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Changes in non-target arthropod populations following application of liquid bait formulations of insecticides for control of rangeland grasshoppers

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Abstract

This study was undertaken to determine the non-target impacts of rangeland grasshopper control using liquid bait formulations of insecticides (canola and corn oil as carriers of carbaryl, diflubenzuron, and malathion). The research was conducted on native rangeland in Wyoming under drought conditions. Three collection methods (pitfall traps, yellow sticky cards, and sweep nets) were used to estimate non-target arthropod densities. The formulated insecticides were applied according to the protocol of reduced agent-area treatments, an application method designed to reduce economic and environmental costs by applying insecticides at low rates with incomplete coverage via alternating treated and untreated swaths). Canola and corn oils are vegetable oils high in linolenic and linoleic acids which function as attractants and phagostimulants for many species of grasshoppers. Crop oil is a biologically inert paraffin-based petroleum product that served as a control. Although all treatments markedly reduced grasshopper population densities, non-target populations were nominally affected. There were no consistent, significant differences in the responses of non-target populations to treatments with the liquid baits (canola and corn oil carriers) relative to those observed with the standard carrier (crop oil). Only one taxonomic group (Formicidae) showed a significant negative response to treatment relative to untreated controls. Logistical and ecological factors associated with grasshopper control methods may account for the nominal effects on non-target taxa. Sweep net and sticky trap sampling were more sensitive to treatment effects and time-by-treatment interactions. Temporal changes in population densities may have made treatment effects difficult to distinguish in several taxonomic groups.

Keywords: *Non-target, barrier treatment, acridid control, attractants*

1. Introduction

Worldwide, large-scale, blanket application of conventional chemical insecticides remains the principal management strategy to reduce crop and forage losses during acridid (grasshopper and locust) pest outbreaks (Pfadt and Hardy 1987; Steedman 1988; Latchininsky 1997; Hunter et al. 1998; Lockwood et al. 2000; Showler 2002). During the Desert locust (*Schistocerca gregaria* [Forskål]) outbreak in Africa in 1986 – 1989, about 14 million litres of organophosphate, pyrethroid and carbamate insecticides were applied to 25.9 million hectares of infestations (Skaf et al. 1990; Showler and Potter 1991). In the western US, during an outbreak of several rangeland grasshopper species in 1985 – 1988, over 8 million hectares were treated with 5 million litres of organophosphate and carbamate insecticides (Lockwood and Schell 1997). A similar area of 8.1 million hectares was blanketed with 947 000 litres of insecticides in Kazakhstan in 2000 to protect crops and rangeland from an outbreak of the Italian locust (*Calliptamus italicus* [L.]) (Khasenov 2001).

Generally speaking, such large-scale, blanket applications of conventional insecticides have been successful in managing acridid outbreaks, but they do have some disadvantages. More specifically, such control programmes can actually increase the probability, duration, and stability of grasshopper and locust outbreaks over the long term (Lockwood et al. 1988). They can also cause the local extirpation of predators and parasites, effectively creating predator-free space and thus constraining the natural mechanisms driving acridid population dynamics (Lockwood et al. 1988; van der Valk et al. 1999). As a result, grasshoppers and locusts exploit this spatiotemporal opportunity and their populations can rapidly and dramatically resurge (Lockwood 1998; Joern 2000; Samways 2000).

Another flaw of traditional blanket applications is that of economic cost. In Africa, where the burden of expenses for acridid pest control is carried primarily by donor countries, the costs of the anti-locust campaign in 1986 – 1989 were estimated between US$250 and US$310 million (OTA 1990; Showler and Potter 1991). In the western US, during the

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1985 – 1988 outbreak the federal governmental agencies spent US$75 million to control rangeland grasshoppers (Lockwood and Schell 1997). The costs of an anti-locust campaign in Kazakhstan in just 1 year (2000) exceeded US$20 million (Khasenov 2001). Despite the enormously high investments in control operations, their abilities to terminate outbreaks is often questionable, as the end of a locust or grasshopper outbreak is often attributed to climatic rather than anthropogenic factors (OTA 1990; Skaf et al. 1990; Showler 2002).

In the western US, the United States Department of Agriculture (USDA) carried the financial burden of large-scale insecticide application until 1996. Until then, the USDA paid 100% of the costs on federal land, 50% of the costs on state land, and 33% of the costs on private land (Lockwood and Schell 1997). Beginning in 1996, however, the USDA revoked its subsidies and transferred the full cost of controlling grasshopper outbreaks to the ranchers and state or local agencies (a partial return of federal cost-sharing has recently been adopted). As such, blanket insecticide applications, over large areas, were no longer economically or ecologically viable. Therefore, a different kind of management programme was introduced; the reduced agent/area treatment (RAAT) programme (Lockwood and Schell 1997; Schell et al. 2001).

Briefly, the RAAT application utilizes lower levels of insecticides, compared to traditional methods, on alternating (but not necessarily equal) strips of infested land. The ecological and environmental benefits of a RAAT programme largely depend on the untreated swaths created by this approach. Such non-toxic refugia appear to be extremely beneficial for protecting non-target fauna and natural enemies of grasshoppers. Compared to standard, blanket applications, RAATs result in higher populations of birds (Norelius and Lockwood 1999) and many non-target arthropod taxa (Lockwood and Schell 1997), including weed biocontrol agents as *Aphthona* spp. (Foster et al. 2001). Because of its lower environmental impact, RAAT was included as an option in the Environmental Impact Statement for grasshopper and Mormon cricket suppression programme (USDA 2002). A similar approach of incomplete insecticidal coverage was developed for locust control in Africa, Australia and Central Asia. This is called barrier treatment, which consists in applying insecticide swaths perpendicular to the movement of the hopper band with very wide, several hundred metre, insecticide-free swaths (Kambulin 2000; Dobson 2001; Hunter and Deveson 2002).

In addition to grasshopper movement into treated swaths and conservation of native biological control agents, other factors, such as the intrinsic properties of the control agent and its formulation, are important to the efficacy of the RAAT programme. More specifically, insecticides with longer residual toxicity and the need for ingestion before they become effective, are the preferred insecticides for use in a RAAT programme. Therefore, organophosphate and pyrethroid insecticides with very short residual toxicity have little potential for use in either a RAAT or barrier treatment programme. Carbamates (e.g., carbaryl) exhibit some stomach action and a certain residual toxicity making their use possible in a RAAT context (Lockwood et al. 2000). Insecticides from the benzoyl-urea group (Insect Growth Regulators, or IGRs) and phenyl-pyrazoles (fipronil), appear to fit best into both RAAT and barrier treatment programmes due to their mode of action primarily by ingestion and their long residual toxicity (Cooper et al. 1995; Lockwood et al. 2000; Dubliazhova 2001; Spurgin 2005). IGRs target only immature stages of insects and are more selective than conventional, broad-spectrum insecticides which kill all developmental stages. The most commonly used IGR, diflubenzuron, was shown to be effective against rangeland grasshoppers in the western US in a blanket coverage of up to 50 g a.i./ha (Catangui et al. 1993, 1994a,b; Jech et al. 1993; Foster and Reuter 2000). Elsewhere, diflubenzuron is used against locusts and grasshoppers at dose rates between 30 and 60 g a.i./ha (Bouaichi et al. 1994a; Gapparov 2001; FAO 2004) although in some cases, sufficient control is achieved at very low dose rates of 6 g a.i./ha (Weiland et al. 2002).

However, blanket application of diflubenzuron may not be necessary as this IGR has a relatively long persistence. For example, barrier treatments with diflubenzuron were shown to be effective against the Moroccan locust (*Dociostaurus maroccanus* [Thunberg]) (Bouaichi et al. 1994b), Italian locust (Dolzhenko 2003), Migratory locust (Scherer and Rakotonandrasana 1993; Scherer and Célestin 1997) and Desert locust (Wakgari 1997). RAAT diflubenzuron treatments have also effectively reduced the numbers of rangeland grasshoppers in the western US (Royer et al. 2001; Weiland et al. 2002).

In addition to the importance of active ingredient, certain properties of the insecticide formulation also play an important role in enhancing the efficacy of locust and grasshopper control programmes. For example, many acridicides are applied as ultra-low volume (ULV), oil-based formulations (Dobson 2001). However, due to their attractant and phagostimulant properties (Bomar and Lockwood 1994c), vegetable oils as insecticide carriers in a RAAT programme provide further improvements in grasshopper management practices, allowing pest managers to further reduce insecticide rates and application coverages. Use of vegetable oils as insecticide carriers works as follows. Grasshoppers can obtain essential nutrients by feeding on a variety of plants, but rangeland vegetation is deficient in fatty acids and proteins which are essential for optimal egg production (Bomar and Lockwood 1994c). However, these limiting nutrients can be acquired in high amounts via feeding on plant reproductive organs (flowers and seeds) or through necrophagy and cannibalism, which are common behaviours in grasshoppers (Lockwood 1989; Bomar and Lockwood 1994a; Smith and Lockwood 2003). Grasshoppers locate cadavers via olfactory cues, and fatty acids serve as the primary stimuli (Bomar and Lockwood 1994b). The most effective fatty acids are linolenic and linoleic acids, which volatilise from cadavers following death. These are particularly abundant in corn and canola oil. Bomar and Lockwood (1994c) considered using such oils to enhance the attractiveness of solid baits, and subsequent studies demonstrated that these oils can function as liquid baits when used as carriers of insecticides (Lockwood et al. 2001). Using such oils as attractant carriers in a RAAT application increases the efficacy of the programme by attracting grasshoppers into treated swaths. However, the use of liquid baits (insecticides formulated in vegetable oil) could represent significant risks to non-targets and beneficial arthropods that might also be attracted to the treated areas (e.g., seed-feeding taxa that might use fatty acids to locate food sources).

Terrestrial arthropods appear to be the most affected group of non-target organisms due to traditional acridicide treatments (van der Valk and Everts 2003). For example, different terrestrial arthropod taxa were found to be reduced in diversity and abundance following both locust (Matteson 1992; Murphy et al. 1994; Balança et de Visscher 1995; Tingle 1996; Peveling et al. 1999a,b) and grasshopper (Pfadt et al. 1985; George et al. 1992; Catangui et al. 2000) management programmes. However, the effects of RAAT programmes on terrestrial arthropods are yet insufficiently studied. Therefore, the goal of this research was to determine both qualitative and quantitative effects of rangeland grasshopper control with oil insecticide carriers on non-target terrestrial arthropods. The oils used in this study were corn oil, canola oil, and crop oil. Corn and canola oils are vegetable oils that are high in linoleic and linolenic acids (Lockwood et al. 2001), and these oils are generally less expensive than the paraffin-based petroleum product that is widely used by commercial pesticide applicators as an insecticide carrier (crop oil).

Given that grasshopper and locust outbreaks occur on every inhabited continent and that the insecticides and application methods examined in our study are similar to those being used in many other agroecosystems, the findings of this research should be pertinent to the worldwide effort to minimise economic and environmental costs of acridid pest management while optimising the returns with regard to food security and agricultural profitability.

2. Materials and methods

2.1. Field sites

Tests were conducted in 2001 and 2002 on rangeland located 10 km north of Lingle, Wyoming, on the west side of US Highway 85 (42°12.5′N, 104°19.25′W; elevation ca. 1300 m) and on rangeland located 13 km southwest of Lingle, Wyoming (42°3.15′N, 104°26.75′W; elevation 1350 m), respectively. Both areas consisted of native mixed-grass prairie, with the dominant flora being: western wheatgrass (*Agropyron smithii* Rybd.), needleandthread (*Stipa comata* Trin. & Rupr.), downy brome (*Bromus tectorum* L.), threeawn (*Arista spp.*), gramma (*Bouteloua* spp.), fringed sagebrush (*Artemisia frigida* Willd.), plains pricklypear (*Opuntia polyacantha* Haw.), and yucca (*Yucca glauca* Nutt.). The plant cover ranged from 25 to 50%, and canopy height ranged from 10 to 20 cm. The summers of 2001 and 2002 were abnormally hot and dry; the only precipitation (10 mm) during the study periods occurred during the third week post-treatment in 2001.

2.2. Insecticides

Three insecticides (diflubenzuron, malathion, and carbaryl) were tested. Diflubenzuron is an insect growth regulator that acts primarily by ingestion (Elliott and Iyer 1982) and affects insects as they molt by interfering with the formation of chitin (Grosscurt and Jongsma 1987). As such, this insecticide targets immature (moulting) insects, both hemimetablous nymphs and holometaboulous larvae. Diflubenzuron was applied as an ultra low volume (ULV) insecticide (17.5 g a.i./ha). At this dose rate it has residual activity of more than 3 weeks (Weiland et al. 2002).

Malathion is an organophosphate neurotoxin that acts through contact by inhibiting cholinesterase, the enzyme responsible for degradation of the neurotransmitter acetylcholine. This insecticide is considered a broad-spectrum insecticide, targeting a wide array of arthropods and being toxic to vertebrates. The malathion used in this study was formulated as a ULV insecticide (693 g a.i./ha). Malathion has a very low residual activity of about 2 – 4 days.

Carbaryl is a *N*-methyl carbamate neurotoxin that is also a cholinesterase inhibitor. Carbaryl, like malathion, affects both immature and adult arthropods and is toxic to vertebrates. The formulation used in this study is typically applied using a water carrier at ULV rates (561 g a.i./ha). Unlike malathion, carbaryl has a relatively long residual activity of 7 – 10 days. It acts both by contact and by ingestion.

Using these insecticides, tests were conducted with a standard, blanket approach (only with malathion), the current recommended RAAT approach, and vegetable oil-enhanced/liquid-bait RAAT methods. The particular treatments were selected to refine grasshopper control methods, with the non-target study being a subsidiary project of the larger, efficacy study. The oil-enhanced strategies were developed using three rationales: decreased coverage (e.g., for carbaryl, the recommended RAAT was 280 g a.i./ha of formulated insecticide applied to 50% of the land [280-50], so the study tested 280-33), decreased rate (e.g., the study included a 140-50 treatment), and decreased rate and coverage (e.g., the study included a 140-33 treatment).

2.3. 2001 treatments

Treatments with diflubenzuron (Dimilin 2L®) were used in combination with corn and canola oil using standard RAATs (17.5 g a.i./ha with 33% coverage or 17.5-33; Table I). Diflubenzuron was also applied in crop and canola oils with reduced-area application (25% coverage). Finally, diflubenzuron was applied in crop oil at a reduced rate (13 g a.i./ha) using the standard RAAT coverage for this insecticide (33%). Carrier volume for diflubenzuron was 710 ml/ha, using one part oil (crop oil concentrate nonionic adjuvant, Crisco® canola oil, or Our Family® corn oil) to two parts water (Table I).

To stabilise the carbaryl, LI 700 adjuvant was added to acidify the water used alone and in combination with oil carriers. Selected rates of carbaryl were applied with water and 730 ml/ha of canola oil or corn oil. The standard RAAT protocol (280 g a.i./ha of carbaryl with 50% coverage) was used with both water and canola oil as carriers. A reduced-coverage RAAT (33%) at the standard rate was tested with corn oil as a carrier. Canola oil was used to test a reduced rate (140 g a.i./ha) treatment with the standard coverage (50%). Finally, canola was also used to test a reduced rate (140 g a.i./ha) and coverage (33%) treatment (Table II). Replicated, 16-ha control plots were situated 0.8 km upwind of the diflubenzuron and carbaryl treatments.

All treatments were applied by air on 27 June 2001 to duplicated, square, 16-ha (40-acre) plots. Application of the insecticides was done by AgFlyers of Torrington, Wyoming. An Eagle DW-1, equipped with eight, CP nozzles (0.157 cm orifices, deflection set at 90°) operating at a boom pressure of 2.7 kg/cm^2 sprayed at an altitude of about 10 m. The weather conditions at the time of application were clear and dry with a wind prevailing from the east-southeast ranging between 1.1 and 2.6 m/s, with gusts reaching 4.0 m/s. Application began at 05:45 and ended at 08:30. The air and ground temperatures at the onset of applications were 12°C, reaching 17 and 15°C, respectively, by the end of the applications.

2.4. 2002 treatments

Malathion (Fyfanon ULV) was used at the standard rate with blanket coverage (693 g a.i./ha with 100% coverage or 693-100), traditional rate with a decreased coverage (693-50), and standard RAAT (347-80). Canola oil was used to test the standard RAAT rate with a further reduction in coverage (347-50) and the traditional rate with extremely reduced coverage (693-33; Table III). Replicated, 16-ha control plots were situated 0.2 km upwind of the treatments.

Application of the insecticide was done on 18 June 2002 by AgFlyers of Torrington, Wyoming using the same equipment and protocols of 2001. The weather conditions at the time of application were clear and dry with a wind prevailing from the west–northwest, ranging between 0.9 and 2.6 m/s, with gusts reaching 4.0 m/s. Application began at 06:00 and ended at 07:00. The air temperature at time of application was 17°C, and the ground temperature was 15°C.

2.5. Sampling protocols

Data were collected using three methods. First, 10 pitfall traps were placed 20 m apart along a transect

Table I. Diflubenzuron treatment parameters for rangeland grasshopper control in southeastern Wyoming in 2001.

Treatment code	Treatment type	Coverage	Insecticide rate (g a.i./ha)	Carrier oil	Oil rate (ml/ha)	Water rate (ml/ha)
d	Standard RAAT	33%	17.5	Corn	584	1160
e	Standard RAAT	33%	17.5	Canola	584	1160
a	Standard rate; decreased coverage	25%	17.5	Crop[1]	584	1160
b	Standard rate; decreased coverage	25%	17.5	Canola	584	1160
c	Decreased rate: standard coverage	33%	13	Crop[1]	584	1160
u	Control	0%	0	0	0	0

[1] Crop oil is a paraffin-based petroleum product that is widely used as an insecticide carrier.

Table II. Carbaryl treatment parameters for rangeland grasshopper control in southeastern Wyoming in 2001.

Treatment code	Treatment type	Coverage	Insecticide rate (g a.i./ha)	Carrier oil	Oil rate (ml/ha)	Water rate (ml/ha)
j	Standard RAAT	50%	280	None	0	1160
i	Standard RAAT	50%	280	Canola	730	584
h	Standard rate; decreased coverage	33%	280	Corn	730	584
f	Standard coverage; decreased rate	50%	140	Canola	730	730
g	Decreased rate and coverage	33%	140	Canola	730	730
u	Control	0%	0	0	0	0

Table III. Malathion treatment parameters for rangeland grasshopper control in southeastern Wyoming in 2002.

Treatment code	Treatment type	Coverage	Insecticide rate (g a.i./ha)	Carrier oil	Oil rate (ml/ha)
a	Traditional blanket	100%	693	None	0
b	Traditional rate; decreased coverage	50%	693	None	0
c	Standard rate; increased coverage	80%	346.5	None	0
d	Standard rate; decreased coverage	50%	346.5	Canola	730
e	Traditional rate; decreased coverage	33%	693	Canola	730
u	Control	0%	None	Untreated	0

in each plot (100 m from plot border, perpendicular to the treated swaths). Each trap was filled with 350 ml of 75% ethanol, and covered with a plastic dinner plate 30 cm in diameter to reduce evaporation. The plates were affixed to the ground using nails (9.0 × 0.5 cm) that were sheathed with a 4-cm long spacing tube underneath the plate to create a gap between the plate and the ground. Second, yellow sticky cards (7 × 8 cm) were affixed next to each pitfall trap using staples to 46-cm high wooden stakes. The height of the yellow sticky card was ca. 25 cm above the ground or just above the canopy. The sticky cards were oriented to the west, as the prevailing winds in the area are from a westerly direction. By placing the cards above the foliage and facing west, a representative sample of low-flying insects was collected. Third, sweep net sampling was conducted with a 0.37-m diameter net. Sampling was conducted with 50 low-slow sweeps to capture young or less active arthropods, followed by 50 high-fast sweeps to capture mature and more maneuverable arthropods. Low-slow sweeps were conducted with the bottom edge of the net at the ground surface and a rate of ca. 50 sweeps/min. High-fast sweeps were conducted with the bottom edge of the net at the top of the vegetation canopy and at a rate of ca. 150 sweeps/min. The 100 sweeps were conducted parallel to the pitfall trap line.

In 2001, pitfall and yellow sticky card traps were set 1 week prior to treatment and emptied the day of treatment to establish a pretreatment baseline. The pitfall traps were then refilled and operated for 24 h, each week after treatment for 3 weeks. Sticky traps were collected weekly for 3 weeks. Sweep net sampling was conducted 1 week prior to treatment, and weekly for 3 weeks after treatment. In 2002, the pretreatment pitfall traps were set for only 24 h before treatments. Post-treatment sampling was the same as in 2001, except an additional sampling time was incorporated at 2 days after applications.

2.6. Sample processing

Non-target arthropods collected in the pitfall traps and sweep nets were identified to the level of family using the keys of Borror et al. (1998). The arthropods collected on the yellow sticky cards were generally identified to the level of order due to difficulties in identification and preservation of captured specimens. Removing specimens from the sticky cards without causing extensive damage was not possible and diagnostic features were difficult to observe and identify *in situ*. Only ants (Formicidae) could be reliably identified to family. Due to the diversity of Dipterans (>12 families) and inconsistent frequencies of those families, these insects were pooled at the order level in all sampling methods. Sweep net sampling also generated erratic assemblages of families of Heteroptera and Coleoptera, so specimens were pooled into their respective orders to generate large enough numbers for statistical analysis. Where samples sizes were sufficient, beneficial families (Carabidae) and ecological 'indicator' taxa (Tenebrionidae) were analysed separately.

2.7. Statistical analysis

Captured non-target organisms were averaged, for each taxonomic group, over all pitfall traps, sticky cards, or sweep net samples that were taken within their respective plots for each sampling week. In several plots, the number of recovered samples was less than the number of traps placed in the field due to losses from scavengers and damage by livestock. Averages for pitfall traps and sticky card captures were then subjected to a weighted, split-plot-in-time ANOVA that was set in a completely randomised design. Analysis of residuals indicated no need for transforming the data. Weights used were the number of pitfall traps or sticky cards per plot. Weights were needed because the destruction of pitfall traps and sticky cards by cattle caused the number of traps and cards to be unequal among plots. Average values for sweep net captures were subjected to an unweighted split plot in time ANOVA as a consistent number of sweep net samples was taken in each plot on each sampling date. In these analyses, the main effects of insecticide treatments (hereafter, treatments) were tested against the null hypothesis that there were no differences among treatments versus the alternate that a difference occurred between at least two. Similarly, we tested the main effects of weeks against the null hypothesis that there were no differences among the weeks versus the alternate that a difference occurred between at least two. If the ANOVA indicated that some differences existed among weeks or treatments and if a week-by-treatment interaction did not occur, then mean separations were conducted using Tukey's honestly significant difference (HSD) procedure, with a maximum level of type I error being set at 0.1. If a week-by-treatment interaction did occur, Tukey's HSD was used to detect differences among treatments separately for each week. Data analyses were performed using the GLM procedure of the Statistical Analysis System (SAS Institute 1999). Although a wide diversity of arthropods was represented in this study, just those taxonomic groups that were sampled with enough frequency and consistency (i.e., being present in virtually all plots pre-treatment) were used in these analyses. Finally, separate analyses were conducted for each year of the study.

3. Results

3.1. *2001 effects for weeks, treatments and their interaction*

In 2001, 26 433 arthropods were collected and identified representing 35 families, seven orders, and two classes. Among these, pitfall traps collected a total number of 15 436 arthropods, yellow sticky cards yielded 8733, and sweep nets collected 2264. Based on these specimens, we conducted 11 statistical analyses. Of those, four showed that differences occurred among the main effects of weeks, just one showed that differences occurred among the main effect of treatments, and three showed that a significant week-by-treatment interaction had occurred. For the analyses in which differences occurred among weeks, two involved pitfall traps, one involved sticky cards, and one involved sweep netting. For the pitfall traps, more Formicidae were captured during week 3 than were captured during all other weeks of the study (Table IV). Also for the pitfall traps, more Carabidae were captured during the middle weeks (1 and 2) than were captured during the week 0 of the study (Table IV). For the sticky cards, more wasps/bees were captured during week 2 than were captured during all other weeks of the study (Table IV). For the sweep netting, more Heteroptera were captured during week 4 than were captured during weeks 1 and 3; the number of Heteroptera captured during week 2 was intermediate (Table IV).

For the analysis for which differences occurred among the main effects of treatments, more Formicidae were captured from plots receiving carbaryl at the decreased rate (with canola oil), but at an increased coverage, than were captured from plots receiving diflubenzuron (with canola oil), but at a reduced coverage. Captures of Formicidae from plots receiving all other treatments were intermediate (Table V).

For those analyses that involved a significant week-by-treatment interaction, two involved the use of sticky cards and one the use of sweep netting. For the sticky cards, the first interaction occurred with Diptera, and was primarily caused by two treatments: (1) the captures in plots receiving the standard RAAT of carbaryl (no carrier oil) increased greatly from week 0 to week 1, then fell from week 1 to week 2, and (2) captures in plots receiving the standard rate (with canola oil), but decreased coverage, of diflubenzuron rose from weeks 0 through week 2, then fell greatly from weeks 2 to 3 (Table VI). When we examined the mean separations of treatment averages by week, some differences occurred among treatments in each of the first 2 weeks; however, no such differences occurred in the remaining weeks (Table VI). In week 0, captures in plots receiving the standard RAAT treatment of carbaryl (with canola oil) was greater than captures in plots receiving all other treatments, including the untreated control. For week 1, captures in plots receiving the standard RAAT treatment of carbaryl (no carrier oil) was greater than captures in plots receiving all other treatments, except the standard rate of diflubenzuron (with canola oil), but with decreased coverage, and those receiving the untreated control.

Table IV. Mean densities of various groups, collected in pitfall traps or on sticky cards from plots treated for rangeland grasshoppers in southeastern Wyoming in 2001 and 2002. Means with differing letters are significantly different according to Tukey's HSD ($P < 0.10$).

2001

Time	Pitfall: Formicidae	Pitfall: Carabidae	Sticky cards: Wasps/bees	Sweep net: Heteroptera
0 (pretreatment)	1.9b	0.4b	0.07b	11.2b
1 week	7.2b	1.4a	0.04b	12.8ab
2 weeks	6.4b	1.3a	0.62a	11.3b
3 weeks	17.5a	0.9ab	0.08b	18.7a

2002

Time	Pitfall: Tenebrionidae	Sticky cards: Formicidae	Sticky cards: Wasps/bees	Sticky cards: spiders	Sweep net: Heteroptera
0 (pretreatment)	1.5b	0.14a	0.11b	0.00b	10.33a
2 days	1.0b	0.07b	0.04b	0.00b	2.17b
1 week	2.2b	0.12ab	0.14b	0.05a	6.25ab
2 weeks	4.0a	0.08b	0.12b	0.00b	4.92b
3 weeks	1.3b	0.34a	0.97a	0.02ab	2.42b

Table V. Mean densities of Formicidae collected in pitfall traps in plots treated for rangeland grasshoppers in southeastern Wyoming in 2001. Means with differing letters are significantly different according to Tukey's HSD ($P < 0.10$).

Insecticide	Insecticide Rate (g a.i./ha)	Coverage	Oil type	Oil rate (ml/ha)	Mean density (Individuals/trap)
Carbaryl	140	50%	Canola	730	18.34a
Carbaryl	280	33%	Corn	730	12.25ab
Diflubenzuron	17.5	25%	Crop[1]	584	11.41ab
Carbaryl	280	50%	Canola	730	10.76ab
Carbaryl	140	33%	Canola	730	8.60ab
Diflubenzuron	13	33%	Crop[1]	584	6.60ab
None	0	0%	None	None	6.50ab
Carbaryl	280	50%	None	None	5.70ab
Diflubenzuron	17.5	33%	Corn	584	4.75ab
Diflubenzuron	17.5	33%	Canola	584	4.60ab
Diflubenzuron	17.5	25%	Canola	584	3.78b

[1] Crop oil is a paraffin-based petroleum product that is widely used as an insecticide carrier.

Table VI. Mean densities of Diptera captured with sticky cards in plots treated for rangeland grasshoppers in southeastern Wyoming in 2001. Means with differing letters are significantly different according to Tukey's HSD ($P < 0.10$).

Treatment code[1]	Pre-treatment	1 week	2 weeks	3 weeks
a	1.50b	4.70b	3.45a	1.85a
b	2.60b	12.30ab	20.05a	5.90a
c	1.90b	4.40b	8.80a	9.50a
d	3.45b	3.45b	9.34a	14.10a
e	4.25b	6.20b	11.75a	6.35a
f	2.10b	4.35b	4.55a	4.80a
g	2.50b	5.70b	2.20a	2.90a
h	0.00b	5.45b	5.00a	5.50a
i	7.70a	5.95b	4.05a	7.05a
j	3.30b	16.75a	5.50a	10.45a
u	1.30b	6.00ab	2.40a	5.55a

[1] Codes correspond to treatments detailed in Tables I and II.

Table VII. Mean densities of Heteroptera captured with sticky cards in plots treated for rangeland grasshoppers in southeastern Wyoming in 2001. Means with differing letters are significantly different according to Tukey's HSD ($P < 0.10$).

Treatment code[1]	Pre-treatment	1 week	2 weeks	3 weeks
a	0.025b	0.050a	0.050a	0.550b
b	0.100b	0.200a	0.600a	0.450b
c	0.070b	0.000a	0.150a	1.100ab
d	0.150b	0.400a	0.050a	1.200ab
e	0.135b	0.200a	0.300a	0.400b
f	0.060b	0.450a	0.050a	0.600b
g	0.030b	0.050a	0.050a	0.950b
h	0.000b	0.100a	0.000a	2.250a
i	1.000a	0.100a	0.000a	1.550ab
j	0.065b	0.050a	0.050a	0.700b
u	0.005b	0.100a	0.000a	0.350b

[1] Codes correspond to treatments detailed in Tables I and II.

The second interaction occurred with the Heteroptera, and was largely caused by the relatively constant captures over time in plots receiving the standard rate (with both crop and canola oil), but with decreased coverage, of diflubenzuron, and the relatively constant captures over time in plots receiving the standard RAAT application of diflubenzuron (with canola oil). In contrast, these responses can be compared with captures of Heteroptera that rose noticeably from week 2 to week 3 in plots receiving all other treatments (Table VII). When we examined the mean separations by week, some differences did occur among treatments for weeks 0 and 3. For week 0, the captures of Heteroptera were greatest in plots receiving the standard RAAT application of carbaryl (with canola oil). For week 3, captures of Heteroptera in plots receiving the standard rate (with corn oil), but decreased coverage, of carbaryl were greater than captures of Heteroptera in plots receiving other treatments except: (1) the decreased rate (with crop oil), but standard coverage, of Diflubenzuron, (2) the standard RAAT of diflubenzuron (with corn oil), (3) the decreased rate (with canola oil), but decreased coverage of carbaryl, and (4) the standard RAAT application of carbaryl (with canola oil).

For the sweep netting, the interaction was caused by the large captures that occurred in the control plots during week 1, that dropped precipitously in week 1 (Table VIII). Mean separations examined by week reflected this phenomenon, showing that captures for the control plots, week 0, were far greater than captures in plots receiving all other treatments. In addition, for week 2, mean separations indicated that more Coleoptera were captured in the control plots than in all other treated plots, except those that received the standard rate (with crop oil), but decreased coverage, of diflubenzuron.

3.2. 2002 effects for weeks, treatments, and their interaction

In 2002, 10 987 arthropods were collected, of which 7303 were collected from pitfall traps, 3159 from yellow sticky cards, and 525 from sweep net sampling. Based on these specimens, we conducted 12 statistical analyses. Of those, five showed that differences occurred among the main effects of weeks, none showed that differences occurred among the main effect of treatments, and three showed that a significant week-by-treatment interaction occurred. For the analyses in which differences occurred among weeks, just one involved pitfall traps, three involved sticky cards, and one involved sweep netting. For the pitfall traps, more Tenebrionidae were captured during week 2 than were captured during all other weeks of the study (Table IV). For the sticky cards, more Formicidae were captured during week 3 than were captured during day 2 and week 3 (Table IV). Also for the sticky cards, more wasps/bees were captured during week 3 than during any other week in the study (Table IV). Sticky cards also showed that more spiders were captured during week 1 of the study than were captured during all other weeks except for week 3 (Table IV). For the sweep netting, more Heteroptera were captured during week 0 than were captured during day 2 and weeks 2, and 3; captures of Heteroptera during week 1 were intermediate (Table IV).

For those analyses that involved a significant week-by-treatment interaction, one involved the use of pitfall traps, one involved the use of sticky cards and one involved the use of sweep netting. For the pitfall traps, the interaction was caused by Formicidae numbers increasing greatly in plots receiving the traditional rate (with no carrier oil), but decreased coverage, of malathion from week 1 to week 2 (Table IX). When we examined the mean separations of treatment averages by week, we found significant differences occurred among treatments for week 0 only. On that week, we captured more Formicidae in the control plots than in plots receiving all other treatments, excepting those that received the standard rate but decreased coverage of malathion (with canola oil).

For the sticky cards, the week-by-treatment interaction was largely caused by similar captures of Diptera occurring over time in plots receiving the standard rate (with canola oil), but decreased coverage, of malathion in contrast with the marked increase in captures that occurred in plots receiving all other treatments, including the control, from day 2 to week 1 (Table X). When we examined the mean separations of treatment averages by week, we found that significant differences occurred among some treatments for week 0 only. On that week, we captured more Diptera on sticky cards placed in the control plots than in all other treated plots, except those that received the traditional blanket application of malathion (with no carrier oil).

For the sweep netting, the week-by-treatment interaction was caused by an increase of captures for Diptera from week 0 to day 2 in plots receiving the traditional rate (with no carrier oil), but decreased coverage, of malathion as well as in plots receiving the standard rate of malathion (with no carrier oil), with increased coverage. These increases were then followed by precipitous decreases from day 2 to week 1 (Table XI). When we examined the

Table VIII. Mean densities of Coleoptera captured with sweep net in plots treated for rangeland grasshoppers in southeastern Wyoming in 2001. Means with differing letters are significantly different according to Tukey's HSD ($P < 0.10$).

Treatment code[1]	Pre-treatment	1 week	2 weeks	3 weeks
a	2.0b	0.5a	2.0ab	0.5a
b	5.0b	1.0a	1.0b	1.0a
c	0.5b	3.0a	1.0b	0.5a
d	1.0b	1.0a	1.0b	1.0a
e	0.0b	0.5a	0.0b	0.5a
f	0.0b	11.5a	1.0b	6.5a
g	5.5b	0.5a	0.5b	0.5a
h	0.0b	3.5a	0.5b	1.0a
i	0.0b	0.0a	1.0b	7.0a
j	1.0b	1.5a	0.0b	4.0a
u	33.0a	4.0a	4.5a	1.0a

[1] Codes correspond to treatments detailed in Tables I and II.

Table IX. Mean densities of Formicidae captured with pitfall traps in plots treated for rangeland grasshoppers in southeastern Wyoming in 2002. Means with differing letters are significantly different according to Tukey's HSD ($P < 0.10$).

Treatment code[1]	Pre-treatment	2 days	1 week	2 weeks	3 weeks
a	4.0b	1.1a	0.7a	3.0a	5.2a
b	3.4b	1.7a	0.5a	0.4a	15.4a
c	4.6b	1.5a	1.1a	2.1a	5.4a
d	5.3ab	5.4a	1.9a	6.7a	8.2a
e	3.9b	5.1a	2.5a	3.7a	6.7a
u	11.0a	5.3a	1.3a	2.7a	4.2a

[1] Codes correspond to treatments detailed in Table III.

Table X. Mean densities of Diptera captured with sticky cards in plots treated for rangeland grasshoppers in southeastern Wyoming in 2002. Means with differing letters are significantly different according to Tukey's HSD ($P < 0.10$).

Treatment code[1]	Pre-treatment	2 days	1 week	2 weeks	3 weeks
a	4.30ab	4.38a	24.93a	2.26a	5.15a
b	3.10b	4.20a	14.79a	2.64a	3.47a
c	1.55b	1.54a	16.58a	1.29a	3.60a
d	2.80b	4.92a	6.73a	2.15a	3.05a
e	2.37b	1.80a	9.51a	2.74a	3.61a
u	7.90a	5.70a	23.93a	4.35a	3.95a

[1] Codes correspond to treatments detailed in Table III.

Table XI. Mean densities of Diptera captured with sweep net in plots treated for rangeland grasshoppers in southeastern Wyoming in 2002. Means with differing letters are significantly different according to Tukey's HSD ($P < 0.10$).

Treatment code[1]	Pre-treatment	2 days	1 week	2 weeks	3 weeks
a	1.0a	3.0a	1.5a	0.0a	0.0a
b	1.0a	4.0a	0.0a	0.5a	0.0a
c	1.0a	4.5a	0.0a	0.0a	0.5a
d	0.0a	1.5a	1.0a	1.5a	1.5a
e	0.5a	1.0a	1.5a	2.0a	0.0a
u	1.0a	0.0a	2.0a	0.0a	0.5a

[1] Codes correspond to treatments detailed in Table III.

mean separations of treatment averages by week, we found no significant differences among treatments.

4. Discussion

Evaluation of non-target effects for locust and grasshopper control presents numerous methodological challenges (Everts and Ba 1997). Such studies are either conducted in conjunction with large-scale operational treatments in the field or are confined to very small-size plots. The former situation is not desired because they often lack replication and thorough planning with respect to acceptable experimental design and execution (Southerton et al. 1988). The latter situation is also not desired as the size of very small plots cannot be confidently extrapolated to large-scale, 'real world' situation (Jepson 1989). Hence it is not surprising that a few reports of such studies have appeared in peer-reviewed scientific journals. For example, a comprehensive review of field studies concerning the environmental impacts of locust and grasshopper control in Africa (Matteson 1992) is based on just 36 citations, 18 of which refer to the so-called 'grey' literature (e.g., unpublished technical reports and bulletins). Unfortunately, North American publications on this subject are even scarcer, which makes the task of relating our results to other works all the more challenging.

4.1. Treatment effects

Previous studies in N. America have reported that terrestrial, non-target arthropods can be negatively affected by rangeland grasshopper treatments with broad-spectrum insecticides. Using a variety of sampling techniques (sweep net collections, visual counts, etc.), Pfadt et al. (1985) found that, for ground-dwelling taxa (e.g., darkling beetles, ground beetles, spiders, centipedes, larval robber flies and certain ants), a blanket treatment with a high dose of malathion (1495 g a.i./ha) produced minimal negative effects. Species with mandibulate mouthparts that foraged on vegetation (several species of bees and an ant *Formica obtusopilosa* [Emery]), however, were susceptible to malathion sprays while leafhoppers, insects with piercing–sucking mouthparts, were unaffected.

Quinn et al. (1990a,b) reported that blanket treatments with malathion spray and carbaryl bran bait resulted in a 49–89% reduction of darkling beetle, ground beetle and field cricket activities the first week after treatment. In their studies, the authors used pitfall traps to monitor non-target populations. Insecticides were applied to large (1400 ha) plots at relatively high rates: 1.5 kg/ha of 5% carbaryl bran bait and 693 g a.i./ha of malathion. Malathion spray also caused the reduction of ichneumonid wasps and blister beetles by 56 and 59%, respectively. This latter finding is of particular importance because blister beetles (Meloidae) are known to be one of the most important groups of grasshopper and locust egg predators (Greathead 1963, 1992; Lavigne and Pfadt 1966; Popov et al. 1990; Greathead et al. 1994). In Wyoming, there are 47 species of blister beetles, many of which are associated with grasshopper egg-pods (Bomar 1993). A decrease in their numbers may result in a higher survival rate of pest grasshoppers, thus perpetuating the grasshopper pest problem (Lockwood et al. 1988).

George et al. (1992) studied the effects of rangeland grasshopper control on non-target arthropods using pitfall traps. In their study, the application of carbaryl bran bait significantly reduced the population density of Coleoptera. However, no differences were detected in populations of Araneae or Orthoptera. This study was conducted using blanket application with large treatment plots (>2000 ha), but used only 2% carbaryl bran bait at 30 g a.i./ha.

In other geographic areas, operational anti-acridid treatments were reported to cause notable reduction in non-target terrestrial arthropods. Peveling et al. (1999a,b) reported that 1 week after an application of the organophosphate insecticide fenitrothion at a rate of 250 g a.i./ha in Madagascar, the four most abundant non-target insect families (Carabidae, Tenebrionidae, Formicidae and Ephydridae) were reduced by 69%. Four weeks post-treatment, these taxa were still reduced by 51%. The authors used pitfall traps, Malaise traps and visual counts for non-target sampling.

Ivie et al. (2002) evaluated non-target impacts of chemical and biological insecticides on Coleoptera in Madagascar using pitfall traps. They found that an application of fenitrothion (245 g a.i./ha) in combination with a pyrethroid insecticide esfenvalerate (5 g a.i./ha) resulted in a significant reduction of beetle species from Elateridae (up to 95%), Carabidae (up to 61%), Nitidulidae (up to 60%), Staphylinidae (up to 100%), Scarabaeidae (25–100%), Lathridiidae (up to 100%) and several other families.

Childebaev (2001) reported that an application of the organophosphate insecticide chlorpyrifos at the dose of 180 g a.i./ha to control rangeland grasshoppers in Kazakhstan resulted in a significant reduction of non-target insects from 25 families. Ten of them (Meloidae, Bruchidae, Apidae, Braconidae, Bombidae, Asilidae, Syrphidae, Cicadellidae, Pentatomidae, Tineidae) re-established their numbers 2 weeks after treatment while the other 15 (Coccinellidae, Chrysomelidae, Curculionidae, Mordellidae, Malachiidae, Carabidae, Ichneumonidae, Formicidae, Cynipoidae, Chrysopidae, Muscidae, Aphididae, Psyllidae, Lygaeidae, and Miridae) reached the pre-treatment levels of abundance only 5 weeks post-treatment. The author used pitfall traps and sweep net sampling as collection methods.

In his study of non-target effects of rangeland grasshopper treatments in East Siberia, Sokolov (2000) reported that an application of chlorpyrifos

(205 g a.i./ha) caused a significant decrease in abundance of several terrestrial arthropod families, in particular, Carabidae, Cydnidae, Cicadellidae, and Lycosidae (Aranei). However, these families reached or exceeded the level of the untreated control 3 weeks after treatment.

Van der Valk et al. (1999) reported some interestingly controversial results regarding the side-effects of grasshopper treatments with an organophosphate insecticide fenitrothion (350 g a.i./ha) in West Africa. Damage to grasshopper egg-pods due to natural enemies (mostly, Tenebrionid larvae) was on average 9% higher in treated plots. The authors attributed this to insecticide impact on hyper-predators or hyper-parasitoids. Furthermore, grasshopper egg-pod densities in treated plots increased by 140% the year after treatments. The authors hypothetically attributed this by the insecticidal impact on natural enemies of nymphs and adult grasshoppers of early-hatching species (*Oedaleus senegalensis* [Krauss]), against which the treatment was targeted. Supposedly, insecticide application early in the season created a 'predator-free' ambience for late-hatching grasshopper species (*Kraussaria angulifera* [Krauss]) which resulted in their higher egg production. This example illustrates a possibility of aggravating grasshopper pest problem as a result of broad-spectrum insecticide application. It also provides an evidence of our insufficient understanding of fine regulatory mechanisms which may play a paramount role in grasshopper population dynamics (Joern 2000).

Extensive database research showed that non-target effects of the third insecticide used in our tests, diflubenzuron, are generally found to be less pronounced than those resulting from applications of broad-spectrum insecticides like malathion or carbaryl (Theiling and Croft 1988; Murphy et al. 1994).

Evaluating non-target impact of operational diflubenzuron (71 g a.i./ha) application to control gypsy moth, Martinat et al. (1988) found no effect on Coleoptera, Diptera, or Heteroptera. However, numbers of non-target Lepidoptera as well as sawflies, katydids and crickets remained consistently lower in the treated plots 31 days post-treatment. The authors hypothesised that open-living, mandibulate herbivores were more exposed to diflubenzuron compared to sheltered, predacious insects or those with piercing-sucking mouthparts.

Applied in an agricultural pest control context, diflubenzuron was shown to cause no reduction in honey bee brood after six to eight consecutive applications within one season, at dose rates between 57 and 140 g a.i./ha (Robinson 1979; Schroeder et al. 1980). Because of its extremely low toxicity to adult insects, diflubenzuron can be used to treat pests while foraging bees are present (Johansen 1977).

First field studies of non-target effects of diflubenzuron in locust and grasshopper control showed that in general, its negative impact was lower than conventional insecticides. Catangui et al. (2000) did not find any significant reduction in numbers of terrestrial arthropods—ants, spiders, predatory or scavenger beetles—7 to 76 days after treatment. Flying insects (mostly beneficials like predators and pollinators) exhibited a temporary decline of 18–59% at 15–41 days post-treatment. However, their numbers subsequently recovered.

Further reduction of negative non-target effects is possible when diflubenzuron is applied against grasshoppers and locusts in an incomplete coverage (barrier treatments or RAAT). Extensive multi-year studies by Tingle (1996) and Tingle et al. (1997) in Madagascar showed that for most of about 300 non-target arthropod species from 120 families and 17 orders, there was no evidence of insecticide effect. However, relative abundance of caterpillars (Lepidoptera) and non-target grasshoppers (Acrididae) declined within 50-m wide barriers sprayed at 93 g a.i./ha, and remained low for several months. Adverse effect was also pronounced on Gryllidae, Heteroptera, and spiders, particularly Salticidae. Five hundred-metre inter-barrier swaths acted as true refugia, with no evidence of spray effects on terrestrial arthropod fauna within the middle 300 m of these areas.

The present research on non-target effects was conducted in conjunction with a programme to enhance the efficacy of RAAT for grasshopper suppression with carrier oils in 2001 and 2002. The 2001 results indicated that the treatments with diflubenzuron generated 85–94% mortality in grasshoppers by 3-weeks post-treatment. Carbaryl generated 69–94% mortality by 3-weeks post-treatment. The low mortality (69%) may have been due to re-infestation of grasshoppers from outside the treated plot. In 2002, grasshopper mortality was highest (98%) in plots treated with the traditional, blanket application of malathion (693-100; no oil). The lowest grasshopper mortality (85%) was found with a high-rate application of malathion used in a low-coverage RAAT (693-50; canola). Thus, it is clear that the insecticides were highly effective against the target insects.

Results of the present study indicate even less environmental harm than previous studies. A lack of significant reductions in the non-target fauna could, in part, reflect the design limitations of the study. That is, with a high degree of spatiotemporal variation the use of only two replicates per treatment may not have provided the statistical power to discern changes in population densities. However, this design was entirely sufficient to find significant reductions in the grasshopper (target) populations in the treatments, so it is apparent that the general lack of decreases in non-target arthropods cannot be entirely attributed to the experimental design. Rather, there are a number of ecological factors that may explain why grasshopper populations were markedly reduced while the numbers of other taxa showed far less effect of the treatments.

In 2001, the results suggest that very little impact to non-target arthropods occurred with diflubenzuron or carbaryl. In fact, only one treatment (diflubenzuron applied at the standard rate using a very low coverage of 25%) yielded a significantly lower population density of a non-target taxa (ants collected by pitfall trapping) than was occurred in the untreated control. In 2002, there were no instances in which treatments had a significant effect, although in both years there were treatment-by-time interactions.

There are plausible ecological explanations reasons for the lack of a strong effect of the treatments on non-target fauna. Grasshoppers are most active in early morning, and consume large amounts of forage at this time. As such, treatments were conducted in the early morning. This time of day also minimises evaporation and drift of insecticide through thermal inversions or winds. By mid-morning, most ground-dwelling arthropods (such as those collected in pitfall traps) are becoming less active and are searching for shady refugia to avoid the heat of the day (Quinn et al. 1990a,b). During the day, ground temperatures become extremely high (45 – 60°C). On the first day of chemical treatments, ground temperatures may become high enough to deactivate insecticides on the soil surface, and degradation by soil binding and ultraviolet radiation may also contribute to chemical breakdown. As such, crepuscular and nocturnal ground-dwelling arthropods will not encounter a lethal dose of insecticides. However, insecticides persist on the vegetation, where temperatures are less extreme. Those residues may provide a low level of contact toxicity, but ingestion is typically needed for insects to acquire a lethal dose. Thus, piercing-sucking herbivores (e.g., Heteroptera) would uptake far less insecticide than would chewing herbivores (e.g., Acrididae).

Very low rates of insecticides can be used to control grasshoppers and locusts because their size and behaviour exposes them to direct contact with the spray during treatment. Moreover, grasshoppers consume so much foliage in such a small amount of time that surficial residues provide a lethal dose (Pfadt 1988). On the rangeland, grasshoppers are by far the most numerous insects that feed by chewing the foliage, so they can be expected to acquire far more insecticide than most other taxa.

This study assessed the effects of liquid bait insecticide treatments in 16-ha plots. The relatively small plot size is one of the most common problems in interpretation of non-target effects (van der Valk and Niassy 1997). The trials conducted in 2001 had many adjacent plots and, the farthest distance from the centre of a treated area to the boundary of a non-treated area was 0.4 km. This distance is much less than would be typical in an operational programme. Results from large scale treatment programmes (e.g., > 4000 ha) could differ because of spatial scale. According to Balança and de Visscher (1997), a 10-fold increase in plot size resulted in a 7-fold reduction in non-target arthropod recolonization within several weeks. Relatively small plots may be rapidly recolonized by insects. Highly mobile insects such as Diptera, Hymenoptera, and even some Heteroptera may either move through a treated area or re-establish populations soon after treatment. Less mobile predators (e.g., carabids and formicids) may have limited food supplies after the treatment due to suppression of grasshoppers, but scavengers (e.g., tenebrionids) may have an abundance of food. However, evidence of such effects may be limited in small-scale treatments.

4.2. *Temporal dynamics*

Naturally the population dynamics of most temperate grassland insects should rise and fall throughout the period of early to mid-summer (Price 1997). In this context, three factors should be considered when interpreting the results of the present study.

First, during the 2001 study, a light rain fell in the third week after treatment. This rain initiated a massive mating swarm of formicids. A significant increase of formicid density occurred at 3-weeks post-treatment (17.5 individuals/trap). Heteropteran populations also appeared to have responded to this rainfall event. Other taxa (carabids and wasps/bees) manifested changes that were not as readily associated with environmental factors. In 2002, three taxa (ants, bees/wasps, and spiders) all increased markedly 1-week post-treatment, suggesting the possibility of some environmental cue. However, it was apparent that other groups (heteropterans) were responding to some other intrinsic or extrinsic factor, as their populations declined after the first week of the study.

Next, we would note that both summers of the study (2001, 2002) were unusually hot and dry. This climatic variation from normal years may have reduced overall non-target populations, making some of them too small to adequately sample and monitor.

Finally, temporal changes in insect population densities can obscure treatment effects (Childebaev 2001). For instance, treatments in 2001 may have negatively affected formicid population densities. However, the onset of rain triggered a surge in the number of formicids that might have masked the reductions caused by insecticide applications. Thus, in a wetter year non-target organisms may occur at higher densities making the effects of grasshopper control more apparent.

4.3. *Sampling effects*

It is well known that different taxonomic groups of terrestrial arthropods respond differently to a variety of sampling methods (Greenslade 1964; Ivie et al. 2002). Carabids, tenebrionids, formicids, and arachnids were the only groups captured in the pitfall traps in sufficient numbers for statistical analysis. Yellow sticky card samples could be used to analyse only Diptera, Hymenoptera (excluding Formicidae), Formicidae, and Heteroptera. Sweep net analysis could only be conducted on Coleoptera, Diptera, and Heteroptera. Thus, sticky trap and sweep net sampling provide the most similar taxonomic portraits, with Diptera and Heteroptera being common in both methods.

The groups most often revealing treatment, time, or interaction effects were non-ground dwelling taxa, such as Hymenoptera (bees/wasps), Diptera, Heteroptera and some Coleoptera (excluding tenebrionids or carabids). These groups were sampled using either sticky cards or sweep nets. Insects that inhabit the vegetation and fly about in search of food sources are more likely to be exposed during application and more likely to come into contact with insecticide residues (Sokolov 2000). They are also more likely to exhibit temporal changes due to migration, emergence, and natural mortality.

Conversely, ground-dwelling arthropods (e.g., carabids, tenebrionids, silphids, arachnids and gryllids) are often large-bodied and nocturnal (at least in part due to high ground temperatures during the day). These organisms forage in the microhabitat that is least contaminated with insecticides. In a previous study, ground-dwelling wolf spiders (Lycosidae) were found to be less affected by insecticide spray than crab spiders (Thomisidae), which inhabit the grass canopy (Sokolov 2000). Furthermore, the silk of spider webs is known to effectively catch pesticides (Samu et al. 1992; Peveling et al. 1997; Tingle 1997), thus increasing exposure. These examples show that, for a meaningful interpretation of non-target effects, it is necessary to take into account ecological characteristics and micro-habitat distribution of terrestrial arthropods in addition to a rather coarse taxonomic analysis, which is often used for such studies (Matteson 1992; Ivie et al. 2002).

Finally, sampling methods undoubtedly reflect changes in arthropod densities, but sampling results are also affected by arthropod activity. In particular, passive traps (pitfall and sticky cards) reflect insect and spider movements, as well as density. This study found no apparent negative treatment effects or even treatment-by-time effects on spider, tenebrionid, or carabid populations that were monitored with pitfall traps (pitfall-trapped formicids were the exception). So it seems that pitfall trapping of large, robust ground-dwelling arthropods is a poor indication of treatment effects, at least for liquid bait insecticides. Moreover, this study found populations of heteropterans and dipterans to be most sensitive to treatment and time-by-treatment effects. As such, sampling with either yellow sticky cards or sweep nets may more adequately reflect changes in non-target population densities.

5. Conclusions

The goal of this study was to determine the non-target impacts of rangeland grasshopper control using liquid bait insecticides. The results suggest either that there are few such effects, or that the effects are much less than the variation arising from heterogeneity of insect populations in time and space. The apparent lack of deleterious effects may be a function of several factors related to grasshopper control.

This study indicates that the use of vegetable oils as liquid bait carriers does not compromise the environmental improvements associated with the RAAT strategy of rangeland grasshopper management. The combination of RAAT methods with vegetable oil formulations of insecticides represents progress toward the goal of suppressing the target insect while minimising harm to the non-target fauna. The concept of a true ‘acridicide’ has been viewed as a toxicological ideal but it appears that this objective might be approximated by relying not only on the mode of action of the chemical, but also on other aspects of a control programme. Residual activity, along with the rate, coverage and time of application appear to be key factors of the efficacy of anti-acridid treatment. Oil carriers can also contribute to this efficacy. They are essential for the chemicals to come in contact with and remain on the vegetation, thus allowing greater potential for grasshopper uptake, which is particularly important in the case of insecticides with stomach action like carbaryl and diflubenzuron. Perhaps more importantly, vegetable oils enhance selectivity by serving as attractants and phagostimulants of grasshoppers.

Finally, some biases in our sampling methods and analyses might be reflected in the interpretation of results. Greater numbers of replicates might have elucidated more subtle effects on non-target taxa. We set traps for only 24 h, and future studies with traps set for longer periods of time may reduce the spatiotemporal confounding effects that were observed in this study. The use of sticky card and sweep net sampling appears to provide the most efficient and sensitive sampling method for non-target taxa. However, pooling the collected arthropods to family or even order level may obscure the analysis. As in other studies, larger areas may also limit those factors that mask treatment effects. Conversely, using RAATs may also increase the effects of these factors by creating spatial heterogeneity via untreated refugia strips within treated areas. Of course, the explicit intention of these refugia is to reduce the negative non-target effects by preserving arthropods that can serve as a source of recolonisation.

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