Ban on triazine herbicides likely to reduce but not negate relative benefits of GMHT maize cropping

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The UK Farm-Scale Evaluations (FSE) compared the effects on biodiversity of management of genetically modified herbicide-tolerant (GMHT) spring-sown crops with conventional crop management[1]. The FSE reported larger weed abundance under GMHT management for fodder maize[2], one of three crops studied. Increased seed production may be important for the long-term persistence of these arable weeds and may benefit invertebrates, small mammals and seed-eating birds[1]. In three-quarters of FSE maize fields, growers used atrazine on the conventionally managed half, reflecting contemporary commercial practice[3]. Withdrawal of the triazine herbicides atrazine, simazine and cyanazine from approved lists of EU chemicals[4] could therefore reduce or even reverse the reported benefits of GMHT maize[1,2,5]. Here we analyse effects of applications of triazine herbicides in conventional maize regimes on key indicators[6], using FSE data. Weed abundances were decreased greatly relative to all other regimes whenever atrazine was applied before weeds emerged. Here, we forecast weed abundances in post-triazine herbicide regimes[7,8]. We predict weed abundances under future conventional herbicide management to be considerably larger than that for atrazine used before weeds emerged, but still smaller than for the four FSE sites analysed that used only non-triazine herbicides. Our overall conclusion is that the comparative benefits for arable biodiversity of GMHT maize cropping would be reduced, but not eliminated, by the withdrawal of triazines from conventional maize cropping.

Herbicide usage for FSE fodder maize[9] is shown in Table 1. We studied the response of five key vegetation indicators[2,5,6] for total weeds, total monocotyledonous weeds (monocots) and total dicotyledonous weeds (dicots) to combinations of herbicide use (Table 2). We found the following consistent trends, exemplified in Fig. 1. Weed abundances were decreased greatly compared to any other regime, whenever atrazine was applied before weeds emerged (pre-emergence[9], see Methods) on conventional crops. For the other conventional regimes, weed abundance for the few sites that were treated only with non-triazines was consistently slightly greater than those for the triazines. With this exception, weed abundance in fields that were treated conventionally (excluding those where atrazine was used pre-emergence) appeared similar. Weed abundance under GMHT management was usually greater than that for atrazine applied post-emergence or for the other triazines applied pre-emergence.

These trends suggested three independent contrasts, tested formally in Table 3. The first comparison is within the three conventional treatment combinations (in which atrazine was applied post-emergence, AĒ; other triazines were applied pre-emergence, ĀE; or non-triazines alone were applied post-emergence, ĀĒ), that is, excluding those where atrazine was used as a pre-emergence herbicide (AE). The second comparison is between AE and all the other treatment combinations (AĒ, ĀE, ĀĒ and GMHT). The third comparison, which is independent of the first two, is between GMHT and treatments AĒ, ĀE and ĀĒ.

Weed abundance for atrazine applied pre-emergence in conventional crops was usually statistically significantly less than the mean of all other regimes (Table 3). Typically, it was reduced by two-thirds; monocot biomass was reduced eightfold. Differences in weed abundance never approached significance for the tests among the three other conventional herbicide regimes (AĒ, ĀE, ĀĒ).

The treatment effect between GMHT and conventional crops in the FSE was presented[1–3,5] as the multiplicative ratio of the geometric-mean half-field GMHT abundance divided by that for the conventional. The value of this multiplicative ratio, R, as defined here, contrasts GMHT with the conventional regimes, excluding atrazine applied pre-emergence. The value previously reported in ref. 2, termed R_0 here, applies to all data including sites with pre-emergence atrazine. Regression analysis of results in Table 3 confirmed that R was a consistent proportion: approximately 0.687 (with s.e. 0.026) of R_0.

These results were consistent with the effects reported previously[2] for GMHT management in maize, which produces a larger number of smaller plants, typically half as large in the reproductive phase, relative to conventional management. All of the more abundant species of weeds in the FSE have seeds that persist in seedbanks for several seasons[5], so the effects of weed management in one season are buffered[1]. Our results for seedbanks have relatively small sample size (N, Table 2), but appear to confirm this buffering effect.

Caution is required in predicting the magnitude of effects on biodiversity of future herbicide regimes[7], but considerable information exists on the probable replacements for triazines in conventional maize in the UK[9] to aid forecasts. The larger weed abundances for GMHT than for conventional maize management reported previously[2], and expressed through the multiplicative treatment-effect ratio (R_0), were caused partly by the effectiveness of atrazine used pre-emergence (AE). Following withdrawal of

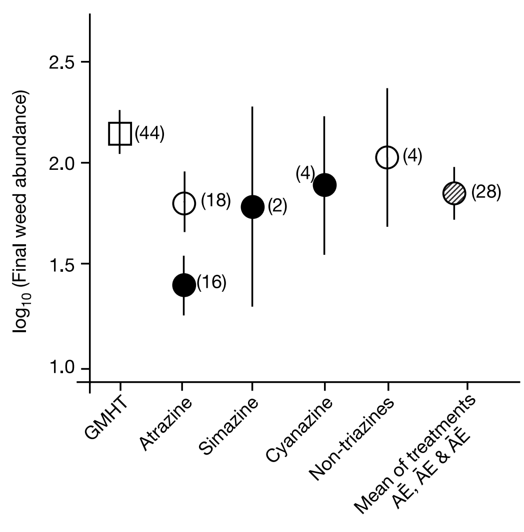

Figure 1 Mean abundance of total pre-harvest weeds and herbicide use. Consistent treatment effects from Table 2, illustrated here by mean abundance of total pre-harvest weeds in FSE fodder-maize per GMHT (square symbol) or conventional (round symbols) half-fields, and treated either with pre-emergence herbicide plus possible post-emergence application(s) (filled symbols, E) or with post-emergence herbicide only (open symbols, Ē). Hatched symbol represents the mean of the three conventional regimes AĒ, ĀE and ĀĒ: that is, all those other than atrazine applied pre-emergence. Numbers in brackets denote N, the number of half-fields. Bar represents 95% confidence interval for each mean.

Table 1 **Herbicides applied to 58 FSE fodder-maize conventional half-fields**

	Pre- (plus possibly post-) emergence (E)		Post-emergence only (Ē)		Total
	Number of half-fields	Application rate ($g\,ha^{-1}$) (s.e.m.)	Number of half-fields	Application rate ($g\,ha^{-1}$) (s.e.m.)	Number of half-fields
With atrazine (A)					
A alone	8	1,272 (75)	11	1,336 (62.6)	19
A + non-triazines (NT)	10	1,628 (302)	17	1,244 (97.0)	27
Total atrazine	18	1,470 (172)	28	1,280 (63)	46
Other triazines					
Simazine alone	2	1,150 (0)	0	–	2
Simazine + NT	0	–	0	–	0
Cyanazine alone	0	–	0	–	0
Cyanazine + NT	5	2,233 (163)	0	–	5
Total of other triazines	7	1,924 (229)	0	–	7
NT alone	1	2,115 (–)	4	420 (146)	5
Total of all treatments	26	1,617 (139)	32	1,173 (77.1)	58

Application rates expressed as total grams of active ingredient per hectare from all herbicides combined, averaged over half-fields[9], with standard error of mean in parentheses.

Table 2 **Weed abundances and herbicide use**

Taxa	AE (atrazine, pre-emergence)		AĒ (atrazine, pre-emergence)		ĀE (other triazines)		ĀĒ (non-triazines)		GMHT	
	N	Mean	*N*	Mean	*N*	Mean	*N*	Mean	*N*	Mean
Total weeds										
Final plant density	16	1.38	18	1.79	6	1.84	4	2.01	44	2.16
Biomass (g)	14	1.97	16	2.53	5	2.44	4	3.02	39	2.64
Seed rain	18	1.75	25	2.18	6	1.78	4	2.57	53	2.27
Seedbank $t+1$	6	1.94	11	2.23	6	2.27	2	2.38	25	2.21
Seedbank change t to $t+1$	6	−0.12	11	0.22	6	0.17	2	−0.08	25	0.09
Dicots										
Final plant density	16	1.12	18	1.37	6	1.62	4	1.91	44	1.92
Biomass	14	1.54	16	2.07	5	2.22	4	2.92	39	2.48
Seed rain	18	1.58	25	1.96	6	1.58	4	2.35	53	2.16
Seedbank $t+1$	6	1.53	11	1.99	6	2.11	2	2.06	25	1.96
Seedbank change t to $t+1$	6	−0.17	11	0.27	6	0.24	2	−0.14	25	0.11
Monocots										
Final plant density	16	0.92	18	1.36	6	1.44	4	1.25	44	1.64
Biomass	14	0.93	16	1.96	5	1.84	4	2.05	39	1.77
Seed rain	16	0.83	19	1.34	6	0.97	4	1.93	45	1.18
Seedbank $t+1$	6	1.54	11	1.58	6	1.60	2	2.03	25	1.73
Seedbank change t to $t+1$	6	−0.18	11	0.11	6	−0.04	2	−0.05	25	0.03

Weed abundances expressed as means of logarithmically transformed totals of final plant densities, biomass (g), seed rain and seedbank densities, per conventional FSE fodder-maize half-field sample, treated either with (A) or without (Ā) atrazine, under regimes that included either pre-emergence (E) herbicide or purely post-emergence (Ē) application, and in GMHT half-fields. t relates to year crop was in ground; $t+1$ relates to subsequent year.

Table 3 **Tests of three independent contrasts of the mean weed abundances described in Fig. 1 and Table 2**

Taxa	Within treatments AĒ, ĀE & ĀĒ (2 d.f.)	AE versus rest (1 d.f.)			GMHT versus mean of AĒ, ĀE & ĀĒ (1 d.f.)				
	P	*d*	s.e.(*d*)	*P*	*d*	s.e.(*d*)	*P*	R_0	*R*
Total weeds									
Final plant density	0.199	−0.65	0.080	<0.001	0.33	0.070	<0.001	3.08	2.16
Biomass	0.479	−0.65	0.161	0.001	0.05	0.139	0.916	1.82	1.12
Seed rain	0.915	−0.48	0.202	0.024	0.11	0.170	0.720	1.87	1.29
Seedbank $t+1$	0.936	−0.29	0.091	0.474	−0.05	0.064	0.860	1.07	0.90
Seedbank change t to $t+1$	0.976	−0.24	0.103	0.433	−0.09	0.072	0.478	0.96	0.82
Dicots									
Final plant density	0.180	−0.64	0.099	<0.001	0.42	0.086	<0.001	3.52	2.61
Biomass	0.397	−0.84	0.217	<0.001	0.24	0.189	0.384	3.02	1.76
Seed rain	0.835	−0.49	0.216	0.012	0.23	0.181	0.456	2.32	1.68
Seedbank $t+1$	0.616	−0.46	0.097	0.032	−0.08	0.068	0.598	1.1	0.83
Seedbank change t to $t+1$	0.730	−0.32	0.103	0.078	−0.11	0.072	0.218	0.97	0.79
Monocots									
Final plant density	0.251	−0.61	0.094	<0.001	0.28	0.082	0.007	2.88	1.91
Biomass	0.657	−0.91	0.206	0.016	−0.19	0.179	0.642	1.58	0.65
Seed rain	0.790	−0.41	0.179	0.124	−0.17	0.154	0.317	1.18	0.68
Seedbank $t+1$	0.217	−0.15	0.146	0.773	0.09	0.102	0.132	1.31	1.24
Seedbank change t to $t+1$	0.648	−0.22	0.135	0.743	−0.02	0.095	0.775	1.09	0.96

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-effect ratio, R_0, repeated from ref. 2. d.f., degrees of freedom. s.e.(*d*), standard error of the difference, *d*.

triazines in the EU, other conventional herbicides will almost certainly be less effective than atrazine used pre-emergence and values of R for future herbicide management for maize crops would therefore be reduced[1,8]. Future conventional management of UK maize crops will probably involve[8]: (1) a greater range of herbicides than in the FSE (Table 1; ref. 9); (2) more use of sulphonyl urea herbicides, together with pendimethalin, bromoxynil and fluroxypyr; (3) non-triazine herbicides with greater residual activity; and (4) non-triazine herbicides applied (unlike the FSE data reported here) pre-emergence.

We therefore expect weed abundances under future conventional herbicide management for maize crops to be considerably larger than that reported here for atrazine used pre-emergence (AE), but smaller than for the four sites analysed that used non-triazines alone. A reasonable but necessarily tentative approximation to future weed abundances is therefore the mean of the pooled categories (A$\bar{E}$, $\bar{A}$E, $\bar{A}\bar{E}$): that is, all sites excluding those where atrazine was used pre-emergence.

If this pooled category of herbicide regimes is indeed representative of weed control in post-triazine conventional crops, and if the weed management in GMHT maize remains the same as observed within the FSE, then final weed numbers would still be larger in GMHT than in conventional maize. Dicot weed biomass would have a value of $R = 1.76$, well above unity, although not significantly so; by contrast, monocot weed biomass would be smaller under GMHT than under future conventional management. The predicted effects on seed rain (amount of seed shed by a plant) would largely follow those for biomass, with more than 1.5 times as many expected under GMHT management, but with a relatively large standard error. Generally, the statistical significance of predicted differences for individual indicators is of less importance than the biological significance of the consistency[1,3] of the relation between R and R_0 over all indicators.

To place these results in context, we reiterate[1] that reported differences in the FSE were as large between crops as between treatments. Conventional maize was the poorest combination for biodiversity, and even under GMHT management seed rain only marginally exceeded that for conventional beet and GMHT spring oilseed rape[2]. However, we conclude that the comparative benefits for arable biodiversity of GMHT maize cropping would be reduced, but not eliminated, by the withdrawal of triazines from conventional maize cropping. □

Methods

Table 1

Of 58 FSE fodder-maize conventional half-fields[9], 46 received atrazine (A), with or without other non-triazines; 12 received no atrazine ($\bar{A}$). The 26 conventional crops that were treated pre-emergence (defined as treated within 14 days after sowing for crops sown on or before 15 May, or within 7 days for crops sown after 15 May) are distinguished from the 32 with purely post-emergence ($\bar{E}$) application. Pre-emergence herbicide use almost always included a triazine, usually atrazine, and was often followed by additional post-emergence herbicide application(s). Besides atrazine, other triazines used were simazine on two half-fields and cyanazine on five. Five half-fields received a non-triazine (NT) alone. Application rates are expressed as total amount of active ingredient (g ha^{-1}) from all herbicides combined, averaged over half-fields[9], with standard error of mean. When one triazine herbicide was used, no other was; however, other non-triazine herbicides were usually used in addition to a triazine. (The use of a non-triazine in addition to the use of a triazine appeared to have little effect on weed abundance and is not considered further here.) Measurement of the seedbank was done in the top 15 cm of soil, using samples usually taken before any herbicide was applied[2]. There was no significant dependence of the use of either atrazine or of a pre-emergence herbicide on the size of the initial seedbank. For crops treated with atrazine, the amount of active ingredient applied[9] (g ha^{-1}) was very similar between the pre-emergence (E) and post-emergence only ($\bar{E}$) treatments, whether atrazine was used in combination with a non-triazine or not.

Table 2

We studied the response of five key vegetation indicators[2,5] for total weeds, total monocots and total dicots to combinations of herbicide use. Values for seedbank change are transition rates per half-field. All indicators and calculations are as described in ref. 2, where weed abundances are expressed as means of logarithmically transformed abundances per FSE half-field sample. Sample size, N, may be reduced from the values in Table 1 because data were missing for a half-field or abundance was too small for analysis[2,3,9].

Figure 1

We found consistent trends in Table 2, exemplified in Fig. 1. Fourteen fields either had missing data or abundance was too small for analysis. Of the 44 remaining conventional half-fields, 34 received atrazine with or without other non-triazines (A), and ten received no atrazine ($\bar{A}$). Of these ten, two received simazine alone, four received cyanazine and another non-triazine, and four received non-triazines alone. Confidence intervals were based on residual variation after removal of site and treatment effects.

Table 3

The mean difference between logarithmically transformed abundances for each contrast examined is termed d. Analyses were regressions where treatment effects were estimated after removal of site effects. Standard errors of d were therefore based on residual variation after removal of both site and treatment effects. The treatment effect, R, for contrasts involving GMHT versus conventional regimes, is presented as the multiplicative ratio of the half-field GMHT abundance divided by that for the conventional, calculated from $R = 10^d$. For each of the three independent contrasts shown, the P-value, from analysis of variance[3], is based on an F-test. The third contrast, intended to compare GMHT with possible future management, is between GMHT and treatments A$\bar{E}$, $\bar{A}$E and $\bar{A}\bar{E}$; for this the value of $R = 10^d$ is also calculated, for comparison with the original GMHT versus conventional treatment-effect ratio[3], R_0, repeated from ref. 2. This contrast was usually based on $N > 25$ sites. Data yet to be analysed[1,2,5] concerning seedbank densities during the first and second year after the treatments, are still required to establish reliable rates of change of maize seedbanks over full rotations.

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1. Firbank, L. G. *et al*. *The Implications of Spring-Sown Genetically Modified Herbicide-Tolerant Crops for Farmland Biodiversity: A Commentary on* 'The Farm Scale Evaluations Of Spring Sown Crops'. (Defra, 2003); at ⟨http://www.defra.gov.uk/environment/gm/fse/index.htm⟩.
2. Heard, M. S. *et al.* Weeds in fields with contrasting conventional and genetically modified herbicide-tolerant crops. 1. Effects on abundance and diversity. *Phil. Trans. R. Soc. Lond. B* **358,** 1819–1832 (2003).
3. Perry, J. N., Rothery, P., Clark, S. J., Heard, M. S. & Hawes, C. Design, analysis and power of the Farm-Scale Evaluations of Genetically-Modified Herbicide-Tolerant crops. *J. Appl. Ecol.* **40,** 17–31 (2003).
4. Pesticide Safety Directorate. *EC Review Programme for Existing Active Substances*. (PSD, York, 2003); at ⟨http://www.pesticides.gov.uk/ec_process/ECreviews/EC_review_programme.htm⟩.
5. Heard, M. S. *et al.* Weeds in fields with contrasting conventional and genetically modified herbicide-tolerant crops. 2. The effects on individual species. *Phil. Trans. R. Soc. Lond. B* **358,** 1833–1846 (2003).
6. Firbank, L. G. *et al.* Farm-scale evaluation of genetically modified crops. *Nature* **399,** 727–728 (1999).
7. British Statutory Nature Conservation Agencies. *Advice to ACRE on the Implications of the Farm Scale Evaluations for Biodiversity in the UK*. Evidence submitted to the ACRE Committee's Farm-scale Evaluation Results Open Meetings, November 2003 (English Nature, Peterborough, 2003); at ⟨https://www.livegroup.co.uk/acrefarmscaleevaluations/SSL/index2.php?page=submissions⟩.
8. Marshall, J. *Glufosinate-tolerant Maize: Implications of the USA Experience for Weed Control in Forage Maize in the UK*. Appendix 2 of evidence submitted by Greenpeace to the ACRE Committee's Farm-scale Evaluation Results Open Meetings, November 2003 (Greenpeace UK, London, 2003); at ⟨https://www.livegroup.co.uk/acrefarmscaleevaluations/SSL/index2.php?page=submissions⟩.
9. Champion, G. T. *et al.* Crop management and agronomic context of the Farm Scale Evaluations of genetically modified herbicide-tolerant crops. *Phil. Trans. R. Soc. Lond. B* **358,** 1801–1818 (2003).

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