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Horizontal movement of seeds following tine and plough cultivation: implications for spatial dynamics of weed infestations

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Summary

Horizontal movement of seeds by different cultivators was investigated in three experiments. Seeds of barley (*Hordeum vulgare* L.), field bean (*Vicia faba* L.) and oilseed rape (*Brassica napus* L.) were positioned on the soil surface or buried 0.1 m deep prior to cultivation. Seed movement was assessed by counting germinated seedlings. The type of tine implement used significantly affected mean seed movement, with surface-sown seeds being moved significantly further than buried seeds. Primary cultivation with flexi- or spring-tine machines moved seeds further than straight-tine or power harrow implements. However, there was no overall difference between plough and flexi-tine mean seed movement. A single pass with a tine attached to a seed drill moved seeds less than the two passes with tine plus seed drill, but the first pass had the greatest effect. Small oilseed rape seeds moved significantly further than larger barley or field bean seeds. More than 84% of seeds moved ≤1 m from the source; no seeds were observed >4.8 m in a forward direction or >0.2 m backwards from the source. In a fourth experiment, plots containing seeds of *Sinapis arvensis* L. were cultivated in alternate directions in successive years. The results broadly validated the findings of the previous experiments. Quantifying the horizontal movement of weed seeds is important to the understanding of the spatial dynamics of weed patches and thus in the prediction of future weed distributions.

Introduction

The distribution of weeds within fields is spatially aggregated or 'patchy' (Marshall, 1988; Mortensen *et al.*, 1993; Rew *et al.*, 1996a). This spatial heterogeneity or 'patchiness' is caused by numerous factors, including soil type and cultivation, harvesting machinery, herbicide efficacy, crop interference and rotations, which all influence seed movement, germination and survival. The patchy distribution of weeds within arable fields provides the potential to reduce herbicide use by only treating the infested areas. A system has been developed in which weed distributions are mapped and then patch-sprayed (Paice *et al.*, 1995; Rew *et al.*, 1996a). To be able to predict future weed distributions from a given weed map, we need to be able to quantify and understand the effects of all the cultural factors identified above on the distribution of weed seeds.

Previous studies of seed movement by cultivation implements have concentrated on vertical seed distribution (Soriano *et al.*, 1968; Froud-Williams *et al.*, 1983; Moss, 1988; Dessaint *et al.*, 1996) rather than horizontal seed movement. These studies have shown that weed seed distribution is not uniform throughout the soil profile and that different types of cultivation move seeds to different depths in the soil, with the plough moving seeds deeper than tine cultivation (Moss, 1988).

Two studies have looked at the horizontal movement of seeds following cultivation with a rotary power harrow. In both studies the ma-

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jority of seeds were moved less than 1 m from source (Fogelfors, 1985; Howard *et al.*, 1991).

The aim of this study was to investigate the importance of seed size, sowing position and cultivation implement on the horizontal movement of seeds. Two experiments concentrated on different tine implements; the other compared flexi-tine and plough. A fourth experiment had a primary pass with a plough or tine implement followed by three further passes with different tine implements and drill, and was therefore more representative of 'normal' UK agricultural practice.

Materials and methods

All four experiments were established at Rothamsted in a clay soil with flints of the Batcombe series. Experiments 1–3 were sown to linseed and Experiment 4 to spring wheat. The experiments were all of split plot design, with cultivation implement as the main plot; each had four replicates. In Experiments 1 and 3, plots were 3 m by 15 m; in Experiment 2, 6 m by 15 m; and in Experiment 4, 5 m by 12 m.

Four different tine implements, straight-, flexi-, spring-tine and rotary power harrow, a mould-board plough and seed drill were used in the experiments. The flexi-tine (Bomford Flexi-tine, 3 m) comprised three rows of tines with four tines in each row. The tines were 2.54 cm square, fitted with narrow points and spaced at 76 cm in the row, and staggered between rows to give 25.4-cm spacing between tines. The spring-tine (Triple K, 3 m) comprised four rows of S tines, spaced at 40.64 cm in the row and staggered between rows to give a 10.2-cm spacing. The straight-tine (Cousins Dutch Harrow, 3 m) had four rows of tines spaced at 20.32 cm in the row, and staggered between rows to give a spacing of 5.1 cm between tines. Tines were 30.5 cm long and 2.54 cm diameter, with a crumble roller mounted on the rear of the implement. The rotary power harrow (Lely Roterra, Model 300-22, 3 m) was a PTO (power take-off) cultivator with counter-rotating pairs of vertical tines. Tines were 30.48 cm long and tapered. The mould-board plough (Ransomes 300 series) was a four-furrow reversible plough with 35.56 cm furrows. The drill (Ransomes/Nordsten CLB 300 Mk II, 3 m) had Suffolk coulters and was mounted behind the Lely Roterra.

Crop species were chosen to model the behaviour of arable weed species in Experiments 1–3, because of their lack of dormancy.

Experiment 1, tine implements

Experiment 1, in 1993, compared seed movement as a result of 'primary' cultivations by four different tine implements: straight-, flexi-, spring-tine and rotary power harrow. The primary cultivations were followed (in the same direction) by a pass with a rotary power harrow attached to a seed drill (see above for machinery details). One thousand seeds each of field bean (*Vicia faba* L.) and barley (*Hordeum vulgare* L.) were positioned on the surface of the soil or buried 0.1 m deep, along a 2 m by 0.1 m strip placed 3 m from the end of each plot, before the cultivation treatment.

The experiment was ploughed on 21–22 January 1993, and flexi-tined once on 19 April to create a finer seedbed. Seeds were positioned on 22 April, immediately after which individual plots were cultivated with the allocated tine implement, rotary harrowed and drilled with linseed, and finally rolled on 23 April. The plots were assessed on 24 May 1993.

Seedlings were counted in 0.01-m^2 areas across the 2-m-wide plot, from 0.5 m behind the sowing position to 6 m in front of it (total 13 m^2) using a subdivided 1-m^2 quadrat. The remainder of each plot (6 m) was searched for any further seedlings.

A log normal distribution was fitted to the barley and bean seedling counts for each plot. From these fitted distributions, the mean and standard errors (on a log scale) were analysed by ANOVA. The distances moved by the furthest 5%, 2.5% and 0.1% of seedlings were estimated for each plot from these fitted distributions [using Maximum Likelihood Programme (Payne *et al.*, 1993)] and analysed by ANOVA. The percentage movement away from the source, into defined areas, was calculated from the raw data and ANOVA was performed.

Experiment 2, flexi-tine and plough

Experiment 2, in 1994, compared one or two passes with a flexi-tine or plough, followed by a pass with a rotary power harrow attached to a seed drill. All cultivations were performed in the same direction. One thousand seeds each of field bean, barley and oilseed rape (*Brassica napus* L.), were used per plot.

The experiment was shallowly ploughed (to a depth of 15 cm) on 28 April 1994. Seeds were positioned, on the soil surface or buried 0.1 m deep (see Experiment 1), on individual plots that were then cultivated with the allocated primary implements, rotary power harrowed, drilled with linseed and rolled on 29 April. The plots were assessed on 4 June 1994 in the same way as Experiment 1. Movement of barley, bean and oilseed rape seeds was analysed as in Experiment 1.

Experiment 3, tine implements

Experiment 3, in 1996, compared rotary power harrow, flexi-tine and drill, with all cultivations performed in the same direction. The aim was to clarify the importance of the seed drill on seed movement, as Experiments 1 and 2 had compared cultivation implements followed by a pass with the rotary harrow attached to the seed drill. Again, one thousand seeds each of field bean, barley and oilseed rape were used per plot, with seeds positioned in the same way as in the above experiments.

The experiment was ploughed on 29 February 1996, and spring-tined prior to seed positioning (surface or buried; see Experiment1) and the allocated cultivation treatment on 17 April 1996. The plots were assessed on 14 May 1996 as above, and data were analysed in the same way as for the other experiments.

Experiment 4. Sinapis arvensis

The fourth experiment investigated the movement of *Sinapis arvensis* L. seeds as a result of 'normal' multiple passes with a plough and/or tine cultivation implements. The source plots (3 m by 3 m) were broadcast with *S. arvensis* (17 100 seeds m^{2}) and plots (full dimensions: 5 m by 12 m) ploughed to a depth of 0.2 m, or flexi-tined to 0.1 m in October 1991. All plots were then spring-tined twice, rotary power harrowed and drilled with spring wheat in March 1992. After the first year, the plough or flexi-tine cultivations were performed in spring immediately before two passes with a spring-tine and one pass with a rotary power harrow attached to a seed drill. All cultivations within one cropping year were performed in the same direction. In the following year, the opposite direction was used. No further *S. arvensis* seed was sown and seeding of plants was prevented.

A preliminary assessment of seed movement was made on the tined plots on 6 May 1992. Seedlings were counted in strips of 0.01 m^{2} by 1 m (central 1 m of the 3-m-wide plot), at 0.5-m intervals from the centre of the plot to 6 m north and south. Ploughed plots were not assessed, as the seeds had been turned down by the furrow, and as a result there was little germination. In the following two years (on 13 and 14 May 1993 and 26 May 1994), seedlings were counted in 0.01-m^{2} areas across the 3 m plot width, at 0.5-m intervals from the centre of the plot to 6 m north and south. Data were fitted to a log normal distribution.

Results

Experiments 1–3, horizontal movement of seeds

In Experiment 1, straight-tine cultivation moved seeds significantly ($P < 0.01$) less (0.51 m) than the rotary power harrow (0.58 m), the flexi- (0.64 m) or spring-tine (0.64 m) cultivators (Table 1). The large field bean seeds moved significantly less ($P < 0.01$) than the smaller barley seeds (0.58 m and 0.61 m, respectively) and surface-sown seeds were moved significantly ($P < 0.001$) further than buried seeds (Table 1). However, there was an interaction between species and sowing position ($P < 0.001$): with surface-sown field bean seeds moving further than barley seeds sown either on the surface or buried, and buried field bean seeds moving the least distance, regardless of implement used (Table 1).

In Experiment 2, the three species had significantly different mean movement distances ($P < 0.001$). Oilseed rape, the smallest seed, moved the furthest (0.87 m), barley was intermediate (0.79 m) and field beans moved the least (0.69 m; Table 2a). There was no overall difference between a flexi-tine cultivator or plough, although two passes with a flexi-tine plus rotary power harrow and drill resulted in greater movement of seeds than one flexi-tine pass plus rotary power harrow and drill (0.82 m and 0.67 m respectively; Table 2a). The sowing position (surface/buried) showed no statistical difference (Table 2b).

In Experiment 3, the mean seed movement distances were significantly affected by the different cultivation implements, seed position (surface/buried) and species ($P < 0.001$). Rotary

Table 1. Experiment 1: mean distance (m) moved by barley and field bean seeds when cultivated with one of four different cultivation implements (straight-, spring- or flexi-tine or rotary power harrow) plus a rotary power harrow attached to a seed drill

		Implement							
	Overall means	Straight-t, RPH and D		RPH × 2 and D		Spring-t, RPH and D		Flexi-t, RPH and D	
		S	B	S	B	S	B	S	B
Barley	−0.503 (0.61)	−0.683 (0.51)	−0.635 (0.53)	−0.506 (0.60)	−0.511 (0.60)	−0.316 (0.73)	−0.504 (0.60)	−0.400 (0.67)	−0.471 (0.62)
Beans	−0.547 (0.58)	−0.606 (0.55)	−0.740 (0.48)	−0.474 (0.62)	−0.679 (0.51)	−0.300 (0.74)	−0.640 (0.53)	−0.391 (0.68)	−0.543 (0.58)
SED	0.0144					0.0838 (except when comparing within S or B, when SED = 0.408)			
All species		−0.666 (0.51)		−0.542 (0.58)		−0.440 (0.64)		−0.451 (0.64)	
SED						0.0556			

Seeds sown on the soil surface or buried prior to cultivation. All data $\log_e$ transformed; back-transformed values in parentheses. S, surface; B, buried seeds; RPH, rotary power harrow; t, tine; D, drill; × 2, two passes.

Table 2. Experiment 2: mean distance (m) moved by oilseed rape, barley and field bean seeds (a) when cultivated once or twice with flexi-tine or plough, followed by rotary power harrow attached to a seed drill, or (b) when seeds were sown on the soil surface or buried prior to cultivation

(a)

		Implement		
	Overall means	Flexi-t, RPH and D	Flexi-t × 2, RPH and D	Plough, RPH and D
Rape	−0.141 (0.87)	−0.299 (0.74)	−0.098 (0.91)	−0.150 (0.86)
Barley	−0.239 (0.79)	−0.411 (0.66)	−0.189 (0.83)	−0.246 (0.78)
Beans	−0.371 (0.69)	−0.476 (0.62)	−0.297 (0.74)	−0.412 (0.66)
SED	0.0386		0.1413	
All species		−0.396 (0.67)	−0.195 (0.82)	−0.269 (0.76)
SED			0.1284	

(b)

	Sowing position	
	Surface	Buried
All species	−0.231 (0.79)	−0.342 (0.71)
SED	0.1048	

All data were $\log_e$ transformed; back-transformed values are given in parentheses. RPH, rotary power harrow; t, tine; D, drill; × 2, two passes.

power harrow alone and rotary power harrow plus seed drill did not differ from each other (0.51 m and 0.52 m respectively), suggesting that the seed drill has little further impact on seed movement. However, two primary cultivations plus seed drill moved seeds between 0.05 m and 0.16 m further than one primary cultivation. The large field bean seeds again moved significantly

Table 3. Experiment 3: mean distance (m) moved by oilseed rape, barley and field bean seeds when cultivated with different combinations of rotary power harrow, flexi-tine and drill, with seeds sown on the soil surface or buried prior to cultivation

	Overall means	Implement							
		RPH		RPH and D		RPH × 2 and D		Flexi-t, RPH and D	
		S	B	S	B	S	B	S	B
Rape	−0.554 (0.58)	−0.557 (0.57)	−0.731 (0.48)	−0.629 (0.53)	−0.754 (0.47)	−0.390 (0.68)	−0.550 (0.58)	−0.312 (0.73)	−0.509 (0.60)
Barley	−0.576 (0.56)	−0.519 (0.60)	−0.809 (0.45)	−0.475 (0.62)	−0.793 (0.45)	−0.289 (0.75)	−0.688 (0.50)	−0.329 (0.72)	−0.706 (0.49)
Beans	−0.612 (0.54)	−0.541 (0.58)	−0.846 (0.43)	−0.336 (0.71)	−0.755 (0.47)	−0.455 (0.63)	−0.816 (0.44)	−0.384 (0.68)	−0.762 (0.47)
SED	0.0166	0.0618 (except when comparing within S or B, when SED = 0.0471)							
All species		−0.674 (0.51)		−0.654 (0.52)		−0.501 (0.61)		−0.501 (0.61)	
SED		0.0342							

All data were $\log_e$ transformed; back-transformed values are given in parentheses. S, surface seeds; B, buried seeds; RPH, rotary power harrow; t, tine; D, drill; × 2, two passes

less far (0.54 m) than barley (0.56 m) or oilseed rape seeds (0.58 m) and surface-sown seeds moved further than buried seeds (Table 3). However, there were significant interactions between species and implements, and species and seed-sowing position. This was because oilseed rape seeds moved less on the surface than those of field bean and barley in two of the treatments, but more on the comparable buried plots. This may be a result of the dry conditions in 1995; fewer oilseed rape seeds were recovered on the surface-sown plots than on buried plots.

Plots that received two passes with the rotary power harrow plus seed drill, or involved flexi-tine, rotary power harrow plus seed drill, were present in either two or three of the experiments and the results are broadly similar. Mean seed movement distances in Experiment 3 tended to be slightly shorter than those of Experiments 1 and 2. This could be attributed to the drier soil conditions in 1996. The data generally fitted a log normal distribution in all years and treatments.

Horizontal movement within defined limits

Data from the experiments were then analysed by ANOVA to investigate the proportion of seeds moved into three defined areas: within 1 m; movement > 1 m and backward movement. Although species differences were observed in the previous analyses, they were not evident when the data were allocated to these broadly defined areas. In all experiments the majority (> 84%) of seeds remained within 1 m of the source, although the proportion of seeds moved > 1 m forward increased with the number of implement passes (Table 4a). Surface-sown seeds also moved further than buried seeds, with more than twice the number having moved more than 1 m (Table 4b).

The above analysis concentrated on the movement distances of the majority. However, the minority that move greater distances is of considerable importance in the context of the future spatial distributions of weeds. Therefore, the movement distance of the furthest 5%, 2.5% and 0.1% was estimated by regression. The estimates obviously reflect the patterns observed in the previous analyses, with field bean seeds moving less than those of barley or oilseed rape, and buried seeds moving less than surface-sown. Making the arbitary assumption that the furthest 2.5% of seeds would represent a significant 'front', these data are shown in Table 5. The furthest 2.5% of surface-sown seeds were predicted to move between 1.2 m and 3.3 m compared with 0.3 and 2.1 m for buried seeds, depending on seed size and number of implement passes (Table 5).

Table 4. Percentage movement of oilseed rape, barley and field bean seeds when cultivated with different cultivation implements: (a) sowing position combined, (b) implements combined

(a)

		Experiment 1				
movement (%)	Overall mean	Straight-t, RPH and D	RPH × 2 and D	Spring-t, RPH and D	Flexi-t, RPH and D	Implement SED
Within 1 m	93.4	95.9	91.0	92.7	93.8	1.420
> 1 m	6.6	4.1	9.0	7.3	6.2	
Backward	5.7	7.3	8.5	2.5	4.4	2.309
		Experiment 2				
		Flexi-t, RPH and D	Flexi-t × 2, RPH and D	Plough, RPH and D		Implement SED
Within 1 m	84.1	87.6	78.9	85.8		7.602
> 1 m	15.9	12.4	21.1	14.2		
Backward	3.5	7.2	2.3	1.4		3.787
		Experiment 3				
		RPH	RPH and D	RPH × 2 and D	Flexi-t RPH and D	Implement SED
Within 1 m	93.1	95.2	94.4	89.4	93.5	1.538
> 1 m	6.9	4.8	5.6	10.6	6.5	
Backward	3.2	3.1	2.8	5.8	1.0	1.640

(b)

	Experiment 1			Experiment 2			Experiment 3		
movement (%)	Surface	Buried	SED	Surface	Buried	SED	Surface	Buried	SED
Within 1 m	91.2	95.7	1.004	79.2	90.3	7.908	88.3	97.9	1.088
> 1 m	8.8	4.3		20.8	9.7		11.7	2.1	
Backward	7.4	3.9	1.632	5.1	13.7	9.193	4.5	1.9	1.160

There were no significant differences between the species. (Experiment 1 used only barley and field beans.) RPH, rotary power harrow; t, tine; D, drill, × 2, two passes.

Table 5. Predictions of the distances (m) moved by the furthest 2.5% of oilseed rape, barley and field bean seeds, based on data from Experiments 1–3

		One pass		One pass plus drill		Two passes plus drill		Three passes plus drill		
Species	Experiment Number	Surface	Buried	Surface	Buried	Surface	Buried	Surface	Buried	SED
Rape	2					1.83	1.83	2.91	2.09	0.400
	3	1.28	0.72	1.16	0.54	1.83	1.06			0.191
Barley	1					1.42	1.14			0.111
	2					1.72	1.41	3.25	1.72	0.518
	3	1.40	0.42	1.67	0.38	2.04	0.76			0.172
Beans	1					1.54	0.78			0.095
	2					1.58	1.19	2.02	1.66	0.474
	3	1.34	0.35	1.81	0.34	1.87	0.63			0.237

Table 6. Percentage movement of *Sinapis arvensis* with a primary pass of spring-tine or plough followed by two passes with a spring-tine and one pass with a rotary power harrow and drill. Plots were cultivated in alternate directions in consecutive years

	Distribution (%)			Mean distance	
S. arvensis	North	Source	South	(m)	(SE)
1992 Tine*	45.4	37.9	16.8	−1.18	(0.163)
1993 Tine	9.9	68.3	21.8	0.37	(0.017)
1994 Tine	21.3	55.4	23.3	−0.06	(0.064)
1993 Plough	4.4	48.0	47.6	1.40	(0.018)
1994 Plough	11.5	60.2	28.3	0.53	(0.061)

*Preliminary assessment

Experiment 4, distribution pattern of S. arvensis

A large proportion of seeds remained within the source area, although there were fluctuations between years: tined plots varied from 38% to 68% to 55% during 1992, 1993 and 1994 respectively, and the ploughed plots fluctuated from 48% to 60% in 1993 and 1994 respectively (Table 6). Cultivations were in alternate directions in successive years. In the first year (1992) cultivation moved seeds from south to north; the opposite cultivation direction in 1993 moved seeds south; and opposite direction again in 1994 showed a shift to a more even distribution on either side of the source (Table 6).

The distribution of the seeds in the tined plots became wider in the second and third year of the experiment: kurtosis values declined from 1.6 in 1993 to 0.8 in 1994 (1992 data were not used because of the restricted sampling). However, the opposite was true of the ploughed plots −0.6 and 1.3 respectively (Fig. 1). The reason for the re-

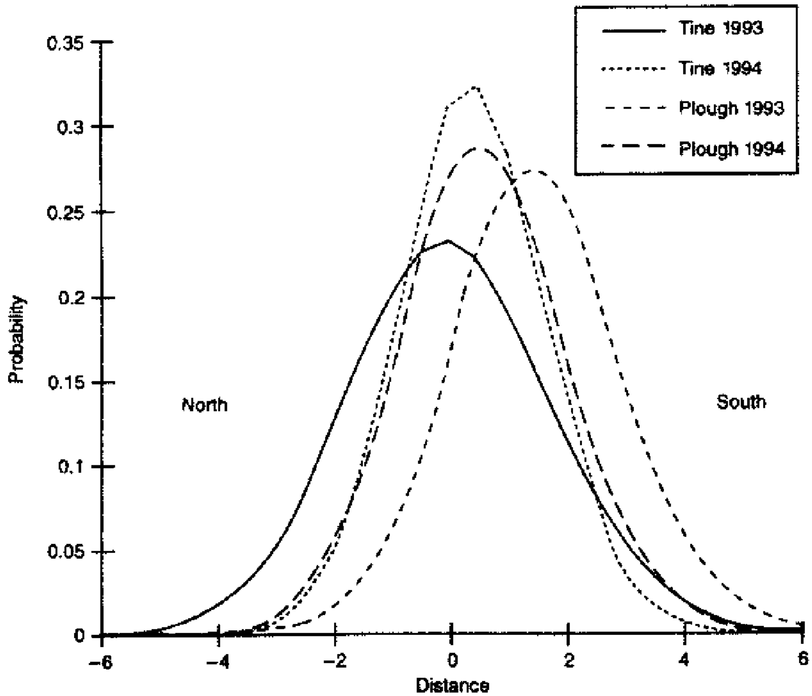

Fig. 1. Distribution of *S. arvensis* after multiple passes with either plough and tine implements, or tine implements alone. All cultivations were performed in the same direction within years but opposite between years (south to north in 1992; north to south in 1993; and south to north in 1994).

striction of the plough distribution curve is not known, although the position of the furrow may be important (turned up in 1993 and down in 1994).

Only a few seeds were observed 6 m from the centre of the source, that is 4.5 m from the edge of the sown plots. The mean distance moved between 1993 and 1994 was 0.43 m for tined and 0.87 m for ploughed plots. Thus, these results are in general agreement with those of Experiments 1–3.

Discussion

In the above experiments (Experiments 1–3), seeds sown on the surface before cultivation moved further than buried ones; and smaller seeds (oilseed rape) moved significantly further than larger seeds (barley or field beans). The type of tine cultivation implement used was important to the mean seed movement, but there was no significant difference between tine and plough cultivations. The main effect of cultivation was that the majority of movement occurred with the first pass of a cultivation implement. However, no seeds were relocated more than 0.2 m behind the source area or 4.8 m in front in any of the experiments, with >84% moving less than 1 m from the source.

Most arable weeds seeds are of similar size to, or smaller than, oilseed rape seed (e.g. *S. arvensis*). Therefore, if predictions of weed seed movement by cultivations are required, the oilseed rape estimates should be used. Two passes with the same implement, and/or rotary power harrow and drill, did not prove to be additive; the second/third pass only moved seeds a small distance (approximately 20%). The non-additive effect of multiple cultivations is presumably due to further cultivations creating a finer seedbed through which implements pass more easily and therefore move soil and seeds less than when the soil is hard-packed, as it would be at the first pass. It is therefore probable, even in 'real' farm situations, that the majority of seed would be moved less than 1 m from source. Results from the *S. arvensis* experiment support this, with mean movement between years of 0.43 m and 0.87 m for tine and plough respectively.

Although the general principles identified in these experiments should apply on all sites, precise parameters of seed movement by cultivation will depend on numerous factors including soil texture, structure and moisture, type and driving speed of cultivation implements used. The importance of soil texture, structure and moisture was not addressed in these experiments. Logically, seeds would be moved further in coarser/wetter soil because larger particles would obstruct the passage of machinery, and therefore soil and seeds would be moved further than in finer/drier soils. Whether these factors would be important in terms of patch stability and dynamics has yet to be defined. However, it was observed (though not quantified) in the above experiments that the drier soil conditions experienced during Experiment 3 resulted in a finer tilth being formed more readily than on the moister soils of Experiments 1 and 2. This could explain the slightly shorter mean movement distances, particularly in the buried plots, of Experiment 3 compared with Experiments 1 and 2.

Normal farm practice in the UK is to prepare a rough seedbed by plough or tine cultivation, followed by further tine cultivations to prepare a fine seedbed immediately prior to drilling. Thus, a field may be cultivated three or four times in one harvest year. Fields are often entered from the same point, and it is therefore probable that the first cultivation would run in the same direction in successive years. However, if two tine cultivations are performed consecutively, it is probable that the second cultivation would run in the opposite direction (if the driver starts the second run where the first was finished) or diagonally to remove wheelways. Either practice would restrict the spread of weed seeds. Farmers who alternated the end of the field in which cultivation commenced between and within years, would further restrict seed spread and thus stabilize or retain patch morphology.

Primary seed dissemination from arable weed species with no specialized dissemination structures (barachorous) is generally limited (Verkaar *et al.*, 1983; Blattner & Kadereit, 1991; Howard *et al.*, 1991). The closed canopy provided by a cereal crop restricts wind movements more than in surrounding field margins or open land, resulting in smaller primary dispersal distances (Rew *et al.*, 1996b). Similarly, secondary movement of seeds by cultivators is also small, as observed in the above experiments and by other researchers (Fogelfors, 1985; Howard *et al.*, 1991). However, the importance of the small proportion that moved >1 m should not be underestimated. The most important element in the patch dynamics of a weed would be the movement of a significant 'front' of seeds in sufficient numbers to guarantee the spread of the patch. Our data predicted that cultivations moved the furthest 2.5% of surface-sown seed between 1.16 m and 3.25 m and buried seed between 0.34 m and 2.09 m (depending on seed size and number of cultivation passes).

Harvesting machinery has the potential to move seeds long distances but the majority remain close to the source, although some seeds are moved considerable distances (Ballaré *et al.*, 1987; McCanny & Cavers, 1988; Howard *et al.*, 1991; Rew & Cussans, 1995; Rew *et al.*, 1996b). In the UK, many annual grass species shed the majority of their seeds before the crop is harvested. Therefore, the proportion of a given population spread by this strategy is small, although still important. However, Moss (1983) observed that seed viability of *Alopecurus myosuroides* Huds. was lower at the beginning and end of the seed-shedding period, and the same has been shown for *Bromus* spp. (NCB Peters, pers. comm.). In addition, it is generally accepted that there is considerable seed loss between seed-shedding and germination. Thus, of the small proportion of seeds moved by the harvest and cultivation machinery an even smaller proportion will survive and germinate. With regard to broad-leaved weeds, most complete their life-cycle within the crop understorey and are therefore unaffected by harvest and only subject to movement by cultivations.

Natural seed dissemination, seed movement by cultivation and harvest machinery can be seen as classic 'phalanx spread' (adapted from Lovett-Doust, 1981). That is the mean movement distance is short and the leading edge or 'front' is small. In contrast, the distance moved by seeds that become lodged on machinery (Schippers *et al.*, 1993) or animals is unpredictable and thus difficult to quantify, and could therefore be seen as 'guerilla spread'. It is probable that only a very small proportion of seeds are affected by guerilla movement.

Therefore, we would expect patches of weeds to retain their position within the field, although a slow phalanx spread would occur. Establishment of new populations as a result of guerilla spread is possible but unquantifiable. The technology to map the spatial distribution of weeds within fields and modify herbicide application accordingly is becoming more accessible and near-market (Miller *et al.*, 1995). The ability to simulate changes in patch shape and size using information on seed movement by cultivation would enable maps to be used for several years before the field needed to be re-mapped. Such a procedure could be further refined if the effect of other variables, such as harvest machinery, rotations and herbicide efficacy, on patch dynamics were more fully understood and quantified.

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