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Management of genetically modified herbicide-tolerant sugar beet for spring and autumn environmental benefit

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When used in genetically modified herbicide-tolerant (GMHT) crops, glyphosate provides great flexibility to manipulate weed populations with consequences for invertebrates and higher trophic levels, for example birds. A range of timings of band and overall spray treatments of glyphosate to GMHT sugar beet were compared with a conventional weed control programme in four field trials over 2 years. Single overall sprays applied between 200 and 250 accumulated day degrees (above a base air temperature of 3 °C; °Cd) and band applied treatments applied at 10% or 20% ground cover within the crop rows generally gave significantly greater weed biomass and seed rain than conventional treatments, while later band sprays (more than 650 °Cd) reduced seed return. Two overall sprays of glyphosate produced low weed biomass and generally lowest seed return of all treatments but tended to give some of the highest yields. However, the early overall sprays (200–250 °Cd) and band sprays gave as good or better yields than the conventional and were generally equivalent to the two overall-spray programme. Viable seeds in the soil after the experiment were generally higher following the early overall (200–250 °Cd) and the band spray treatments than following the conventional. The results show that altered management of GMHT sugar beet can provide alternative scenarios to those of the recent Farm Scale Evaluation trials. Without yield loss they can enhance weed seed banks and autumn bird food availability compared with conventional management, or provide early season benefits to invertebrates and nesting birds, depending on the system chosen. Conventional weed control does not have the flexibility to enable these scenarios that benefit both agriculture and environment, although there may be some options for increasing weed seed return in autumn.

Keywords: genetically modified herbicide-tolerant sugar beet; band spray; seed rain; seed bank; environment; yield

1. INTRODUCTION

The Farm Scale Evaluations (FSE) of the environmental impact of growing genetically modified herbicide-tolerant (GMHT) crops in the UK concluded that the management of weeds in the GMHT beet, both sugar and fodder (*Beta vulgaris* ssp. *vulgaris*), resulted in fewer weeds later in the season, which produced significantly less biomass and seed return to the soil compared with conventional crops. This in turn resulted in fewer weeds in the soil seed bank the following year, and a suggestion that the effect lasted for a second year (Heard *et al.* 2003*a*). Some invertebrates, that relied on these weeds for food, were also affected by the herbicide regime (Brooks *et al.* 2003; Haughton *et al.* 2003). However, the weed-management programme that produced these results (Champion *et al.* 2003) was designed to give cost-effective weed control in beet. It achieved that goal because control of weeds by glyphosate (a broad-spectrum herbicide) was superior to that by conventional herbicides, which have a relatively poor spectrum of activity and margin of selectivity (May 2001).

Our previous research (Dewar *et al.* 2003) showed that the retention of weeds in GMHT beet, by delaying sprays and/or applying them as a band over the rows at first application, can enhance the number of invertebrates within the crop canopy, particularly carabid and staphylinid beetles. Increasing weed cover in beet crops can also decrease infestation by aphids (Dewar *et al.* 2000), which can reduce infection by viruses (Dubois & Ammon 1997). However, concern was expressed by organizations such as English Nature (2000) and the Royal Society for the Protection of Birds (2003) that the use of glyphosate would reduce seed availability for bird food in the autumn. Freckleton *et al.* (2004) postulated that the later-applied sprays in those early experiments would not allow surviving weeds to set seed, and thus would result in few weed seeds returning to the soil. Although seed rain was not recorded in those experiments, observations tended to corroborate this hypothesis. Thus, although later spraying and band spraying provided spring and early summer benefits, it did not address the problem of weed seed production. Lack of bird food in the autumn is considered one of the major problems of present-day agricultural production in the UK (Chamberlain *et al.* 2000).

In this paper, we address the problems of yield and bird food in the autumn and describe further experiments that examine refined timings of band and overall sprays of glyphosate in GMHT beet to produce greater weed seed rain than from conventional herbicides, while still maintaining or even increasing yield.

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Table 1. Site details and details of conventional herbicides (number of sprays, AI and total AI ($g\,ha^{-1}$)).

	site 1: 2001	site 2: 2001	site 3: 2002	site 4: 2002
sowing date	27 April	3 May	27 March	4 April
harvest date	7 September	3 September	2 September	10 September
soil type	sandy loam	peaty loam	sandy loam	peaty loam
conventional herbicides				
numbers of pre-em sprays	1	0	1	0
numbers of post-em sprays	4	4	4	4
numbers of AIs (including repeats)	6 (9)	6 (17)	6 (9)	7 (16)
total AI $g\,ha^{-1}$	2772	1928	2314	2974

2. METHODS

Four experiments, two per year, were conducted in Suffolk and Cambridgeshire, UK, on sandy loam and black fen (peaty loam) soils, respectively, during 2001 and 2002 (table 1). Crops were sown relatively late in 2001 (April or May) owing to a wet spring, and at a more typical time in 2002 (March or April). All plots (12 m × 12 m, four replicates and randomized complete block design) were sown with genetically modified (GM) glyphosate-tolerant sugar beet (event L no. 77 from Monsanto). Within each block, one plot was left untreated, one treated with conventional herbicides and the rest with glyphosate at various timings.

Between four and five herbicide sprays, comprising six to seven different active ingredients, were applied to the conventional plots in response to the different weed flora present at each site and comprised between 1928 g and 2974 g active ingredient (AI) ha^{-1} (table 1). The glyphosate treatments were applied overall or as a 20 cm band over the rows, which were 50 cm apart, at a range of timings from sowing (table 2), but were sometimes delayed owing to poor spraying weather. Single overall glyphosate treatments were applied at *ca.* 200, 300, 400 and more than 600 accumulated day degrees (°Cd) from sowing calculated above a base air temperature of 3 °C, which is the development threshold for beet (Werker & Jaggard 1997). Where two overall glyphosate sprays were tested, the first was applied at 10% ground cover (by crop and weeds) within the row (i.e. 279–414 °Cd after sowing) and the other as required (i.e. more than 800 °Cd at sites 1, 3 and 4 and 551 °Cd at site 2). Band sprays were applied at either 10% or 20% ground cover within the row, and were either applied alone or followed by one subsequent overall spray at *ca.* 600 or 800 °Cd. All glyphosate sprays were applied at a *pro rata* rate of 1080 g AI ha^{-1}, so the quantity used ranged between 432 g AI ha^{-1} for a single band spray to 2160 g AI ha^{-1} for two overall sprays.

Above-ground foliage was collected from three 1.0 m × 1.0 m quadrats per plot in July, and the dried weight of each weed species was determined. The return of weed seeds to the soil was determined throughout the season using seed rain traps (Heard *et al.* 2003*a*), and their viability determined by a 'squeeze' test (Ball & Miller 1989). Weeds were counted using ten 0.5 m × 0.5 m quadrats per plot. Counts were made throughout the growing season and then weed seedlings that emerged after harvest were counted in November (sites 1 and 3) or December (site 4); site 2 was sown to winter wheat and could not be assessed. Plots were machine harvested in early September (to comply with sugar industry requirements for separation of GM trials and the commercial crop), and root and sugar yields were determined using standard methods (Schneider 1979) in the tarehouse at Broom's Barn. Post-harvest weed seed banks were determined once the soil had been ploughed (inverted) twice. For this, six 5 cm diameter cores were taken to 15 cm depth per plot in November 2003 (sites 1, 2 and 4) and April 2004 (site 3). The soil from each plot was weighed and thoroughly mixed and one subsample of 500 g was removed for processing. Where necessary, samples were stored frozen at −20 °C prior to processing. The extraction technique was based on that described by Roberts & Ricketts (1979). Soil samples were processed using a wet-sieving technique. A Fritsch Analysette vibratory shaker was set up with a stack of sieves (4 mm, 1 mm, 0.5 mm and 0.25 mm) with water running through them. The machine was set to vibrate and sieve for *ca.* 20–25 min depending on soil type. The process was completed once the outflow water was clear. Seeds were removed from the sieves and the sediment was checked for seeds by adding 50–100 ml of a saturated solution of calcium chloride ($CaCl_2$) which caused the seeds to float. The solution was stirred and inspected for seeds under a large lens. Once dry, seeds were identified and the 'squeeze' test was used to determine apparent viability.

The data other than yields from untreated plots were used to indicate the scale and context of effects but were excluded from the ANOVA (GENSTAT, v. 6.1). Data other than yields were log transformed prior to analysis. One seed rain sample from site 2 and four seed bank samples from site 4 were missing.

Dewar *et al.* (2003) showed that the effect of delay in single glyphosate treatment on sugar yield follows a logistic curve described by the following model:

$$Y = Y_0 + A/(1 + e^{B(T-T_0)}),$$

where Y is sugar yield, Y_0 is the sugar yield from the untreated plots, A is the maximum reduction of sugar yield in untreated plots, and B is the rate of sugar yield reduction caused by delays in spraying the herbicide. The sum of Y_0 and A determines the maximum obtainable sugar yield if weeds are efficiently and effectively controlled. T is the thermal time from sowing and T_0 is thermal time at which the reduction of sugar yield reaches half the value of A. Data in this experiment were fitted to this model.

3. RESULTS

(a) *Weed flora and crop population*

On the untreated plots, weed densities were generally greater on the peaty loam than on the sandy loam soil (table 3). On the sandy loam soils, *Chenopodium album* was the major weed (64% of the population) at site 1, and *C. album* (32%) and *Stellaria media* (26%) at site 3. On the peaty loam, *Persicaria maculosa* (57%) and *Fallopia convolvulus* (18%) were the common species at site 2, and *Veronica persica* (32%) and *P. maculosa* (29%) at site 4. Where weed competition had been removed by conventional treatments, site 1 had low beet populations (63 840 ha^{-1}) compared with between 81 000 and 91 160 ha^{-1} at the other sites.

Table 2. Application timings from sowing to treatment as °Cd above a base temperature of 3 °C.

	site 1	site 2	site 3	site 4
treatments	°Cd	°Cd	°Cd	°Cd
untreated (to harvest)	1675	1596	1826	1835
conv. (to first treatment)	72	159	60	116
timings of overall glyphosate sprays				
200–250 °Cd	204	208	235	221
250–350 °Cd	316	279	348	
350–450 °Cd	373	396		414
450–550 °Cd			467	451
550–650 °Cd	605			
650–750 °Cd			735	683
$250-350+500-650°$ Cd		279 551		
$250-350+800-850°$ Cd	316 816		348 809	
$350-450+850-955°$ Cd				414 955
timing of band sprays (some with second spray overall)				
10% cover	316	279	348	414
10% cover/550–650 ° Cd	316 605	279 551		
10% cover/650–750 ° Cd			348 735	414 683
10% cover/800–950 ° Cd	316 816		348 809	414 955
20% cover	433	396	467	451
0% cover/550–650 ° Cd		396 551		
20% cover/800–950 ° Cd	433 816		467 809	451 955

Table 3. Average weed densities, crop and weed biomass, total weed seed rain, sugar yield and subsequent weed seed banks on untreated plots.

	site 1	site 2	site 3	site 4
weed density (m^{-2})				
date of assessment	23 July	16 July	10 July	29 July
weeds m^{-2}	32.8	88.7	46.7	55.5
crop and weed biomass (g DM m^{-2})				
date of assessment	23 July	16 July	15 July	19 July
total crop	371	330	708	405
foliage weed	972	474	166	192
weed seed rain (m^{-2})				
seeds	42 144	55 641	7066	31 133
crop population (ha^{-1})				
beet plants	65 200	76 300	87 300	72 800
sugar yield (t ha^{-1})				
sugar	1.6	2.3	4.9	4.2
weed seed banks in 2003/2004 (seeds m^{-2})				
total	167 493	47 026	75 385	5485
total viable	54 095	28 656	26 325	1466
percentage viable	32	61	35	27

(b) *Weed biomass*

Weed biomass in July was positively correlated with weed density and weed seed return at three of the sites (table 4). However, although site 1 had the lowest weed density, owing to the low crop population it had the greatest weed biomass and high seed rain, especially on band-sprayed plots. In general the band-sprayed treatments produced weed biomasses equivalent to or higher than the conventional treatments; the exception was the band treatment at 10% cover followed by an overall spray at 683 °Cd at site 4 (table 4).

(c) *Yield*

Two overall applications of glyphosate gave higher yields (by at least 11%) than the conventional herbicide programmes at sites 2, 3 and 4 (significantly greater ($p < 0.05$) at sites 2 and 3; table 4).

Treatments involving a band spray at 10% ground cover followed by an overall application of glyphosate produced similar yields to two overall glyphosate sprays and significantly higher ($p < 0.05$) yields than conventional herbicide treatments at three out of the four sites (table 4). There was no significant difference between treatments where the first (band) spray was applied at 10% or at 20% ground cover

Table 4. Log transformed weed biomass in mid July (g DM m^{-2}) and total seed rain (seeds m^{-2}) and yield of sugar (t ha^{-1}) and viable seeds in the soil seed bank in 2003/2004.

	log weed biomass				log viable seed rain				sugar yield (t ha^{-1})				viable seeds in soil (m^{-2})			
Trts (°Cd)	site 1	site 2	site 3	site 4	site 1	site 2	site 3	site 4	site 1	site 2	site 3	site 4	site 1	site 2	site 3	site 4
conv.	0.91	0.45	0.86	1.14	0.00	0.98	2.05	2.67	3.65	7.43	6.23	7.41	2770	1860	2393	946
overall sprays of glyphosate																
200–250	1.89[a]	0.86	2.24[a]	1.58[a]	3.58[a]	2.57[a]	3.52[a]	3.75	3.20	8.70[a]	6.01	7.82	16852[a]	3920	4188	485
250–350	1.00	1.23[a]	0.90		1.41[a]	1.92	1.68		3.20	7.69	7.30[a]		7085	3613	3689	
350–450	0.56	1.28[a]		0.89	2.04[a]	0.53		2.58	3.64	8.68[a]		8.43[a]	4077	381		1449
450–550			1.12	0.23			1.78	1.60			7.24[a]	8.00			5584	1539
550–650	1.92[a]				1.45[a]				3.33				3994			
650–750			0.43	0.45[b]			0.73[b]	1.49[b]			6.15	7.09			2792	1474
two overall sprays	0.32[b]	0.29	0.68	0.57[b]	0.71	0.47	1.71	1.31[b]	3.78	8.46[a]	7.25[a]	8.26	2896	2091	1097	2137
band and overall sprays of glyphosate																
10% cover	2.77[a]	1.86[a]	1.94[a]	1.67[a]	4.24[a]	3.49[a]	3.03[a]	3.55	2.10[b]	7.51	6.95	7.85	64499[a]	10004[a]	4387	1740
10%/550–650	1.52[a]	1.74[a]			1.26[a]	0.36			3.91	8.52[a]			3482	3066		
10%/650–750			1.22	0.48[b]			1.80	1.48[b]			7.15[a]	8.56[a]			997	1646
10%/800–950	2.26[a]		1.83	1.92[a]	1.14[a]		0.77[b]	1. 66	2.51[b]		7.15[a]	8.64[a]	4828		1595	3636
20% cover	2.45[a]	1.81[a]	2.31[a]	1.53	4.00[a]	3.27[a]	3.21[a]	2.63	2.95	7.82	6.96	7.99	34918[a]	954	3689	750
20% + second overall spray	2.00[a]	1.72[a]	1.69	1.20	0.88	0.00	1.39	1.42[b]	3. 31	8.21	6.81	9.15[a]	5041	853	2692	2101
p-value	< 0.001	< 0. 001	< 0.001	< 0.001	< 0. 001	< 0.001	< 0.001	< 0. 001	0.036	0.01	0.02	0.004	< 0.001	0.022	< 0.001	0.519
d.f.	30	24	30	30	30	23	30	30	30	24	30	30	30	24	30	26
s.e.d.	0. 251	0.290	0. 297	0.2836	0.514	0. 737	0.422	0. 565	0.510	0.391	0. 417	0.445	8780. 6	2434.2	1792. 2	1235.8

[a] Figures significantly larger than conventional.
[b] Figures significantly lower than conventional.

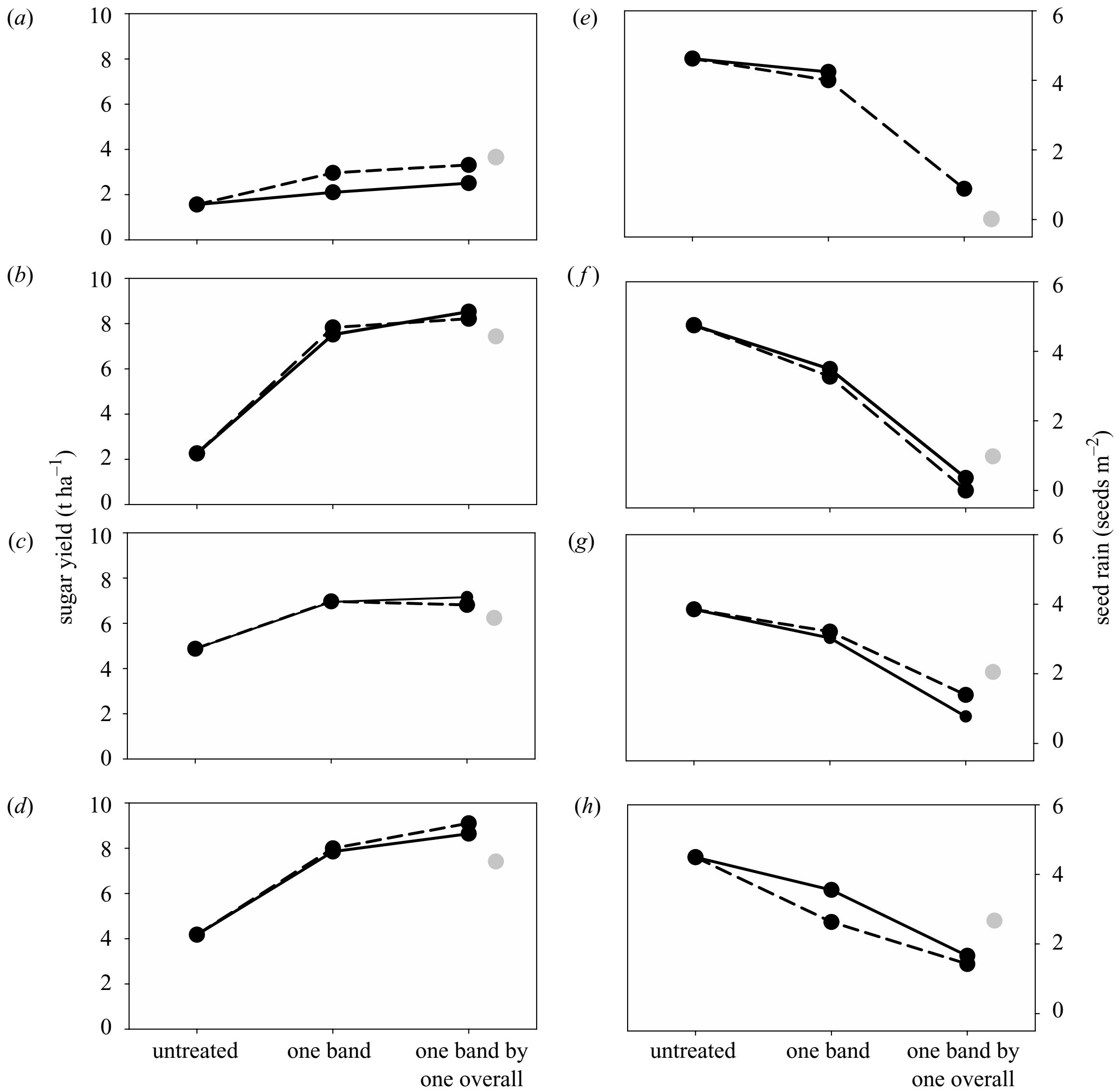

Figure 1. Sugar yields ((*a–d*), t ha^{-1}) and log-transformed total seed rain ((*e–h*), seeds m^{-2}) for untreated, band spray or band spray plus one overall spray plots (solid symbols) and conventional plots (grey circle) at four sites in 2001 and 2002. (*a*, *e*) site 1; (*b*, *f*) site 2; (*c*, *g*) site 3; and (*d*, *h*) site 4. Band sprays were applied when the ground cover was 10% (solid line) or 20% (dashed line).

(figure 1). However, there were general yield reductions when the second (overall) spray was omitted. Delaying the second overall spray from 605 to 816 °Cd at site 1 reduced yield (by over 30%), but there was no reduction when the second spray was delayed from 735 to 809 °Cd at site 3 or 683 to 955 °Cd at site 4.

Single overall sprays of glyphosate at an early stage (200–250 °Cd) produced yields equivalent to or better (by 14% at site 2) than conventionally treated plots. There were few differences in yield as a result of timing of single spray applications over the range tested, but mid-range timings outyielded the conventional treatments at three out of the four sites and were equivalent to two overall glyphosate applications (table 4).

Fitting the Dewar *et al.* (2003) model to data from the untreated plots and the plots with a single overall spray resulted in a total variance accounted for (r^2) of 98.4% (d.f. = 9) when Y_0 and A were allowed to vary but the other parameters were fixed from site to site. The estimated parameters are shown in figure 2.

(d) *Seed rain*

Seed production (of viable seed) was positively correlated with weed biomass in July ($r^2 = 0.67$, d.f. = 44). Treatments producing significantly higher seed return compared with the conventional treatments were those treated overall once with glyphosate at 200–250 °Cd (figure 2), or those treated only with a band spray at 10% or 20% ground cover (figure 1). However, delaying single overall sprays (more than 235 °Cd) reduced the seed rain sharply. Seed rain on band sprayed plots was greater in 2001 than in 2002, and was only lower than in the conventional treatments when glyphosate was applied later than 650 °Cd.

Seed viability varied greatly with treatment, but tended to be lower as delays increased. Seed from untreated plots had highest viability (range 70–99%) while on the

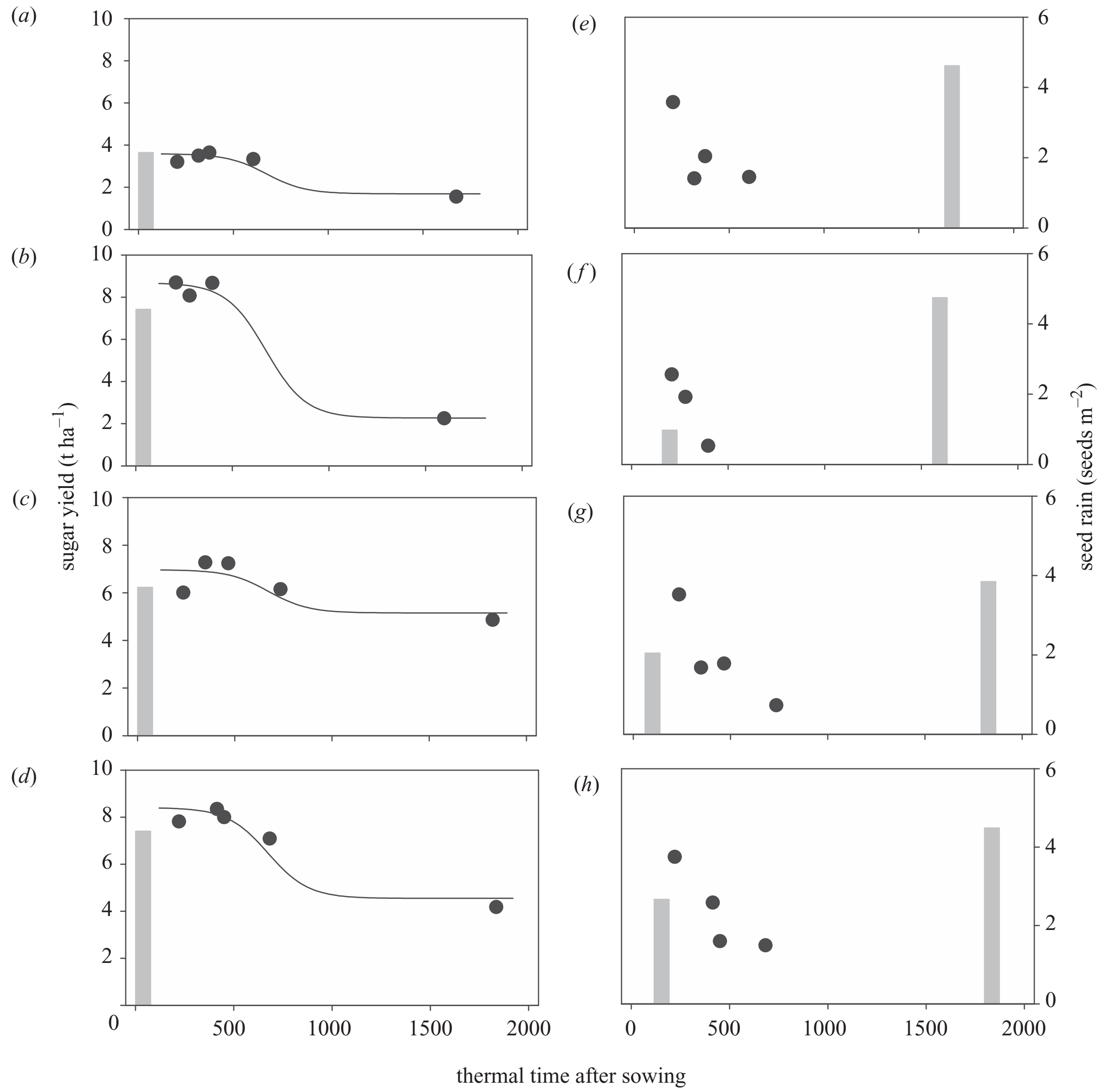

Figure 2. Effects of the timing of one single overall spray of glyphosate on sugar yield ((*a*–*d*), t ha^{-1}) and log-transformed total seed rain ((*e*–*h*), seeds m^{-2}) at four sites in 2001 and 2002. (*a*, *e*) site 1; (*b*, *f*) site 2; (*c*, *g*) site 3; and (*d*, *h*) site 4. Sugar yields and log-transformed total seed rain from the conventional plots (left) and the untreated plots (right) are given by vertical bars. The fitted curves are: $Y = 1.5562 + 1.8929/(1 + \exp(0.0107^*(T - 723.4))$ at site 1, $Y = 2.2558 + 6.2292/(1 + \exp(0.0107^*(T - 723.4))$ at site 2, $Y = 4.9164 + 1.9478/(1 + \exp(0.0107^*(T - 723.4))$ at site 3 and $Y = 4.1544 + 3.8859/(1 + \exp(0.0107^*(T - 723.4))$ at site 4.

conventional it varied from 0–90%. Viability ranged from 63–94% for single glyphosate treatments applied between 200–250 °Cd, from 23–65% for treatments applied between 600–750 °Cd, and 19–78% following two overall treatments of glyphosate. This compared with 59–99% on single band spray treatments applied at 10% and 60–95% at 20% cover.

(e) *Post-harvest weed seedling emergence and weed seed banks in the soil*

At the 2001 sites the number of weed seedlings in the autumn following harvest was greatest on treatments that had the highest seed rain (data not presented). However, the most numerous species in the seed rain were not the most abundant in the seedling counts.

Viable seed banks from untreated plots were not necessarily higher than treated plots (tables 3 and 4) and the seed bank was low at site 4 and only at site 1 were there significant differences between treatments. Viability of seeds from untreated plots ranged from 27% (site 4) to 61% (site 2). Treatment at 10% cover only increased seed banks compared with the conventional (by 23-fold at site 1, five-fold at site 2 and twofold at sites 3 and 4). While glyphosate treatments did not significantly reduce seed banks compared with the conventional, there was a trend for effects to follow those of the weed biomass and seed rain.

4. DISCUSSION

The enforced early harvest, some two months earlier than mean commercial harvesting dates, meant that yields were lower than would otherwise have occurred, though within the normal on-farm range at three sites out of the four and treatment relativities were not affected (Jaggard *et al.* 1983). At site 1, yields were low because of very late drilling (as a result of wet conditions) which resulted in an infection of *Aphanomyces cochlioides* root disease and this, combined with virus yellows later in the season, reduced the crop's ability to compete with weeds. These problems affected the entire trial and would not have altered treatment yield-relativities, although they necessitated some changes in timing of conventional intended herbicide treatments. While such pest and/or disease attack will reduce the profitability of the crop and would decrease, but not obviate, the options for increasing weed seed production, they are generally rare in commercial sugar beet crops. Most diseases and pests can be controlled.

The use of seed rain traps may underestimate total seed return. Mature weed seeds may remain on the plants but be incorporated into the seed bank during sugar beet harvesting. However, traps provide a means of comparing treatments and, assuming that the seeds shed are proportional to those retained on the plants, are an acceptable surrogate for estimating treatment effects on the seed bank. The enforced early harvest may also affect the estimates in these experiments. Some species, such as *C. album* and *Polygonum aviculare*, shed the majority of their seed in October or November (Leguizamón & Roberts 1982). If these experimental crops had been harvested at a more commercially realistic date in late October or November they are likely to have produced even more seeds than were recorded. The seed rain data, therefore, provide comparative but not absolute values of treatment differences. These restrictions mean that caution is required if extrapolating to longer-term weed seed dynamics.

Earlier work (Dewar *et al.* 2003) showed that band-spraying techniques with glyphosate could provide yields equal to conventional herbicide usage, but sometimes slightly less than those after a two overall spray system similar to that tested in the FSE (Champion *et al.* 2003). Here, by timing the band spray earlier, we have demonstrated yields equal to two overall sprays (i.e. the highest yielding system). Furthermore, there was no yield difference between band application at 10% and 20% ground cover, which means a wide time frame is available for such band applications. In addition, we found no yield penalty from delaying the second overall spray to as late as 950 °Cd after sowing (normally around mid-June) providing the crop was normally competitive. Thus, the band spray system, managed appropriately, can provide the early to mid-season environmental benefits found by Dewar *et al.* (2003) with no loss of grower profitability compared with use of two overall glyphosate sprays (the FSE system), and greatly superior profitability to conventional practice (May 2003). Retention of a viable population of common weeds in arable crops is recommended if farmland bird conservation is your goal (Clarke *et al.* 2003). The presence of weeds can increase invertebrate numbers (Dewar *et al.* 2003) and survival of second broods of birds such as the skylark can rely on food supply.

The band spray approach discussed above does not address the problem of reduced provision of autumn weed seed for bird food and replenishment of weed seed banks, where effective weed control using glyphosate is employed. The treatments all had a late overall spray and weed seed production was lower than under conventional management, as reported in the FSE (Heard *et al.* 2003*a*,*b*). Freckleton *et al.* (2004) modelled the likely effects of date of spraying on seed return, by comparing the phenologies of common sugar beet weeds. They suggested that only spraying before mid-May would ensure that species such as *C. album*, *F. convolvulus* and *P. aviculare*, which provide important seed for birds, would be able to produce seed before the crop was harvested. Although there were a few significant yield differences owing to timing among our single spray treatments, an overall trend was apparent as was the trade-off between maximizing yield and providing environmental benefit as measured by weediness indicators. Yields increased slightly from the earliest to the mid timings (250–450 °Cd) and then tended to decline for later timings. The earliest timing allowed significant weed growth later in the season, as evidenced by high seed rain and seed bank results. Although this level of competition may have slightly reduced yield compared with the best two overall sprays treatment, there was no reduction compared with conventional treatment and a very large increase (12–38-fold) in seed rain at the sites where the crop was competitive. While small delays in treatment reduced weed seed rain, the results were still greater than for the conventional crop, showing that this management technique can provide both agricultural and environmental advantage. The mid timing treatments, with the highest yields, had seed rain similar to that of the conventional herbicide treatment, demonstrating maximum agricultural advantage with no environmental penalty. The later timings suffered from weed competition early in the season, as one would expect, and had reduced yield and low seed rain, thus showing both agricultural and environmental disadvantage.

There is great flexibility in this approach. Farmers with pernicious weed problems or situations where low weed burdens would allow the production of vegetable or other crops with low or nil herbicide input could, if necessary, apply a second spray, though regulatory restrictions might preclude this where conservation objectives predominate. Such an approach would be likely to lead to proportionally greater seed returns on low weed pressure fields than on those with high weed populations, thus providing a more equitable distribution of weeds between beet growing fields.

Thus, we have demonstrated a range of weed management approaches, using a single overall spray of glyphosate, that offers options to optimize the trade-off between maximum yield and environmental benefit (figure 3). Four situations can be explored in figure 3. Options in the lower left quadrant present losing conditions for both sugar beet husbandry and weed-related biodiversity. This scenario will not happen naturally or agriculturally unless sites experience problems other than weeds (e.g. as at site 1). Options in the upper-left quadrant present winning conditions for weeds but losing ones for sugar beet production. This scenario could happen naturally (e.g. with untreated) or inadequately treated crops, but are not economically sustainable. Options in the lower-right quadrant present losing conditions for weeds but winning ones for sugar beet yields. So, only these approaches in the upper-right quadrant can give win–win situations for healthy sugar beet crop productivity and weed-related wildlife conservation.

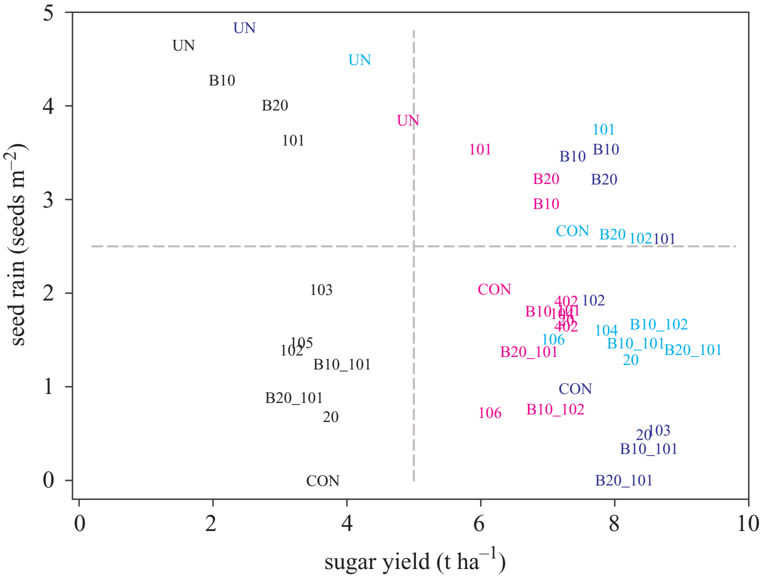

Figure 3. Relationship between sugar yield (t ha^{-1}) and log-transformed total seed rain (seeds m^{-2}) in various herbicide spray options in 2001 and 2002 at site 1 (black symbols), site 2 (blue symbols), site 3 (pink symbols) and site 4 (cyan symbols). CON, conventional spray; UN, untreated plot; 1O1, 1O2, 1O3, 1O4, 1O5 and 1O6 represent one single overall spray at various timings after sowing; 2O is for two overall sprays; B10, B20 are for one band spray at 10% and 20% ground cover; B10_101, B10_102 and B20_101 indicate one band spray at 10% and 20% ground cover followed by one overall spray at various timings after sowing.

Therefore, by altering management of the GMHT crop we provide different scenarios to those of the FSE trials where the GM crop showed biodiversity reductions. Autumn bird food availability could be enhanced, as opposed to the decline that seems inevitable as conventional management is intensified in response to anticipated output price reductions (Anon. 2003). Enhanced profitability would ensure rapid uptake of such approaches if GMHT beet was permitted. Unfortunately conventional weed-control systems in sugar beet (both chemical and mechanical) are effective only on small weeds and are not suitable for the approaches that we have adopted here. However, it may be feasible to manage conventional crops in other ways, albeit without the economic benefits of GMHT beet, to produce more weed seeds, and this is being investigated.

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