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MANAGING THE DISPERSAL OF LADYBIRD BEETLES (*COL.: COCCINELLIDAE*): USE OF ARTIFICIAL HONEYDEW TO MANIPULATE SPATIAL DISTRIBUTIONS

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We tested whether large-scale distributions of aphidophagous ladybirds could be manipulated by localized application of artificial honeydew. In addition to enhancing local build-up of ladybird numbers (*e.g.*, in areas of incipient aphid outbreak), such an approach may prove useful for drawing ladybirds out of a crop scheduled for insecticide treatment. In six experiments, we sprayed sucrose dissolved in water to small plots in the center of large alfalfa fields in Utah. Within 48 hours, ladybird densities in the plots increased 2-13x, whereas ladybird densities at distances of 40-150 m from the plots decreased to a mean of less than two-thirds their former density. We then applied sucrose in a narrow band along the entire perimeter of an alfalfa field; densities of ladybirds increased following treatment both along the treated field edge and in untreated alfalfa throughout the field. Finally, we compared the numerical responses of two ladybird species to sucrose application; both species responded positively, but *Coccinella transversoguttata* did so consistently more strongly than did *C. septempunctata*. Our results suggest that both promise and challenges lie in the use of artificial honeydew to direct the dispersal and spatial patterns of ladybirds.

KEY-WORDS: alfalfa, aphid honeydew, biological control, *Coccinella septempunctata, Coccinella transversoguttata,* Coccinellidae, dispersal, ladybird beetles, predation.

Adult aphidophagous ladybird beetles (Coccinellidae) are highly mobile, move readily among habitats over the landscape, and tend to aggregate in areas of high prey density (*e.g.*, see Evans, 1991; Hemptinne *et al.*, 1992; Ives *et al.*, 1993). Direct contact with aphids or their honeydew may promote area-restricted search by individual ladybirds that leads to population aggregation (Nakamuta, 1982; Carter & Dixon, 1984; Kareiva & Odell, 1987). When sprayed on vegetation, a simple solution of sucrose dissolved in water can be used as an "artificial honeydew" to promote aggregation of ladybird adults (Ewert & Chiang 1966; Schiefelbein & Chiang, 1966; Carlson & Chiang, 1973; Hagen *et al.*, 1976; Evans & Swallow, 1993). Field experiments confirm that sucrose serves as an arrestant, but not as an attractant, for ladybirds (Hagen *et al.*, 1971, 1976; Nichols & Neel, 1977). The rapid, dramatic increases in population density of ladybird adults in plots treated with sucrose dissolved in water reflect that these active predators, when not engaged in area-restricted search, are constantly moving through the environment at high rates.

The responsiveness of adult ladybirds to artificial honeydew suggests that the dispersal and spatial distribution of these insects might be managed by local applications of artificial honeydew to enhance these predators' impact on aphids and other pest insects. For example, early season applications in particular crops when pest aphids are still at low numbers may speed the development of high densities of ladybirds (and other predators such as lacewings) in the crop. At high numbers, these predators might check aphid population growth sufficiently to prevent the pest from reaching damaging levels later in the season (Hagen *et al.*, 1971; see also Kareiva, 1987).

Artificial honeydew might also be used to draw ladybird beetles out of a crop prior to insecticide application; this is similar in some respects to the use of trap crops for insect pests (*e.g.*, Pedigo, 1996). We report here on our initial efforts to explore the potential for such an approach. Field experiments were used to determine whether the spatial distribution of ladybirds in an alfalfa field can be altered by localized application of sucrose dissolved in water. In one set of experiments, artificial honeydew was applied to small areas in the center of fields. In another experiment, the honeydew was applied in a narrow band along the entire perimeter of an alfalfa field. A third set of field experiments addressed whether individual species of ladybirds differ in their responsiveness to artificial honeydew, as reflected in their spatial distribution among treated and control plots.

Our experiments were conducted in northern Utah, where ladybirds aggregate in alfalfa fields in response to high densities of the pea aphid *Acyrthosiphon pisum* (Harris) that may develop in any of the several crops of hay that are cut and harvested each year (Evans & Youssef, 1992). In the past few years, the Palearctic species *Coccinella septempunctata* L. has invaded Utah alfalfa fields; as it is in the Palearctic (*e.g.*, Hodek, 1973; Honek, 1985), this species is now among the most abundant species of ladybirds inhabiting these fields. In addressing the issue of variation among ladybirds in their response to artificial honeydew, we have focused on the responses of this introduced species and the very similar native species *Coccinella transversoguttata richardsoni* Brown, which apparently is being displaced in North America by *C. septempunctata* (Elliot *et al.*, 1996).

MATERIALS AND METHODS

Methods common to all field experiments

To simulate deposition of aphid honeydew, sucrose dissolved in water (150 g per l) was applied as fine droplets to alfalfa using a hand-held sprayer. Adult ladybirds in treated and untreated alfalfa were sampled using a canvas sweep net (38 cm in diameter) by taking a 180° sweep through the upper canopy at each step (the number of sweeps per sample varied among experiments as described below). Sweep sampling was completed in the late morning and afternoon on generally clear, calm days.

Artificial honeydew applied to centers of fields

Field experiments were conducted in three alfalfa fields during July (second hay crop) and August-September (third hay crop) 1993, for a total of six field experiments; the alfalfa in these fields at the time of experiments varied from 30-75 cm in height. The same procedure was followed for each experiment. A 20 × 20 m plot was marked out near the center of the field. Sampling transects were established both within each of four quarters of the central plot, and at set distances from the plot's edge along each of the four cardinal directions. In July experiments, these sampling transects were laid parallel to the edge of the plot at distances of 15, 30, 45, and 60 m. In August-September, the transects were set at greater distances from the central plot; transects were sited at 20, 40, 60, and 80 m from the edge of the central plot in one field, and at 30, 60, 90, 120 and 150 m in the two larger fields.

TABLE 1

The total number of adult ladybirds (N) collected in sweep samples, and the percentages of these individuals belonging to individual species, for experiments in which artificial honeydew was applied to central plots within alfalfa fields in 1993

Month	Experiment	N	%		
			C. septempunctata	*C. transversoguttata*	*Hippodamia* spp.[1]
June	1	336	82.7	0.9	16.4
	2	172	72.1	0.6	27.3
	3	142	85.2	1.4	13.4
Aug-Sept	4	551	81.9	1.8	16.3
	5	143	74.8	3.5	21.7
	6	416	90.9	0.5	8.6

[1] Primarily *H. convergens* Guerin, *H. quinquesignata quinquesignata* (Kirby), and *H. tredecimpunctata tibialis* (Say).

Six liters of sucrose dissolved in water were applied to the foliage throughout the central plot on a single occasion in each experiment. Immediately before spraying (*i.e.*, on the same day) and then again one day (experiment 3) or two days later (all other experiments), sweep samples were taken along each transect (parallel sweeps were taken 2 m apart on the two occasions to prevent sampling the same alfalfa stems twice). Forty-eight sweeps were taken along transects at each sampling location both before and after spraying, yielding four replicates (of 48 sweeps each) at each sampling distance from the sprayed central plot (including 0 m for the four replicate samples from within the central plot). Adult ladybirds were counted and identified to species at the time of capture, and then released back into the alfalfa. Aphid densities were not quantified.

ARTIFICIAL HONEYDEW APPLIED TO FIELD EDGES

In August 1994 (third hay crop), sucrose dissolved in water (32 l) was applied to a band of alfalfa two meters wide around the entire perimeter of a 4 ha field on a single occasion (the alfalfa throughout the field was 60-70 cm high). Immediately before spraying (*i.e.*, on the same day, "Day 0"), and then again one, three, and five days after spraying ("Days 1, 3, and 5"), sweep samples were taken along transects through the sprayed band, and at distances 15, 45, and 75 m into the field. Starting points for sweep sampling were set before Day 0 at regular intervals along transects through the sprayed field edges or along transects parallel to the edges (*e.g.*, 15 m into the field). A starting point along each transect was selected randomly on each sampling day and a set of 30 sweeps was taken beginning at that point, yielding four replicate samples (30 sweeps each) for each distance (*i.e.*, 0, 15, 45, and 75 m distant from the sprayed field edge) for each of the four sampling days. Pea aphid density in the field was determined on each sampling day by taking a single sweep at each of ten arbitrary locations throughout the field. Samples were transferred from the sweep net to plastic bags and placed in a laboratory freezer; thereafter, adult ladybirds or pea aphids were removed and counted, and ladybirds were identified to species.

DIFFERENTIAL RESPONSES OF *COCCINELLA* SPECIES TO ARTIFICIAL HONEYDEW

In 1991-1996, six field experiments were conducted in which (i) small plots were laid out in a grid within alfalfa fields and were treated or not treated with sucrose dissolved in

TABLE 2

The number of instances in which densities of ladybird adults (all species combined) increased or decreased at varying distances from a central plot in an alfalfa field over 24-48 hours following application of sucrose to the central plot. Results were obtained from the experiments shown in table 1 (G_{adj} = 23.63 with Williams' correction for small sample size, d.f. = 2, $P < 0.001$, in a G-test of whether positive vs. negative response is independent of distance; Sokal and Rohlf 1981)

Distance[a]	Number of instances in which density:	
	Increased	Decreased
0 m	6	0
15-30 m[b]	5	3
40-150 m	0	17

[a] Distance from the edge of the treated central plot (0 m = in the plot).
[b] In one instance, the density did not change from before to after application of sucrose.

water, and (ii) both *Coccinella septempunctata* and *C. transversoguttata* were present in large numbers at the time of the experiment. Three of these experiments were conducted in June (second hay crop) and August (third hay crop) in 1991 and 1992; experimental treatments were applied to plots (10 × 12 m) separated by 10 m (see Evans & Swallow, 1993 for a full description). Three more experiments were conducted in May (first crop) in 1993, 1994, and 1996. Details of the 1993 experiment (12 × 12 m plots separated by 20-30 m) are presented in Evans and England (1996); similar experiments were performed in 1994 (12 × 12 m plots separated by 70-75 m) and 1996 (24 × 16 m plots separated by 20-30 m).

In all six experiments, sweep samples (typically 15 sweeps per plot) were taken 1-4 days after water with or without dissolved sugar was applied to the alfalfa foliage (in 1991-1992 experiments, a protein source was also applied to half of both sugared and non-sugared plots; see Evans & Swallow, 1993). We consider here the number of adults of the two species of *Coccinella* that were collected in these sweep samples from plots sprayed with or without sugar dissolved in water.

RESULTS

ARTIFICIAL HONEYDEW APPLIED TO CENTERS OF FIELDS

Coccinella septempunctata was the most abundant ladybird present in all field experiments in July-September 1993, with the native *C. transversoguttata* and various *Hippodamia* species present in much smaller numbers (table 1). In all experiments, densities of ladybirds increased rapidly and dramatically (2-13x) within the central plots following spraying (fig. 1 and table 2). In contrast, densities of ladybirds at distances of 40-150 m from the central plot always were reduced following spraying; densities after spraying varied (without consistent relationship to distance) from 17% to 91% ($\bar{x}$ = 62%) of densities before spraying. At distances of 15-30 m, ladybird densities sometimes increased and sometimes decreased.

ARTIFICIAL HONEYDEW APPLIED TO FIELD EDGES

Aphid densities in the study field were high during the experiment; on average, 155-165 pea aphids per sweep occurred on days 0, 1, and 3, and 300 per sweep occurred on day 5. In response to such high aphid density, a diverse assemblage of ladybirds

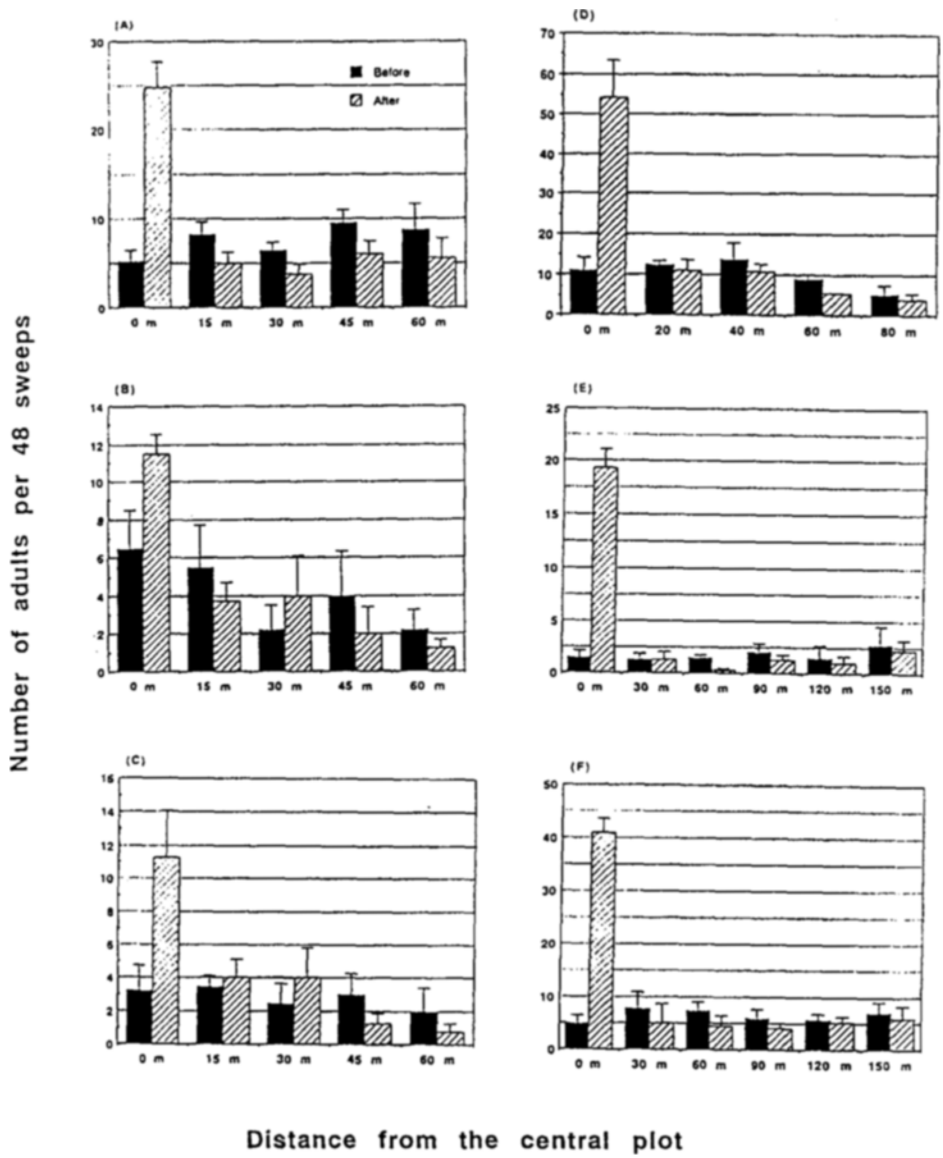

Fig. 1. Mean (+ one standard error) number of adult ladybirds (all species combined) collected per 48-sweep sample at varying distances in alfalfa fields from a central plot sprayed with sucrose dissolved in water; means are given for the day of (and immediately prior to) application of sucrose ("before"), and one or two days thereafter ("after"). Results for Experiments 1-6 (as listed in table 1) are given in (A)-(F), respectively.

occurred in the study field during the experiment: 44% of individuals belonged to *Hippodamia quinquesignata quinquesignata* (Kirby), 19% to *C. septempunctata,* 17% to *H. convergens* Guerin, 8% to *C. transversoguttata,* 8% to *H. sinuata crotchi* Casey, and 4%

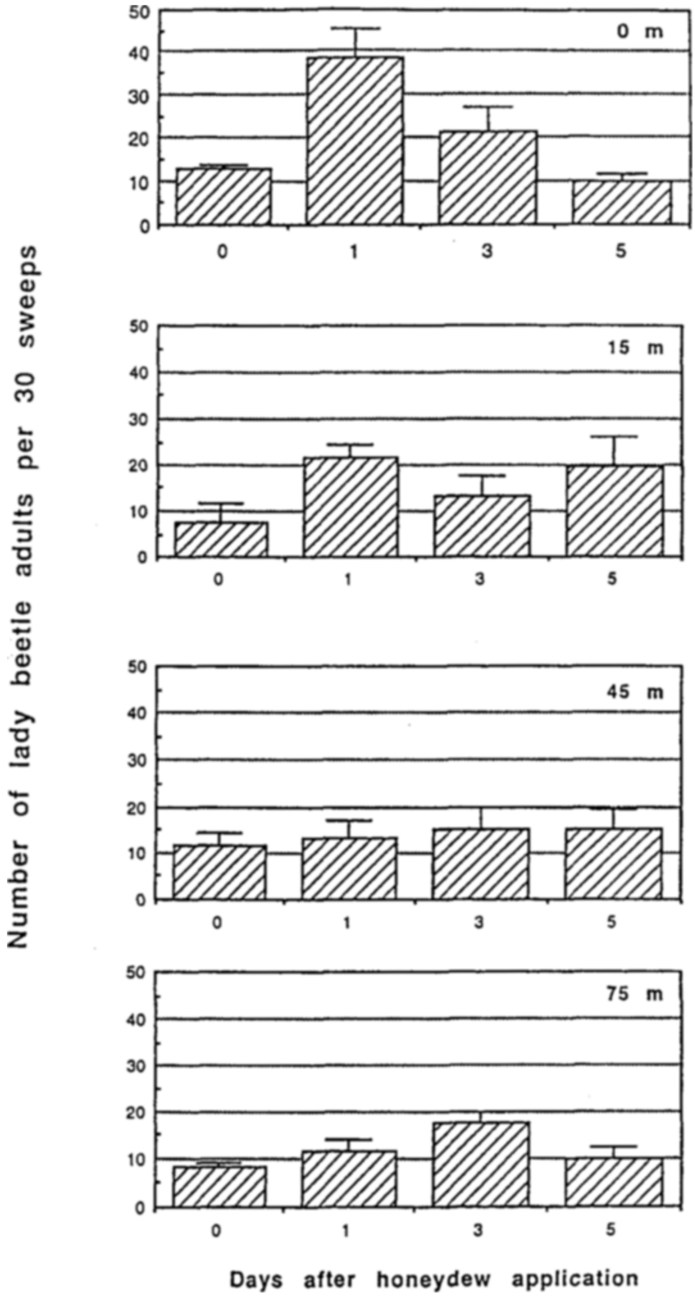

Fig. 2. Mean (+ one standard error) number of adult ladybirds (all species combined) collected per 30-sweep sample in an alfalfa field at varying distances (0, 15, 45, and 75 m) from the field's edge. Sucrose dissolved in water was applied to the field's edge; means are given for the day of (and immediately prior to) application (Day 0), and for Days 1, 3, and 5 thereafter.

to several other species combined (based on a total of 980 individuals for all species combined captured by sweep net during the experiment).

A two-way analysis of variance (with blocking by transect [SAS Institute, 1988]) for the number of ladybirds per 30 sweeps (all species combined) revealed a significant interaction of distance from the sprayed edge (0 to 75 m) with sampling day ($F_{3,9} = 2.59$, $P = 0.011$; similar results were obtained for separate analyses of individuals for *Coccinella* species combined and for *Hippodamia* species combined). In the sprayed edge itself (*i.e.*, at distance 0 m), ladybird density tripled in the first day after spraying, and gradually declined thereafter (fig. 2). Ladybird density also tripled along transects 15 m from the sprayed edge in the first 24 hours after spraying, and was still almost 3x as great as initial density 5 days after spraying. At 45 and 75 m into the field from the sprayed edge, ladybird density gradually increased over the first three days after spraying (density remained relatively high at 45 m on day 5, but declined from day 3 to day 5 at 75 m; fig. 2).

Differential response of *Coccinella* species to artificial honeydew

Both *C. transversoguttata* and *C. septempunctata* consistently responded positively to artificial honeydew in that greater numbers of adults of both species occurred in plots sprayed with versus without dissolved sugar in the first several days following treatment. The response of *C. transversoguttata,* however, was stronger than that of *C. septempunctata* in each of the six experiments (table 3; two-tailed binomial test, $N = 6$, $P = 0.03$). Almost all adults of *C. transversoguttata* (88-100%) occurred in sugar-treated plots in each experiment, whereas substantial numbers of *C. septempunctata* occurred in plots not treated with sugar (in the most extreme case, only a slight majority of individuals occurred in sugar-treated plots in the May 1994 experiment).

DISCUSSION

Application of sucrose to small central plots in alfalfa fields consistently resulted in dramatic changes in the spatial distributions of ladybird adults in these fields within 24-48 hours. While beetle densities increased markedly within treated plots, and often also increased (to a lesser degree) in the general area up to 30 m distant from treated plots, beetle densities at greater distances invariably declined. These results illustrate how quickly populations of highly mobile ladybirds can redistribute themselves over large spatial scales in response to changing environmental conditions such as incipient aphid outbreaks as simulated by artificial honeydew. Frazer *et al.* (1981) suggested that such constant motion of individual ladybirds and continual spatial redistribution of populations often prevents local build-up of aphid populations, and Kareiva (1987) demonstrated that aphid outbreaks in stands of goldenrod indeed occur when ladybird dispersal among prey patches is impeded.

Our results suggested that artificial honeydew might be used successfully to trigger the rapid removal of large numbers of ladybird adults from fields scheduled to be treated with insecticides. Our field experiment did not produce such an outcome, however. Application of artificial honeydew around the entire periphery of an alfalfa field was associated not only with increased densities in and near the sprayed field edges, but also with increased densities well into the field's interior. These results suggest that movement of individuals into the field during the experiment outweighed redistribution of individuals already present. Perhaps application of artificial honeydew along the field's borders led to the

TABLE 3

The percentage of individuals for C. transversoguttata *and* C. septempunctata *that were collected in plots sprayed with (vs. without) dissolved sucrose in field experiments in alfalfa. Individuals were collected by sweeping 1-4 days after sucrose was applied*

Year	Month[a]	*C. transversoguttata*		*C. septempunctata*	
		%	(N[b])	%	(N[b])
1991	August	95	(41)	91	(149)
1992	June	100	(10)	83	(150)
1992	August	90	(42)	71	(150)
1993	May	96	(25)	84	(74)
1994	May	88	(25)	57	(69)
1996	May	100	(14)	86	(76)

[a] Month during which experiment was conducted.
[b] N = total number of adults collected in plots both with and without dissolved sucrose.

population build-up by "enticing" ladybirds into the field, but it is also possible that such build-up occurred independently of such application (e.g., in response to high densities of aphids in the field). In any event, application of artificial honeydew to the field's edges did not lead to reduced densities of adult ladybirds within the field.

As an alternative management technique, it may be feasible to use artificial honeydew to concentrate ladybirds in the center of a field (as in our field experiments) and avoid treating this central area with insecticide. Another approach might be to spray an adjacent crop with artificial honeydew (e.g., an alfalfa field or strip [Stern 1969] might be sprayed with the honeydew two days before an insecticide is applied to an adjacent cotton field). But even this approach may prove ineffective if high aphid densities occur in the crop targeted for insecticide treatment (note that Schiefelbein & Chiang [1966] and Carlson & Chiang [1973] found sugar sprays to be ineffective in concentrating natural enemies when corn leaf aphids occurred at high densities).

The effectiveness of using artificial honeydew may not only depend on background aphid densities, but may also depend to some degree on the species of ladybird. We have treated adult ladybirds as a single group, as all species appeared to respond positively to artificial honeydew in our experiments. But the relatively subtle differences that we have documented in responses of the congeners *C. transversoguttata* and *C. septempunctata* are instructive: *C. transversoguttata* consistently responded very strongly to artificial honeydew but *C. septempunctata* was much more variable in its response. Efforts to manipulate spatial distributions using artificial honeydew are hence likely to be more successful for the former than the latter species. Nevertheless, the general approach seems promising for aphidophagous ladybirds as a group, and is worthy of further study.

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RÉSUMÉ

Gestion de la dispersion des coccinelles (Col. : Coccinellidae) : utilisation de miellat artificiel pour agir sur les distributions spatiales

Nous avons essayé de voir s'il était possible d'agir sur la distribution à grande échelle des coccinelles aphidiphages par une application localisée de miellat artificiel. Outre le renforcement de la multiplication locale des coccinelles (par exemple dans des zones de pullulation naissante de pucerons), une telle approche peut se révéler utile pour attirer les coccinelles en dehors d'une culture dans laquelle un traitement insecticide est prévu. Au cours de 6 essais, nous avons pulvérisé du saccharose dissous dans de l'eau sur de petites parcelles situées au centre de vastes champs de luzerne, en Utah. Dans les 48 heures, les densités de coccinelles dans ces parcelles ont augmenté entre 2 et 13 fois, alors que les densités de coccinelles dans les zones éloignées de 40 à 150 m de ces parcelles diminuaient jusqu'à une moyenne inférieure aux 2/3 de leur densité initiale. Nous avons ensuite pulvérisé du saccharose sur une bande étroite tout autour du périmètre d'un champ de luzerne ; les densités de coccinelles ont augmenté à la suite du traitement tant sur la bordure traitée du champ, qu'à l'intérieur du champ de luzerne. Enfin nous avons comparé les réponses numériques de deux espèces de coccinelles suite à l'application de saccharose ; les deux espèces répondent positivement mais *Coccinella transversoguttata* présente une réponse nettement plus forte que *C. septempunctata*. Nos résultats suggèrent que l'utilisation de miellat artificiel devrait permettre de modifier la dispersion et la répartition spatiale des coccinelles.

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