)	343 (64)	127 (20)
	Decis	14	4.40 (0.79)	46.8 (6.2)	178 (24)	515 (10)	124 (26)
	Furadan	18	3.31 (0.60)	40.1 (6.7)	124 (23)	305 (58)	113 (27)
	Total	49	3.52 (0.35)B	40.3 (3.6)AB	135 (13)	378 (43)	122 (16)
Late	Unsprayed	4	2.82 (1.82)	25.7 (5.1)	71 (45)A[d]	227 (194)	147 (12)
	Decis	14	3.00 (0.62)	67.1 (14.9)	183 (40)B	419 (90)	139 (21)
	Furadan	5	2.70 (1.37)	28.9 (8.5)	97 (47)A	361 (140)	145 (44)
	Total	23	2.90 (0.54)B	51.6 (10.0)B	145 (28)	373 (69)	141 (19)

[a] Mean (standard error).

[b] Number of nests.

[c] Period means (pooled across treatments) followed by differing uppercase letters are significantly different ($p < 0.05$; analysis of variance and Tukey's Honestly Significant Difference [HSD] test).

[d] Means within the same period followed by differing uppercase letters are significantly different ($p < 0.05$; analysis of variance and Tukey's HSD test).

significantly greater in the Decis-sprayed plots than either the control or the Furadan-sprayed plots (183 vs 71 and 97 m, respectively, Table 6). Although this appeared to be a function of longer mean distance per trip (67 vs 26 and 29 m, respectively, for the three treatments), this difference was not significant ($p > 0.76$).

Total wet arthropod biomass (ethanol-preserved) fed on a per nest basis in 30 min did not vary among treatment groups in any time period (p values > 0.3). In all periods and for all treatment groups, the total number of nestlings in the nest significantly affected the weight of arthropod food delivered (p values < 0.05). However, biomass fed on a per nestling basis was not significantly different among treatments within period or among periods. There tended to be greater biomass fed per nest during the prespray period than the early and late periods ($p = 0.10$), although this tendency was less obvious when expressed on a per nestling basis ($p = 0.13$). No food was delivered to nestlings during the 30-min observation period at 17 nests throughout the season. There was no difference ($p > 0.4$) in the frequency of this occurrence among treatment groups in any period. Grasshoppers always accounted for the largest number of items fed, and in the unsprayed plots this number tended to increase over the season (Fig. 1). During the postspray period, however, the nests in plots sprayed with either Furadan or Decis received significantly fewer grasshoppers then those in the unsprayed plots, although the total number of food items received did not differ. There appeared to be an increase in the number of lepidoptera (larva and adults) and beetles (included in the "other" category) in the diet of nestlings in the Decis plots, whereas in the Furadan plots diptera and hymenoptera seemed to compensate for the reduction in grasshoppers (Fig. 1). Only the increase in diptera was significant. During the late period, grasshoppers continued to be more prevalent in the diets in the unsprayed versus sprayed plots, but because of high variability this difference was not significant. However, nests in the Furadan-sprayed plots received a significantly higher number of food items in the other category, a difference that was accounted for by an unusually high number of snails delivered.

Brain AChE activity and behavioral observations

A total of 33 nestlings (ages ranging 1–10 d) were collected from 20 nests in Furadan-sprayed plots during the day of spraying. At both daytime visits for collection of chicks (2–4 h after spraying) and at subsequent evening visits, at least one parent was observed nearby at every nest, either scolding or watching us, displaying behavioral patterns typical of usual nest visits.

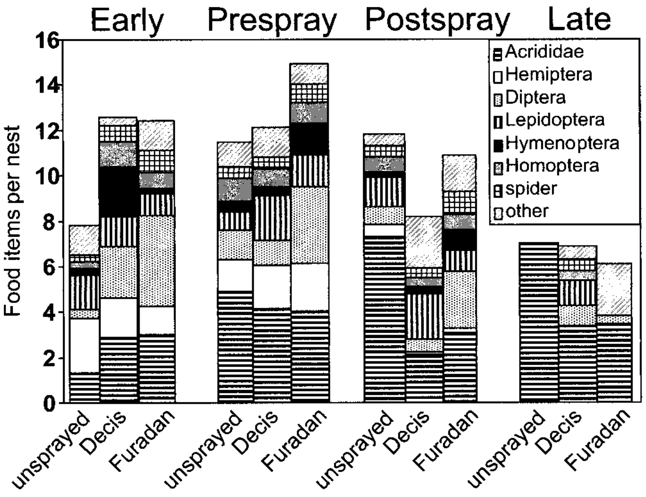

Fig. 1. Prey items in the diet of chestnut-collared longspurs in unsprayed native pasture and in plots sprayed with Decis™ or Furadan™.

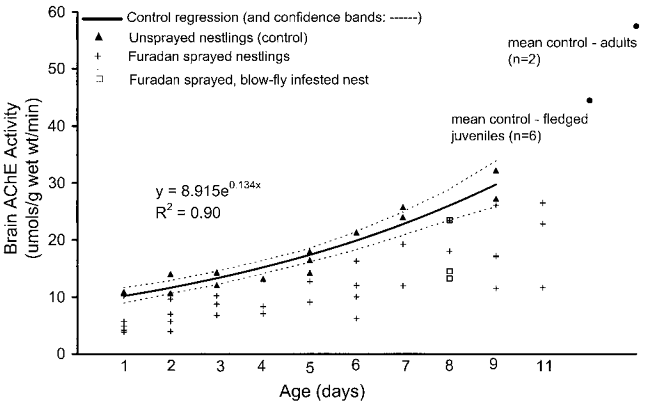

Fig. 2. Regressions of brain acetylcholinesterase (AChE) activity to age of longspur nestlings in unsprayed plots (control) and plots that had been sprayed with Furadan 450F™ (Furadan) at 132 g active ingredient (a.i.)/ha.

Nestlings were also judged to be behaving normally, either begging for food or sitting quietly, depending on age. In only one nest was any unusual observation made during collection. Two of three 8-d-old nestlings were dead in this nest 2 h after spraying, and all three were badly infested with parasitic blowfly larvae (Diptera: Calliphoridae; 10 6–8-mm-long larvae dropped out of the dead nestlings on handling). One dead nestling may have died overnight as it had been crushed by its siblings and brooding parents; the other appeared more recently deceased. AChE activity of the nestling that appeared long dead was equivalent to that of controls (23.4 vs a predicted value of 26.1 μmol/g/min for control 8-d nestlings), whereas activities of the surviving nestling and the more recent mortality were depressed by 30 and 49% (18.1 and 13.3 μmol/g/min), respectively (Fig. 2), indicating exposure to Furadan.

The relationship of brain AChE activity to age (days) in control nestlings ($n = 14$; ages ranging 0–9 d) appeared to be exponential and was appropriately described by the equation $\text{AChE} = 8.915e^{0.134\text{age}}$, with an R^2 of 0.90. The effect of exposure to Furadan on brain AChE, taking age into account, was highly significant ($p < 0.0001$). Activities of almost every nestling collected from Furadan-sprayed plots fell outside of the 95% confidence limits of mean predicted control values. A few older nestlings showed severe depression of AChE activities. For example, a 6-d-old nestling had 70% depression relative to the predicted control 6-d value (6.3 vs 21.0 μmol/g/min); a 9-d-old nestling exhibited 60% depression from the predicted control value for this age (11.6 vs 28.6 μmol/g/min) (Fig. 2).

We examined the reproductive success of the 20 nests from which we collected nestlings at the time of spraying with Furadan and compared these parameters to nests in control plots over the two-week period immediately preceding spraying ($n = 19$ nests). We accounted for the removal of nestlings for AChE analysis in the following way: If at least one nestling in the nest subsequently fledged, we assumed that the removed nestling would also have fledged; if the entire nest was unsuccessful (destroyed or abandoned), we assumed the removed nestling would also have died. A comparison of the fate of each nest at nestling age 7 indicated that only two of 20 Furadan-exposed nests failed completely, compared to eight of 19 control nests in the prespray period, and this difference was significant ($\chi^2 = 4.58$, $p = 0.03$).

Table 7. Productivity of Baird's sparrows over the entire breeding season in plots in areas sprayed for grasshopper control. Only plots with at least one occupied territory were used to determine productivity parameters per plot[a]

	Unsprayed	Decis™	Furadan™	*p*
n[b]	12	12	12	
Occupied plots	9	10	9	NS[c]
Productive plots	6	4	1	0.08
Territories/plot	1.4 (0.2)	1.4 (0.2)	1.3 (0.2)	NS
Productivity territories/plot	0.7 (0.2)	0.4 (0.2)	0.1 (0.1)	0.05
Mean productivity score/plot	2.7 (0.6)	2.1 (0.6)	1.3 (0.3)	NS
Abandoned territories/plot	0.4 (0.2)	0.5 (0.2)	1.1 (0.2)	0.06

[a] Mean (standard error).
[b] Number of plots censused.
[c] Not significant at $p < 0.10$.

In successful nests, however, individual nestling survival was significantly greater ($p = 0.04$) in control nests (0.91; $n = 11$ nests) than Furadan-exposed nests (0.74; $n = 18$ nests).

Baird's sparrow productivity

Baird's sparrows occurred in a similar proportion of census circles in all treatments but tended to show productivity in fewer Furadan-sprayed circles than Decis and control circles ($p = 0.08$; Table 7). Among occupied circles, those sprayed with Furadan had fewer productive Baird's sparrow territories and a greater number of abandoned territories per circle than the other treatments (Table 7).

DISCUSSION

By the time of spraying in late June, grasshopper densities were at levels that would economically justify pesticide applications for their control in grazing land (8–13 grasshoppers/m² [1]). Both Decis and Furadan provided excellent control of the pest species, although Decis provided somewhat better long-term suppression.

Spraying 56-ha (140-acre) grassland plots with either Furadan or Decis flowable formulations at rates recommended for grasshopper control in Canada did not appear to affect reproductive output of the dominant ground-nesting grassland songbird, the chestnut-collared longspur. The number of eggs, nestlings, and fledglings produced per nest was similar among all treatments after spraying. Martin et al. [15] found that the depredation rate of nests of chestnut-collared longspurs in the egg stage was significantly higher in Decis-sprayed versus unsprayed plots and that hatching success in surviving nests in plots sprayed with Decis was statistically less than in unsprayed plots. In the present study, we observed a fairly low rate of loss of complete nests in the incubation stage, and hatching success was uniformly high in all treatments (>70%). Overall rates of total nest depredation in our study were similar to those found by Martin et al. [15] of 26 to 40% in chestnut-collared longspurs. These rates are slightly lower than those of around 50% reported for other chestnut-collared and McCown's (*Calcarius mccownii*) longspur populations [33–35]. In addition, rates of loss of individual eggs and nestlings in otherwise successful nests were low in our study (2–17% for eggs, 0–13% for nestlings) with the exception of nestling success in the Furadan prespray plots (22% mortality). Losses of individual eggs and nestlings from successful nests may be attributed to such predators as American crows (*Corvus brachyrhynchos*) or Richardson's ground squirrels (*Spermophilus* *richardsonii*), both of which were abundant in some areas on the study site. Larger mammalian predators are more likely to consume the entire contents of nests.

Reductions in productivity and increases in territory abandonment of Baird's sparrows on Furadan-sprayed plots suggest that this species may be more sensitive to toxic pesticide effects than were the longspurs, although numbers are so low as to make conclusions tenuous. Nevertheless, it is possible that differences in nest placement or parental behavior make them less able to tolerate exposure to cholinesterase-inhibiting insecticides. It is possible that nestlings may be more sensitive to Furadan toxicity. Because we do not have information on the chronology of individual Baird's sparrow nests relative to spraying, we can only speculate on the causes of productivity declines.

The size of longspur nestlings just prior to fledging was unaffected by spraying with either insecticide. Despite an obvious reduction in food resources, most notably grasshoppers, in both Furadan and Decis plots during the four weeks following spraying, parent longspurs were able to provide enough food to their nestlings to raise them successfully to fledging stage at a normal body size. Esophageal samples indicated that there were no differences in the total biomass of food being brought to nestlings during a set period. Systematic surveys of the ground surface for dead and moribund insects following spraying revealed that large numbers of Noctuidae larva (Lepidoptera: cutworms) and Scarabidae beetles were present on the Decis-sprayed plots and less so in the Furadan-sprayed plots (D. Forsyth, unpublished data). At 72 h postspray, 78 and 64 mg dry weight of noctuid larva and scarabid adults, respectively, were found per 10-m transect in Decis-sprayed plots compared to 2.3 and 6.5 mg dry weight for the two taxa in the Furadan-sprayed plots. Few scarabids (3.6 mg dry weight/transect) and no dead or moribund noctuids were located in unsprayed plots. Thus, at least shortly after spraying, birds in Decis-sprayed plots had a ready alternate food source. In fact, examination of nestling diet in the postspray period shows that Decis sprayed nests did rely more extensively on beetles and lepidoptera, whereas this trend was not apparent in the Furadan-sprayed nests. Martin et al. [15] suggested that the availability of cutworm larvae for several days following spraying of grassland with Decis also contributed significantly to the foraging success of adult longspurs. Byers et al. [16] observed that control of cutworms with the pyrethroid permethrin was delayed for several days because 50% of the target population was molting underground at the time of pesticide application. These animals did not come into contact with the residue on the soil surface until molt was completed, and mortality ensued up to 7 d after application.

Observations of parental foraging indicated that in the two-week period following pesticide application, adults fed nestlings as frequently and did not fly further in sprayed plots than in control plots during the 30-min observation period, corroborating findings of Martin et al. [15] following spraying with Decis. As we observed birds for only a single session, it is unknown whether parents in sprayed plots spent a larger proportion of the day foraging to fulfil the energy requirements of their nestlings. However, the fact that insect biomass obtained within 30 min was similar among treatments indicated that there was no need for parent birds to increase foraging time in sprayed plots relative to controls. Later in the season (after July 12), however, parent birds on Decis-sprayed plots foraged farther from the nests than birds in either Furadan-sprayed or control plots to obtain the same amount of food. This may have been due to longer-term efficacy of Decis in grasshopper control exacerbated by normal seasonal declines in insect numbers. The extent to which the extra energy expenditure of longer foraging flights might affect parental success is unclear. Mock [36] determined that western bluebird (*Sialia mexicana*) adults were able to fulfil their own energy requirements as well as those of four to six nestlings by foraging for less than 10% of daylight hours, concluding that they were neither time limited nor working maximally. Clark and Ricklefs [37] calculated that time and energy demands would seldom constrain parent European starlings (*Sturnus vulgaris*) except during the early posthatch period before nestlings had reached full homeothermic capacity, during prolonged periods of inclement weather when constant brooding by one parent is necessary. For savannah sparrows (*Passerculus sandwichensis*), it was calculated that both parents must spend almost twice as much time foraging to support four nestlings compared to effort required to meet their own energetic demands [38]. However, single-parent sparrows were able to successfully raise broods on their own by more than doubling the number of feeding trips made to the nest compared to the number of trips made by each parent in an intact pair. This suggests that under the normal condition in which two parents are present, savannah sparrows are not working maximally. Thus, doubling the distance flown by longspur parents during foraging, as seen in the Decis-sprayed plots, is within the limits of typical energetic demands put on passerine birds in temperate environments and would probably not have a detrimental effect. In fact, the mean distances flown in Decis-sprayed plots after spraying were similar to those observed early in the season before spraying. Reductions in food availability may have the greatest impact on avian reproduction during the critical period shortly after juvenile birds have gained independence from their parents and are foraging on their own [36,39].

Although effects of spraying either the pyrethroid or the carbamate insecticide on longspur reproduction through the removal of insect food resources appeared to be minimal, our objective was also to determine whether Furadan was affecting reproductive success as a result of acute toxicity. As expected, brain cholinesterase activity in control birds increased linearly with nestling age, although at a much greater rate and reaching a higher adult level than previously measured in three other species of passerine. Mean adult brain AChE activity of chestnut-collared longspurs was 57 μmol/g/min ($n = 2$), compared to activities for house wrens (*Troglodytes aedon*) of 35.9, European starlings of 26.6, and eastern bluebirds (*Sialia sialis*) of 35.2 μmol/g/min [40,41]. Although brain AChE was significantly reduced in most Furadan-exposed birds and by as much as 70% in a few individuals, no mortalities could be attributed solely to Furadan poisoning. A single chick found dead with depressed AChE activity was already badly infested with blowfly larvae and probably severely weakened. AChE depression in that nestling was of a level typically associated with death by Furadan poisoning [42,43]; nevertheless, other surviving chicks had greater levels of inhibition. Nestling success and total number of fledged nestlings per nest were indistinguishable between broods directly sprayed with Furadan and control broods during the prespray period. These findings indicate that nestlings did not receive enough toxicant in their diets to constitute an acute dose, and that they were able to withstand substantial reductions in brain AChE with no detrimental effects up until the time of fledging. Postfledging survival was not assessed. Forsyth et al. [5] determined that a 12-g nestling clay-colored sparrow could consume approx. 0.8 g of grasshoppers in a bout of feeding to satiety. At the concentration of carbofuran found on grasshoppers in a pasture sprayed at the same rate as in the present study, 2.5 μg/g, Forsyth and Wescott [32] calculated that nestling clay-colored sparrows would consume 0.2 mg of carbofuran/kg body weight in a day, approx. 14% of the LD50 of adults (1.4 mg/kg [5]). Some studies have shown nestlings to have greater sensitivity to cholinesterase-inhibiting chemicals [44,45]; others suggest that age-related sensitivity varies with species and chemical [46,47]. Even if nestling longspurs were more sensitive to carbofuran than adults, it is possible that the rapid onset of sickness may have reduced their appetites sufficiently to prevent them from accumulating a lethal dose. Because the depression of AChE by carbofuran is short-lived (approx. 4 h to return to normal in 3-d-old mallard ducklings [43]) and it breaks down rapidly in grassland vegetation (2 d to less than 50% [32]), the risk of nestlings receiving a lethal dose after the first day seems to be slight.

Adult birds feeding on contaminated insects also risked poisoning, which, even if sublethal, could be of consequence to the survival of their young. Grue et al. [48] found that adult starlings dosed with the organophosphorus insecticide dicrotophos decreased feeding efforts and that nestling weights were significantly reduced. Powell [49] also found reductions in nestling weight of red-winged blackbirds (*Agelaius phoenicus*) nesting in one of two areas sprayed with fenthion. However, Meyers et al. [47] reported that, although female red-winged blackbirds dosed with methyl parathion spent significantly less time on the nest within 2 h of dosing, hatching success of eggs was not affected. In the present study, as least one parent at each nest was observed behaving normally 2 h after spraying occurred and in the evening of the same day. Such concerns as nest abandonment, either permanent or short termed, that might make nestlings more susceptible to depredation did not appear to be a factor, as overall success of Furadan-sprayed nests was slightly greater than that of control nests. Nevertheless, when nests that were totally destroyed, presumably by predation, were removed from the data set, the success of individual Furadan-exposed nestlings is 17% less than that of control nestlings. Although the overall comparison of parental feeding rates during the two-week postspray period reveals no differences between nests in unsprayed and Furadan-sprayed plots, smaller individuals within a nest might have succumbed as a result of reduced parental food deliveries during the hours following spraying. It is possible that one parent bird at some nests suffered sublethal Furadan poisoning resulting in behavioral impairment, as we did not always see both parents during the nest checks on the day of spraying. White et al. [50] found that, while one member of each pair of laughing gulls (*Larus atricilla*) was administered a sublethal dose of parathion, the undosed individual was able to maintain incubation constancy until the other had recuperated (about 3 d). In chestnut-collared longspurs, however, only the female incubates and broods, and it is possible that sublethal exposure of the female to an AChE inhibitor during incubation or in the early nestling period, particularly during inclement weather, might have negative consequences for her offspring. We observed no reductions in hatching success of egg nests in Furadan-sprayed plots during the postspray period, however.

Acknowledgement—We thank M. Uchikura, R. Maw, N. Michaud, E. Fitzner, S. VanWilgenburg, D. Becker, D. Drader, and C. Andrews for assistance in the field. D. Inaba and M. Mills conducted sampling and analysis of pesticide residues and spray droplet cards. Three anonymous reviewers provided useful comments on the manuscript. Funding was provided in part by the Canada-Alberta Environmentally Sustainable Agriculture Fund.

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