Invertebrate biodiversity in maize following withdrawal of triazine herbicides

David R. Brooks^{1,*}, Suzanne J. Clark¹, Joe N. Perry¹, David A. Bohan¹,
Gillian T. Champion², Les G. Firbank³, Alison J. Haughton¹, Cathy Hawes⁴,
Matthew S. Heard⁵ and Ian P. Woiwod¹

¹Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK

²Broom's Barn Research Station, Bury St Edmunds, Suffolk IP28 6NP, UK

³Centre for Ecology and Hydrology, Lancaster Environment Centre, Lancaster, Lancashire LA1 4AP, UK

⁴Scottish Crop Research Institute, Invergowrie, Dundee DD2 5DA, UK

⁵Centre for Ecology and Hydrology, Monks Wood, Huntingdon, Cambridgeshire PE28 2LS, UK

Responses of key invertebrates within Farm Scale Evaluations (FSEs) of maize reflected advantageous effects for weeds under genetically modified herbicide-tolerant (GMHT) management. Triazine herbicides constitute the main weed control in current conventional systems, but will be withdrawn under future EU guidelines. Here, we reappraise FSE data to predict effects of this withdrawal on invertebrate biodiversity under alternative management scenarios. Invertebrate indicators showed remarkably consistent and sensitive responses to weed abundance. Their numbers were consistently reduced by atrazine used prior to seedling emergence, but at reduced levels compared to similar observations for weeds. Large treatment effects were, therefore, maintained for invertebrates when comparing other conventional herbicide treatments with GMHT, despite reduced differences in weed abundance. In particular, benefits of GMHT remained under comparisons with best estimates of future conventional management without triazines. Pitfall trapped Collembola, seed-feeding carabids and a linyphiid spider followed closely trends for weeds and may, therefore, prove useful for modelling wider biodiversity effects of herbicides. Weaker responses to triazines applied later in the season, at times closer to the activity and capture of invertebrates, suggest an absence of substantial direct effects. Contrary responses for some suction-sampled Collembola and the carabid *Loricera pilicornis* were probably caused by a direct deleterious effect of triazines.

Keywords: genetically modified crops; invertebrate biodiversity; maize; triazine herbicides

1. INTRODUCTION

Forage maize, *Zea mays* L., accounts for ca 100 000 ha of arable land in the UK and provides an important food source for livestock (Champion *et al.* 2003). Maize was one of the four crops assessed within the Farm Scale Evaluations (FSEs) that compared the effect of genetically modified herbicide-tolerant (GMHT) and conventional crop management on farmland wildlife. The GMHT maize cultivar used in the FSE (Chardon LL., Aventis, now Bayer Crop Science, Cambridge, UK) was modified to be resistant to the broad-spectrum herbicide glufosinate-ammonium (Liberty, 200 g AI ha⁻¹) (Firbank *et al.* 2003a). More arable weeds were found in the GMHT treatment than in conventional maize crops (Heard *et al.* 2003). In particular, biomass of dicotyledonous weeds and counts of their seed-rain were greater in GMHT maize, and as reduced availability of these food resources is a critical component in the demographic decline of farmland birds (Fuller *et al.* 1995) such crops may have benefits for wildlife (Firbank *et al.* 2003b).

Consideration of FSE results was an important component of the regulatory process leading to possible commercialization of GMHT maize. The Advisory Committee for Releases into the Environment (ACRE)

used them to provide advice on the likely benefits for within-field biodiversity if GMHT maize was adopted (ACRE 2004), which led to conditional, commercial approval by the UK government for this crop (Defra 2004). Herbicide management of conventional maize crops in the FSE reflected accurately current commercial practice in the UK (Champion *et al.* 2003). Triazine herbicides were used at the majority of sites, with atrazine being the most commonly applied product. Triazine use, however, will be prevented under future EU regulations (PSD 2003). Further analysis of FSE data was recommended for predicting biodiversity trends in maize following triazine withdrawal (ACRE 2004). Re-analysis of data, separating sites not using triazines, enabled Perry *et al.* (2004) to predict that, although weed abundance would be likely to increase without triazines, the benefits of GMHT management would remain. Here we predict trends for invertebrates after withdrawal of triazines using similar methods to those employed by Perry *et al.* (2004).

Invertebrates were included in the FSE because of their importance within agro-ecosystems and for assessing wider biodiversity effects of herbicides (Firbank *et al.* 2003a). They are an obligatory component in the diet of many bird species (Barker 2003) and provide protein for chick rearing (Potts & Aebischer 1991). Changes in abundance of weeds are known to affect invertebrates by

* Author for correspondence (david.brooks@bbsrc.ac.uk).

altering food resources or micro-climate (Chiverton & Sotherton 1991; Honek 1988) and herbicides are known to mediate such responses (Ewald & Aebischer 2000). The FSE reported positive effects of GMHT maize for invertebrates, attributable to changes in weed abundance (Firbank *et al.* 2003b). Larger counts of Collembola, seed-eating carabids, Staphylinidae and some linyphiid spiders were recorded for this treatment (Brooks *et al.* 2003; Haughton *et al.* 2003).

In this paper, we re-examine FSE data to understand better how invertebrates respond to different herbicide treatments in maize, particularly those involving non-triazines. We assess: (i) effect of triazines used prior and post-seedling emergence; (ii) suitability of pooling sites across management types to provide data with power for estimating effects of future non-triazine use; and (iii) biological significance of trends in weed abundance for invertebrates and likely biodiversity indicators for herbicide use.

2. METHODS

All data used here were derived from the FSE of GMHT maize conducted between 2000 and 2003. The methodology used in the FSE was described in detail by Firbank *et al.* (2003a) and Perry *et al.* (2003). Maize crops were grown on 58 fields throughout the UK. Agronomic management of conventional crops was representative of normal commercial practice, while GMHT crops were managed according to industry advice (Champion *et al.* 2003). Arable weeds and invertebrate indicators were surveyed throughout the growing season (Firbank *et al.* 2003a). Treatment differences were previously assessed using a randomised block ANOVA, termed the lognormal model by Perry *et al.* (2003), in which paired half-fields represented blocks. Total counts per half-field, transformed on a logarithmic scale, across number of sites (n), were included. The null hypothesis (H_0) of no treatment effect was tested using paired randomizations of a statistic, d , the mean of the differences between GMHT and conventional treatments on the logarithmic scale. The treatment effect was measured as R , the multiplicative ratio of the GMHT treatment divided by the conventional, calculated as $R = 10^d$.

(a) Invertebrate sampling methodology

Three techniques were used to sample invertebrates analysed in this paper: (i) pitfall traps sampled soil-surface active invertebrates (Brooks *et al.* 2003); (ii) Vortis suction samplers were used to collect invertebrates on weeds (Haughton *et al.* 2003); and (iii) earthworm casts were counted within quadrats used for weed assessments (Heard *et al.* 2003). Abundance of casts was used as a surrogate for earthworm activity in preliminary unpublished investigations, and are included because of a significant early season effect when counts were larger from GMHT maize ($n=21$, $R=2.14$ (95% CI, 1.18–3.88), $p=0.01$).

(b) Taxa tested

Analyses were restricted to taxa with large treatment effects in maize (Brooks *et al.* 2003; Haughton *et al.* 2003) and are listed in table 1. It should be noted that counts of *Bembidion* spp., *Trechus quadristriatus* and *Oedothorax* spp. were significantly greater in conventional crops where weed abundance was diminished. This is consistent with their biology (Baker &

Dunning 1975; Burn 1989; Alderweireldt 1994) and direction of treatment effects are therefore reversed compared with all other taxa considered here.

(c) Statistical analysis

Weed management in conventional crops observed during the FSE predominantly used triazine compounds, the most common being atrazine (A) which was used on three-quarters of all sites (Electronic Appendix part 1). Of the other herbicides ($\bar{A}$), four sites used the triazines simazine or cyanazine and five used only non-triazines. Half of all sites were treated pre-emergence (E), defined as sprayed within 14 days after sowing for crops drilled on or before May 15, or within 7 days when sown after this date. Pre-emergence applications always included either atrazine, simazine or cyanazine. Sites treated only by post-emergence ($\bar{E}$) herbicides used atrazine or exclusively non-triazines. Atrazine application rates were similar regardless of spraying time. All GMHT crops were treated post-emergence with glufosinate-ammonium and are considered as one group. Initial covariate analyses showed that atrazine, especially applied pre-emergence, often increased treatment effects for invertebrates. This is consistent with the results of Perry *et al.* (2004) for weeds. The classifications of herbicide management and statistical methods employed by Perry *et al.* (2004) were therefore considered equally applicable for invertebrates. Management was evaluated using three independent contrasts. The first was a comparison of similarity within the group ($A\bar{E}, \bar{A}E, \bar{A}\bar{E}$), and was used to justify considering non-triazine management ($\bar{A}\bar{E}$) as analogous to atrazine applied post-emergence ($A\bar{E}$) and the other triazines ($\bar{A}E$) in strength of treatment effect. The second tested differences between atrazine applied pre-emergence (AE) and all other treatments. The third contrast was between GMHT and treatments within ($A\bar{E}, \bar{A}E, \bar{A}\bar{E}$) and tested our best estimates of the effect of non-triazine management compared to GMHT. The original multiplicative ratios of treatment effect for the indicators, $R(o)$, were plotted against values for this statistic, R , adjusted for this third contrast and the relationship was investigated by standard regression analysis. Covariate analyses for higher invertebrate taxa, which previously showed no treatment response, suggested this result would not be modified by the above categories of management.

3. RESULTS

(a) Largest treatment effects for pre-emergence atrazine

For most of the invertebrate indicators the results are similar to those for total weed abundance reported by Perry *et al.* (2004). For example, when atrazine was applied pre-emergence, abundance was usually decreased compared with other treatments for both invertebrates and weeds. Also, abundance associated with atrazine applied post-emergence, other triazines, and non-triazines ($A\bar{E}, \bar{A}E, \bar{A}\bar{E}$), and GMHT management, often followed similar trends to those for weeds (tables 1 and 2). This is exemplified by *Amara* spp. (Carabidae) (figure 1), with similar trends for *Harpalus rufipes* (Carabidae), the spider aggregate *Erigone*, pitfall trapped Collembola and their family Isotomidae. Approximately 70% of the indicators mirrored previous results for weeds. This is reflected in the consistent reduction in the values of R compared with previously reported values ($R(o)$) (Brooks *et al.* 2003; Haughton *et al.* 2003), when limiting contrasts of GMHT

Table 1. Invertebrate abundance and herbicide use.

(Abundances expressed as means of logarithmically transformed half-field totals for treatments which are either conventional, with (A) or without ($\bar{A}$) atrazine, applied pre-emergence (E) or purely post-emergence ($\bar{E}$), or GMHT. Sample size, n , is the number of half-fields used in the analysis and may be smaller than indicated in table 1 owing to missing values or a total of zero or one individual per field as such data were removed from the analysis. Notation in parenthesis indicates the method used to survey the applicable taxon; P denotes pitfall traps, V, vortis and C, counts within quadrats.)

taxon	sample period	AE (atrazine, pre-em)		A $\bar{E}$ (atrazine, post-em)		$\bar{A}\bar{E}$ (other triazines)		$\bar{A}\bar{E}$ (non-triazines)		GMHT	
		n	mean	n	mean	n	mean	n	mean	n	mean
Collembola											
totals (P)	August	14	1.89	21	2.02	5	1.98	4	1.63	44	2.15
Entomobryidae (P)	August	14	1.63	20	1.73	5	1.21	4	1.35	43	1.75
Isotomidae (P)	August	13	0.93	19	1.12	7	0.84	3	0.64	42	1.44
Sminthuridae (P)	August	12	0.78	18	1.02	4	1.21	4	0.93	38	1.08
totals (V)	year	17	1.93	28	1.87	7	1.89	4	1.79	56	2.08
Entomobryidae (V)	year	17	1.46	26	1.42	7	1.20	4	1.06	54	1.55
Isotomidae (V)	year	16	1.07	26	1.40	7	1.55	4	0.98	53	1.55
Sminthuridae (V)	year	16	1.19	25	1.11	7	0.89	4	1.37	52	1.30
Carabidae											
<i>Amara</i> spp. (P)	year	13	0.40	20	0.47	5	0.54	3	0.51	41	0.66
<i>Bembidion</i> spp. (P)	year	18	1.80	28	1.74	7	1.71	4	1.27	57	1.61
<i>Pterostichus niger</i> (P)	year	13	0.83	18	1.13	3	0.89	4	1.64	38	1.21
<i>Loricera pilicornis</i> (P)	year	13	0.70	20	0.55	6	0.50	3	0.55	42	0.85
<i>Harpalus rufipes</i> (P)	July	13	0.80	19	0.86	5	1.01	2	0.87	39	1.12
<i>Trechus quadristriatus</i> (P)	year	17	1.13	22	0.99	4	0.77	4	1.41	47	0.88
<i>Agonum dorsale</i> (P)	year	8	0.56	18	0.52	4	0.66	3	0.80	33	0.90
Staphylinidae											
totals (P)	year	18	1.97	28	2.12	7	1.97	4	2.30	57	2.14
Araneae											
<i>Erigone</i> agg. (P)	year	18	1.41	28	1.61	6	1.35	4	1.96	56	1.73
<i>Oedothorax</i> spp. (P)	year	15	1.84	20	1.85	6	1.64	4	1.70	45	1.62
earthworms											
totals (C)	May	4	0.54	12	0.73	12	0.73	4	1.31	20	1.13

to (A $\bar{E}$, $\bar{A}\bar{E}$, $\bar{A}\bar{E}$). Regression analysis of these data, across all indicators, confirmed such reductions in R were consistent at a proportion of 0.913 (s.e. = 0.08, $p < 0.001$), with an intercept and coefficient of 0.07 and 0.59, respectively (figure 2).

(b) Similar treatment effects for all conventional management

Some indicators, although following the trend for weed abundance between GMHT and conventional treatments, did not display the precision of response to herbicides described above. Here, the effect of atrazines applied post-emergence, other triazines and non-triazines (A $\bar{E}$, $\bar{A}\bar{E}$, $\bar{A}\bar{E}$) was at least as strong as atrazines applied pre-emergence (AE). This is typified by total Collembola (Electronic Appendix part 2), and their families Entomobryidae and Sminthuridae, sampled by Vortis.

(c) Taxa most influenced by post-emergence atrazine

For the carabid, *Loricera pilicornis*, atrazine applied post-emergence caused the largest reductions in abundance. Here, tests of (A $\bar{E}$, $\bar{A}\bar{E}$, $\bar{A}\bar{E}$) contrasted against GMHT were more significant than those of pre-emergence atrazine against all groups. Uniquely for this species, there was a significant effect when comparing treatments within the pooled group (A $\bar{E}$, $\bar{A}\bar{E}$, $\bar{A}\bar{E}$) (table 2). A further independent test, which contrasted only post-emergence atrazine (A $\bar{E}$) against all other treatments, confirmed a highly

significant reduction in abundance under this herbicide management regime (s.e.d. = 0.064, $p < 0.0001$).

(d) Retention of treatment effects between GMHT and non-triazines

The previously reported effects of GMHT cropping are likely to persist for around three-quarters of all indicators when comparisons are limited to only non-triazine management. For contrasts of abundance between GMHT cropping and conventional management, there is no evidence that the non-triazine treatment ($\bar{A}\bar{E}$) differs significantly from others within the pooled group (A $\bar{E}$, $\bar{A}\bar{E}$, $\bar{A}\bar{E}$) (table 2). Significance is maintained for contrasts between this group and GMHT cropping for total Collembola and their families Entomobryidae, Sminthuridae (sampled by Vortis), and Isotomidae (sampled by pitfall traps), the carabids *L. pilicornis*, *H. rufipes* and *Agonum dorsale*, the spiders *Erigone* agg. and *Oedothorax* spp., and earthworms. Similarly, retention of large treatment effects for most of the remaining taxa under such contrasts strongly suggests the majority of indicators will respond differently to GMHT and future non-triazine management.

4. DISCUSSION

For the majority of invertebrates assessed there is good evidence that differences between GMHT and conventional management will be maintained after triazines are

Table 2. Tests of three independent contrasts of the mean invertebrate abundances.

(Each test has a p value. For the last two contrasts, the mean difference, d , and standard error of logarithmically transformed abundance is given. For the third contrast the value of $R=10^d$ is also calculated, for comparison with the original GMHT versus conventional treatment ratio previously reported by Brooks *et al.* (2003) and Haughton *et al.* (2003), $R(o)$, repeated with 2 d.f., s.e.(d), standard error of the difference, d . Notation in parenthesis indicates the method used to survey the applicable taxon; P denotes pitfall traps, V, vortis and C, counts within quadrats.)

taxa	sample period	contrast								
		within { $\bar{A}\bar{E}$, $\bar{A}\bar{E}$, $\bar{A}\bar{E}$ } (2 d.f.)	AE versus rest (1 d.f.)			GMHT versus mean ($\bar{A}\bar{E}$, $\bar{A}\bar{E}$, $\bar{A}\bar{E}$) (1 d.f.)				
			p	d	s.e.(d)	p	d	s.e.(d)	p	$R(o)$ R
Collembola										
totals (P)	August	0.871		-0.19	0.110	0.006	0.19	0.089	0.230	1.62 1.54
Entomobryidae (P)	August	0.811		-0.06	0.105	0.013	0.17	0.086	0.543	1.44 1.47
Isotomidae (P)	August	0.155		-0.33	0.126	<0.001	0.44	0.101	0.001	2.85 2.78
Sminthuridae (P)	August	0.831		-0.29	0.163	0.083	0.05	0.132	0.932	1.32 1.11
totals (V)	year	0.944		-0.07	0.091	0.025	0.22	0.072	0.040	1.56 1.64
Entomobryidae (V)	year	0.890		-0.01	0.091	0.138	0.21	0.073	0.037	1.46 1.62
Isotomidae (V)	year	0.538		-0.41	0.112	<0.001	0.16	0.089	0.238	1.78 1.46
Sminthuridae (V)	year	0.825		-0.03	0.121	0.426	0.21	0.097	0.060	1.54 1.61
Carabidae										
<i>Amara</i> spp. (P)	year	0.138		-0.19	0.077	<0.001	0.18	0.063	0.169	1.59 1.50
<i>Bembidion</i> spp. (P)	year	0.907		0.15	0.059	0.001	-0.08	0.048	0.396	0.76 0.84
<i>Pterostichus niger</i> (P)	year	0.749		-0.37	0.093	0.241	0.03	0.078	0.087	1.43 1.07
<i>Loricera pilicornis</i> (P)	year	0.026		-0.02	0.075	0.034	0.31	0.060	<0.001	1.76 2.04
<i>Harpalus rufipes</i> (P)	July	0.688		-0.23	0.105	0.010	0.23	0.088	0.043	1.77 1.69
<i>Trechus quadristriatus</i> (P)	year	0.700		0.20	0.076	0.001	-0.13	0.067	0.262	0.67 0.74
<i>Agonum dorsale</i> (P)	year	0.792		-0.21	0.160	0.002	0.32	0.113	0.098	2.14 2.09
Staphylinidae										
totals (P)	year	0.859		-0.16	0.043	0.002	0.02	0.035	0.651	1.16 1.05
Araneae										
<i>Erigone</i> agg. (P)	year	0.385		-0.27	0.075	0.017	0.12	0.062	0.021	1.54 1.33
<i>Oedothorax</i> spp.(P)	year	0.413		0.15	0.088	0.111	-0.17	0.074	0.028	0.64 0.68
earthworms										
totals (C)	May	0.473		-0.48	0.223	0.459	0.25	0.142	0.037	2.14 1.78

withdrawn. Contrasts between GMHT and pooled herbicide classifications, which included non-triazines, resulted in little alteration to treatment effects that were often significant. Only four sites in the FSE relied exclusively on non-triazines providing low power for tests of similarity, but the characteristics of these sites strengthen our predictions. To be reflective of widespread practice the FSE required a range of intensity of conventional herbicide management, including sites at the normal upper and lower tiers of effective weed control. Non-triazine sites represented this expected lower limit for weed control, probably because of the individual requirements of an atypical group of farms. Such management is unlikely to reflect future widespread practice when triazine herbicides are withdrawn as it is reasonable to predict that weed control will be more intensive and diverse. Firstly, it is expected that a wider range of herbicides will be used than those (bromoxynil, bromotril, prosulfuron and fluroxypyr) applied in the FSE (Champion *et al.* 2003). Alternatives, such as sulphonyl urea compounds, may prove more efficacious, especially if there is more residual activity (PSD 2003). Secondly, first applications for sites exclusively using non-triazine compounds occurred at a mean time of 37 days after sowing. This was considerably later than the average of 22 days after sowing for all sites and within one day of the mean for first applications to

GMHT crops. This delay in spraying almost certainly reduced the effectiveness of weed control. Future conventional management is likely to employ earlier applications, many of which will be pre-emergence. Therefore predictions for differences in weed abundance, and hence response of invertebrates, between future GMHT and conventional systems could be under-estimated.

Contrasts excluding pre-emergence atrazine resulted in remarkably consistent reductions to the treatment effects previously reported (Brooks *et al.* 2003; Haughton *et al.* 2003). This consistency is similar to trends for weeds where Perry *et al.* (2004) found approximately one-third reductions in R values compared to $R(o)$ (Heard *et al.* 2003). The magnitude of these reductions, however, is noticeably smaller for invertebrates at just one-tenth of $R(o)$. As the reduction in overall treatment effect caused by removal of pre-emergence atrazine sites is small, other contrasts, including the estimation of the effects of future non-triazine management, preserve their significance. Expectations for future differences between conventional and GMHT maize are therefore somewhat larger and more consistent over a range of invertebrates than is the case for weeds (Perry *et al.* 2004). These analyses demonstrably link invertebrate and weed abundance. They are thus consistent with the conclusion that changes in weed abundance mediated treatment responses for

Figure 1. Mean abundance of yearly pitfall captures of carabid *Amara* spp. for different categorisations of herbicide use. Represented here by GMHT (square symbol) or conventional (round symbols) half-fields with herbicides applied either pre-emergence (filled symbols) or purely post-emergence (open symbols). The grey filled symbol represents the mean of all conventional regimes other than atrazine applied pre-emergence and indicates our best estimate of future abundance under non-triazine management. Numbers in brackets denote N , the number of half-fields. Bars represent upper and lower 95% confidence intervals for each mean.

invertebrates within the FSE (Firbank *et al.* 2003b), an established correlation between invertebrate herbivores and weed abundance in the FSE (Hawes *et al.* 2003), and with other studies suggesting weed abundance is the most influential driver of change for invertebrates in herbicide management systems (Ewald & Aebischer 2000). Our results, however, suggest a lack of one single linear relationship between weed and invertebrate abundance that is generic to all herbicide systems. For example, large differences in weed abundance between pre-emergence and post-emergence atrazine treatments were not associated with correspondingly large changes for invertebrate counts. It seems likely that the mechanisms involved are sufficiently complex to warrant inclusion of a number of parameters to model weed and invertebrate relationships accurately. For example, apart from herbivory, weeds may influence invertebrates by increasing prey abundance (Speight & Lawton 1976), providing suitable microclimate (Armstrong & McKinlay 1997) or causing changes in community composition (Pavuk *et al.* 1997). Additionally, herbicides are known to have sub-lethal effects on many invertebrates (Jepson 1989) and could contribute to treatment effects in ways that are specific to the chemicals used.

Appreciable direct, negative effects of herbicides on invertebrates are unlikely as abundance is usually greater when spraying occurs at times closer to their capture and activity. Vortis captured Collembola are an exception to this observation, however, as treatment effects are strengthened for post-emergence applications that occur closer to sampling. Using data collected around the time when post-emergence atrazine was applied shows significant reductions in abundance are caused by this management when contrasted against all others (s.e.d = 0.093, $p < 0.05$; s.e.d = 0.097, $p < 0.05$; s.e.d = 0.109, $p > 0.10$ for total Collembola, Entomobryidae and Sminthuridae,

Figure 2. Plot of $R = 10^d$ for contrasts of conventional regimes which exclude atrazine applied pre-emergence with GMHT against original values of multiplicative treatment ratios, $R(o)$, calculated previously by Brooks *et al.* (2003) and Haughton *et al.* (2003). The estimated contrast of mean logarithmically-transformed abundance, d , is derived from tests of $\{AE, AE, AE\}$ against GMHT (see table 2.) for the 19 invertebrate indicators. The line shows a consistent trend of each value of R , in the absence of pre-emergence atrazine, being approximately nine-tenths that of $R(o)$.

respectively). For these taxa it is unlikely that post-emergence atrazine had time to kill weeds and produce detritus on which Collembola feed (Rusek 1998). The mechanism of response is thus more likely to be toxicological or antagonistic effects on feeding caused by residues on leaf surfaces or reduced fitness of plants. This is consistent with previous work demonstrating direct effects of triazines on Collembola (Edwards & Stafford 1979). Such contrasting results between pitfalls and Vortis may be owing to varying efficiency for capturing distinct taxa as treatment differences have been detected at the species level when absent overall for Collembola (Rebecchi *et al.* 2000). It is, therefore, likely that both techniques are required for rigorous environmental assessment. The carabid *L. pilicornis* may also be affected directly by triazines as abundance was reduced most when applications coincided with trapping. This species is a spring breeder with diurnal and early-season activity (Luff 1998). *L. pilicornis* is, therefore, active during post-emergence spraying which may render it susceptible to toxic effects or lead to suppression of activity. *L. pilicornis* captures have been dramatically reduced by herbicides (Gregoire-Wibo 1982) and triazines have a repellent effect on carabids (Brust 1990), so it is likely that this response is mediated directly.

Such subtlety of response of invertebrates highlights their importance for comprehensive environmental assessment within studies of herbicide management. Although the FSE demonstrated clear responses of invertebrates to weed abundance, erroneous assumptions may result from simply inferring likely effects from botanical data alone. Responses can vary with type of herbicide management and may not be systematically proportional to weed abundance. Indicator taxa which respond to herbicides appear fairly sensitive to changes in arable weeds. For maize, the

seed-feeding carabids *H. rufipes* and *Amara* spp. appear especially sensitive to weed abundance and could be good indicators of ecosystem level effects of changes in herbicide management. Isotomid Collembola and their linyphiid spider predators *Erigone* agg. (Alderweireldt 1994) may also prove good indicators of change within food chains, while *L. pilicornis* and Vortis captured Sminthuridae may be useful for assessing direct deleterious effects of agrochemicals. Our analyses suggest that even comparatively small changes in weeds can have implications within agroecosystems and affect populations of some invertebrates. In conclusion, although triazine withdrawal is likely to cause increased weed abundance in conventional maize we predict that benefits of GMHT management for some key invertebrates will remain.

We thank members of the Scientific Steering Committee of the FSEs, farmers and field staff for their support. The FSEs were funded by Defra and the Scottish Executive. Rothamsted Research receives grant-aided support from the BBSRC.

REFERENCES

- Advisory Committee on Releases to the Environment 2004 Advice on the implications of the farm-scale evaluations of genetically modified herbicide-tolerant crops. ACRE, London. (http://www.defra.gov.uk/environment/acre/advice/pdf/acre_advice44.pdf.)
- Alderweireldt, M. 1994 Prey selection and prey capture strategies of linyphiid spiders in high-input agricultural fields. *Bull. Br. Arachnol. Soc.* **9**, 300–308.
- Armstrong, G. & McKinlay, R. G. 1997 Vegetation management in organic cabbages and pitfall catches of carabid beetles. *Agric. Ecosys. Environ.* **64**, 267–276.
- Baker, A. N. & Dunning, R. A. 1975 Some effects of soil type and crop density on the activity and abundance of the epigeic fauna, particularly Carabidae, in sugar-beet fields. *J. Appl. Ecol.* **12**, 809–818.
- Barker, M. B. 2003 *Insects as food for farmland birds—is there a problem? Insect and bird interactions*. Andover: Intercept Ltd pp. 37–50.
- Brooks, D. R. *et al.* 2003 Invertebrate responses to the management of genetically modified herbicide-tolerant and conventional spring crops. 1. Soil-surface-active invertebrates. *Phil. Trans. R. Soc. B* **358**, 1847–1862. (doi:10.1098/rstb.2003.1408.)
- Brust, G. E. 1990 Direct and indirect effects of four herbicides on the activity of carabid beetles (Coleoptera: Carabidae). *Pestic. Sci.* **30**, 309–320.
- Burn, A. J. 1989 Long-term effects of pesticides on natural enemies of cereal crop pests. In *Pesticides and non-target invertebrates*. Wimborne: Intercept Ltd.
- Champion, G. T. *et al.* 2003 Crop management and agronomic context of the Farm Scale Evaluations of genetically modified herbicide-tolerant crops. *Phil. Trans. R. Soc. B* **358**, 1801–1818. (doi:10.1098/rstb.2003.1405.)
- Chiverton, P. A. & Sotherton, N. W. 1991 The effects on beneficial arthropods of the exclusion of herbicides from cereal crop edges. *J. Appl. Ecol.* **28**, 1027–1039.
- Defra 2004 <http://www.defra.gov.uk/corporate/ministers/statements/mb040309.htm>.
- Edwards, C. A. & Stafford, C. J. 1979 Interactions between herbicides and soil fauna. *Ann. Appl. Biol.* **91**, 132–137.
- Ewald, J. A. & Aebischer, N. J. 2000 Trends in pesticide use and efficacy during 26 years of changing agriculture in southern England. *Environ. Monit. Assess.* **64**, 493–529.
- Firbank, L. G. *et al.* 2003a An introduction to the Farm Scale Evaluations of genetically modified herbicide-tolerant crops. *J. Appl. Ecol.* **40**, 2–16.
- Firbank, L. G. *et al.* 2003b The implications of spring-sown genetically modified herbicide-tolerant crops for farmland biodiversity: a commentary on the Farm Scale Evaluations of spring sown crops. <http://www.defra.gov.uk/environment/gm/fse/results/fse-commentary.pdf>.
- Fuller, R. J., Gregory, R. D., Gibbons, D. W., Marchant, J. H., Wilson, J. D. & Baillie, S. R. 1995 Population declines and range contractions among lowland farmland birds in Britain. *Conserv. Biol.* **9**, 1425–1441.
- Gregoire-Wibo, C. 1982 Ecologie de *Loricera pilicornis* F. (Coleoptera, Carabidae) en culture. *Med. Fuk. Land. Rijk. Gent.* **47**, 729–739.
- Haughton, A. J. *et al.* 2003 Invertebrate responses to the management of genetically modified herbicide-tolerant and conventional spring crops. 2. Within-field epigeal and aerial arthropods. *Phil. Trans. R. Soc. B* **358**, 1863–1877. (doi:10.1098/rstb.2003.1408.)
- Hawes, C. *et al.* 2003 Responses of plants and invertebrate trophic groups to contrasting herbicide regimes in the Farm Scale Evaluations of genetically modified herbicide-tolerant crops. *Phil. Trans. R. Soc. B* **358**, 1899–1913. (doi:10.1098/rstb.2003.1406.)
- Heard, M. S. *et al.* 2003 Weeds in fields with contrasting conventional and genetically modified herbicide-tolerant crops. 1. Effects on abundance and diversity. *Phil. Trans. R. Soc. B* **358**, 1819–1832. (doi:10.1098/rstb.2003.1402.)
- Honek, A. 1988 The effect of crop density and microclimate on pitfall trap catches of Carabidae, Staphylinidae (Coleoptera) and Lycosidae (Araneae) in cereal fields. *Pedobiologia* **32**, 233–234.
- Jepson, P. C. 1989 The temporal and spatial dynamics of pesticide side-effects on non-target invertebrates. In *Pesticides and non-target invertebrates*. Wimborne: Intercept Ltd.
- Luff, M. L. 1998 *Provisional atlas of the ground beetles (Coleoptera, Carabidae) of Great Britain*. Huntingdon: Institute of Terrestrial Ecology.
- Pavuk, D. M., Purrington, F. F., Williams, C. E. & Stinner, B. R. 1997 Ground beetle (Coleoptera: Carabidae) activity density and community composition in vegetationally diverse corn agroecosystems. *Am. Midl. Nat.* **138**, 14–28.
- Perry, J. N., Rothery, P., Clark, S. J., Heard, M. S. & Hawes, C. 2003 Design, analysis and statistical power of the Farm-Scale Evaluations of genetically modified herbicide-tolerant crops. *J. Appl. Ecol.* **40**, 17–31.
- Perry, J. N. *et al.* 2004 Ban on triazine herbicides likely to reduce but not negate relative benefits of GMHT maize cropping. *Nature* **428**, 313–316.
- Pesticide Safety Directorate 2003 EC review programme for existing active substances. PSD, York. (http://www.pesticides.gov.uk/ec_process/ECreviews/EC_review_programme.htm)
- Potts, G. R. & Aebischer, N. J. 1991 Modelling the population dynamics of the grey partridge. In *Bird population studies: their relevance to conservation and management*. Oxford University Press.
- Rebecchi, L., Sabatini, M. A., Cappi, C., Grazioso, P., Vicari, A., Dinelli, G. & Bertolani, R. 2000 Effects of a sulfonylurea herbicide on soil microarthropods. *Biol. Fertil. Soils* **30**, 312–317.
- Rusek, J. 1998 Biodiversity of Collembola and their functional role in the ecosystem. *Biodivers. Conserv.* **7**, 1207–1219.
- Speight, M. R. & Lawton, J. H. 1976 The influence of weed-cover on the mortality imposed on artificial prey by predatory ground beetles in cereal fields. *Oecologia* **23**, 211–233.

The supplementary Electronic Appendix is available at <http://dx.doi.org/10.1098/rspb.2005.3102> or via <http://www.journals.royal.soc.ac.uk>.