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Factors affecting the yield of winter cereals in crop margins

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SUMMARY

Yields of arable crops are commonly lower on the crop margins or headlands, but the nature of the relationship between yield and distance from the crop edge has not been clearly defined, nor have the reasons for lower marginal yields. Surveys of 40 winter wheat headlands were carried out in 2 years to determine how yield changed with distance, and what factors might influence this relationship. Two field experiments were also conducted over 3 years in winter cereal headlands, in which the effect of distance was measured under conservation headland and conventional (fully sprayed) management.

Yields in the headland surveys varied from 0·8 to 10·2 t/ha. An inverse polynomial regression model was fitted to yield and weed data. Best fits were obtained by using separate parameters for each site. Adjusting yields to take account of weed dry matter improved the non-linear fit between yield and distance from crop edge. Field experiments provided similar results but the non-linear relationship was not as apparent.

There was a negative relationship between soil compaction, as measured by a cone penetrometer, and yield in one field experiment, where soil density values were relatively constant. No relationship was found between pattern of nitrogen fertilizer application and yield. Conservation headland management resulted in lower yield at one experimental site, especially in the third year, but not at the other site. Where yields were affected, weed dry matter was higher in conservation headland plots than in fully sprayed plots.

Although greater weed competition appears to account for at least part of the observed yield reductions on headlands, the role of other factors, particularly soil compaction, needs further study. Increased weed infestation may be an indirect result of reduced crop competition caused by other adverse conditions.

INTRODUCTION

Within arable field margins, the area between the boundary (e.g. hedge, fence, wall) and its associated vegetation, and the edge of the crop to the first tramline or tractor wheeling, is referred to as the crop margin or headland (Boatman 1994). Yields in this area are often lower than those from the mid-field (Boatman & Sotherton 1988; Speller *et al*. 1992; de Snoo 1994; Sparkes *et al*. 1994), though in some cases the sheltering effect of hedges can lead to increased yields (Marshall 1967). Quantitative data on the extent of headland yield reductions are few but yield losses of more than 15% are known to occur (Cook & Ingle 1997). The exact nature of the relationship between yield and distance from the crop edge is not well defined. Low yields within crop margins are generally attributed to greater weed abundance, pest and disease incidence, soil compaction, shading and root competition from hedges and trees (Boatman & Sotherton 1988), but little research has been carried out on the relative importance of these factors.

Many weed species are more abundant in field margins than in the main cropped area (Marshall 1989; Wilson & Aebischer 1995). Some farmers have attempted to eliminate weeds at field edges by spraying close to the base of hedges or other boundaries with broad spectrum herbicides such as glyphosate. This practice has exacerbated problems by encouraging competitive annual weeds such as *Galium aparine* and

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Bromus sterilis (Marshall & Smith 1987; Boatman 1992*a*), as well as destroying potential wildlife habitat.

Crop margins can be modified for conservation purposes by treating grass weeds and *G. aparine* with selective herbicides which leave less competitive broad-leaved weed species to encourage game birds, particularly grey partridge *Perdix perdix* (Sotherton 1991). Partridge chicks feed almost exclusively on insects associated with arable broad-leaved weeds during the early stages of their life. Crop edges treated in this way are termed 'conservation headlands'. Conservation headland management can cause a reduction in yield compared to fully sprayed headlands (Boatman & Sotherton 1988; Fisher *et al.* 1988; Boatman 1992*b*; de Snoo 1994), but estimates of yield loss vary, and studies differ in the types of pesticide used or excluded (e.g. in some cases, fungicides were also withheld from the crop margin).

In the UK, farmers can apply for grant aid for 2 m grass margins or 6 m uncropped margins positioned alongside field boundaries, under the Ministry of Agriculture, Fisheries and Food's Countryside Stewardship scheme (MAFF 1999), although little is known about the yield that will be lost by removing these areas from crop production. In addition to the 2 m or 6 m uncropped margin, the first 6 m of a cereal crop adjacent to the margin must be managed as a conservation headland where soil type and conditions allow. Payments for 6 m wide conservation headlands or uncropped strips are also available in certain Environmentally Sensitive Areas. The implications of these prescriptions in terms of yield loss have not been fully quantified.

This paper describes a study of the relationship between cereal yield and distance from the field edge. Possible factors influencing the nature of the relationship, including the effects of conservation headland management, were investigated via quantitative surveys and field experimentation.

MATERIALS AND METHODS

Surveys

Two surveys of winter wheat headlands were conducted in August 1994 and August 1995. Sixteen headlands were sampled in 1994; nine in Shropshire on predominantly sandy loam soils and seven in Leicestershire on predominantly clay soils. Twenty-four headlands were sampled in 1995; eight each in Shropshire, Leicestershire and Hampshire (calcareous soils). In 1994, four transects were set out 10 m apart at each site, running at right angles to the field boundary from the crop edge to 11·5 m into the field. Quadrats (0·25 m^2) were placed along the transects at 0, 1, 2, 3, 4 and 11·5 m from the crop edge. All vegetation within the quadrats was cut and separated into crop and weeds. The crop was threshed and the grain cleaned, dried and weighed. Weed biomass was dried and weighed. It was noted whether the headland was a turning or non-turning headland and the aspect (facing north, south, east or west) of the site was recorded. A similar procedure was carried out in 1995, except that three transects per site were recorded, with quadrats positioned at 0, 1, 3, 5, 9, 15, and 30 m from the crop edge. The boundary type (hedge < 2 m or trees) was noted, in addition to aspect (on an eight point scale as north, north-east, east, south-east, south, south-west, west or north-west) and turning/non-turning headland. Other boundary types were excluded from the 1995 sample.

Field experiments

Replicated field experiments were conducted within winter cereal headlands over 3 years, at Harper Adams University College, Newport, Shropshire (grid reference SJ702196) and the Allerton Research and Educational Trust, Loddington, Leicestershire (grid reference SK797010), to investigate factors affecting cereal yields at field edges. Site and cropping details for each site are provided in Tables 1 and 2. The boundary type at both sites was a hedge 1·5–2 m high. The two treatments were 'fully sprayed' or 'conservation headland' management (Sotherton 1991) and were part of a larger experiment studying field margin management practices. Conservation headland management consisted of withholding broad-spectrum herbicides in order to encourage dicotyledonous weed growth. Specific graminicides were applied as required for the control of black-grass (*Alopecurus myosuroides*) and wild oats (*Avena* spp.). Fungicides were applied as for the rest of the crop. Further details of general crop husbandry are also given in Tables 1 and 2.

Plots were established in a randomized block design with three blocks at each site in each year. Each block contained two plots of each treatment at each site. Different management treatments were applied to the hedgebank within replicate plots, but had no effect on headland yield (Perry 1997) and are not considered further here. In 1994, permanent quadrats (0·25 m^2) were marked out in the plots at 0–0·5, 1–1·5, 2–2·5, 3–3·5 and 10·5–11 m from the crop edge to allow destructive dry matter (DM) assessments of crop and weeds at harvest. In 1995 and 1996, an additional quadrat was sited at 4–4·5 m. At the Leicestershire site, all vegetation within the quadrats was cut by hand at ground level and the crop and weeds separated, dried and weighed at harvest in 1994, 1995 and 1996. At the Shropshire site in 1994, quadrats were harvested by plot combine. These results were not comparable with harvesting by hand, as the width of the combine did not allow accurate determination of yield changes across the headland, and are not

Table 1. *Crop, cultivar and husbandry details for Shropshire site between 1994 and 1996*

	1994	1995	1996
Crop	Winter wheat	Winter wheat	Winter barley
Cultivar	Hunter	Hunter	Intro
Drilling date	20 October	14 October	26 September
Fertilizer (kg/ha)			
N	140	150	160
P	—	—	—
K	—	—	—
Herbicides (g ai/ha)			
sprayed headland	fluroxypyr (200) metsulfuron-methyl (6)	bromoxynil (196) ioxynil (196) mecoprop-P (938)	metsulfuron-methyl (60) fluroxypyr (200)
Conservation headland	amidosulfuron (30)	amidosulfuron (30)	amidosulfuron (30)
Fungicides (g ai/ha)	flusilazole (160) tebuconazole (125) tiademenol (165)	carbendazim (78) flusilazole (156) febuconazole (37·5) propiconazole (47)	fenpropimorph (750) tebuconazole (250) tiademenol (330) tridemorph (250)

Table 2. *Crop, cultivar and husbandry details for Leicestershire site between 1994 and 1996*

	1994	1995	1996
Crop	Winter wheat	Winter barley	Winter barley
Cultivar	Hereward	Fighter	Fighter
Drilling date	16 October	23 September	21 September
Fertilizer (kg/ha)			
N	206	168	196
P	54	74	89
K	54	49	89
Herbicides (g ai/ha)			
sprayed headland	tralkoxydim (194) fenoxaprop-P-ethyl (60) fluroxypyr (200) metsulfuron-methyl (6)	diclofop-methyl (611) fenoxaprop-P-ethyl (60) difenzoquat (764) fluroxypyr (200) metsulfuron-methyl (6)	diclofop-methyl (618) fenoxaprop-P-ethyl (28) metsulfuron-methyl (6) fluroxypyr (200)
Conservation headland	tralkoxydim (194) fenoxaprop-P-ethyl (60)	diclofop-methyl (611) fenoxaprop-P-ethyl (60) difenzoquat (764)	diclofop-methyl (618) fenoxaprop-P-ethyl (28)
Fungicides (g ai/ha)	fenpropimorph (223) fenpropidin (224) tebuconazole (252) triadimenol (126) chlorothalonil (226)	carbendazim (62) flusilazole (123) propiconazole (26)	fenpropimorph (173) propiconazole (71)

reported further. In 1995 and 1996, the Shropshire site quadrats were harvested by hand in the same manner as for the Leicestershire site. Following harvest, the crop was threshed mechanically and the grain cleaned, dried and weighed to determine yield.

In March 1995, a cone penetrometer was used to measure soil compaction along the transects where the fixed quadrats were positioned, from 0 to 11 m into the field at both sites (Anderson *et al.* 1980). Fertilizer traps were positioned at ground level along a transect perpendicular to the field boundary at each site prior to nitrogen fertilizer application in March 1995. Cardboard boxes (0·25 m^2 in Shropshire and 1 m^2 in Leicestershire) were used as traps and were positioned continuously from the field boundary to 12 m into the crop. Fertilizer was applied as ammonium nitrate, using a pneumatic spreader in Shropshire and a twin disc spreader in Leicestershire, and the prills (solid spheres of fertilizer) collected and weighed.

Statistical analyses

All statistical analyses were performed using Genstat (Genstat 5 Committee 1987). Grain yield data were assumed to be normally distributed but a $\log_e$ transformation was needed for weed dry matter (WDM) to produce a distribution close to normality. For both the survey and experimental data, preliminary inspection showed that yield approached an asymptotic maximum with distance away from the boundary, whereas $\log_e$ WDM declined to an asymptotic minimum. To describe this non-linear relationship between either yield or $\log_e$ WDM (y) and distance (x), a simple non-linear inverse polynomial regression model was assumed of the form:

$$y = a+\left(\frac{b}{1+dx}\right) \tag{1}$$

This model was chosen for its mathematical simplicity and for its ability to explain the observed biological relationship. At the boundary, $x = 0$ and the yield or $\log_e$ WDM is $a+b$, whereas for large values of x, yield or $\log_e$ WDM approaches the asymptote, a. For increasing yield with distance from the boundary, b will be negative whereas for $\log_e$ WDM, b will be positive. The parameter d is always positive.

Non-linear regressions of yield and $\log_e$ WDM against distance from the boundary were undertaken for the survey data from 1994 (16 sites) and 1995 (24 sites) using equation (1) and the 'Fitcurve' directive in Genstat (Genstat 5 Committee 1987). An accumulated ANOVA table was constructed that determined the effects of distance from the boundary and the effects of sites. It was not possible to directly test the effect of weed dry matter as a covariate for Eqn (1) because this option was not available in Genstat. Instead, separate linear regressions of yields against square root WDM for the 1994 and 1995 data were undertaken. The assumed regression relationship between yield and square root WDM was:

$$Y_{ij} = \mu_j+\beta_j X_{ij}+\gamma_{ij} \tag{2}$$

Here Y_{ij} and X_{ij} were crop yield and square root weed yield respectively, from quadrat i and site j and μ_j and β_j were regression parameters for site j. The γ_{ij} was random error. The crop yield Z_{ij} for quadrat i at site j adjusted to eliminate weed dry matter correlations was:

$$Z_{ij} = Y_{ij}-\beta_j X_{ij} \tag{3}$$

Equation 3 is consistent in that, in the absence of weeds, $X_{ij} = 0$ and the adjusted yield Z_{ij} is equal to the observed yield Y_{ij}. The optimum linear fits were obtained between yield and square root WDM and these were used to calculate all adjusted yields. The adjusted yields were then analysed in the same way as the unadjusted yields by using the non-linear model shown in Eqn (1) to investigate boundary effects independent of weed effects. The effect of aspect, headland and boundary type (1995 only) on yield, adjusted yield and WDM were also investigated by analysing the sites factor into components and making further non-linear regression analyses on the individual site components.

The experimental data were analysed in a similar manner to the survey data. Using the 'Fitcurve' directive in Genstat and Eqn (1), separate non-linear regressions of yield and $\log_e$ WDM against distance from the boundary were undertaken and the model fits evaluated. This exercise produced 12 sets of non-linear parameters (a, b and d) from the three blocks (6 sets each for conservation headlands and fully sprayed headlands), at each site (Leicestershire and Shropshire), for each year (1994–96). Differences in the generated yield and $\log_e$ WDM parameters between treatments, sites and years were analysed by Genstat ANOVA. Linear regression was used to analyse the relationship between crop yield at harvest and the corresponding square root WDM and this allowed the calculation of adjusted yields using Eqns (2) and (3). The adjusted yields were then analysed using the non-linear regression model shown in Eqn (1). The relationships between crop yield and soil compaction (to 15 cm depth), and also crop yield and fertilizer spread pattern were analysed using separate linear regression analyses.

RESULTS

Survey of winter wheat headlands in 1994 and 1995

The non-linear analysis process initially fitted a combined model to the individual site data (for each year separately) and sought a parsimonious model parameterization for the whole data set, irrespective of different site effects. If poor fits were obtained as a result of site differences, parameterization was increased by sequentially fitting separate a, b and d parameters to the model. Statistical changes in the goodness of fit of the model were assessed at each stage of the fitting process.

Changes in mean grain yield, $\log_e$ WDM and adjusted yield with increasing distance from the boundary for the 1994/95 survey data are shown in Fig. 1*a–c*. Fitting the combined inverse polynomial regression model to grain yield, $\log_e$ WDM and adjusted yield data for all sites (1994 and 95), using distance from the boundary as the explanatory variable produced non-linear parameter estimates that were equivalent to those generated by fitting the model to the mean responses values shown in Fig. 1*a–c*. Parameter values are shown in Table 3.

Fitting the inverse polynomial regression model directly to grain yields for the full set of individual sites using constant model parameters (a, b and d) and distance from the boundary as the explanatory

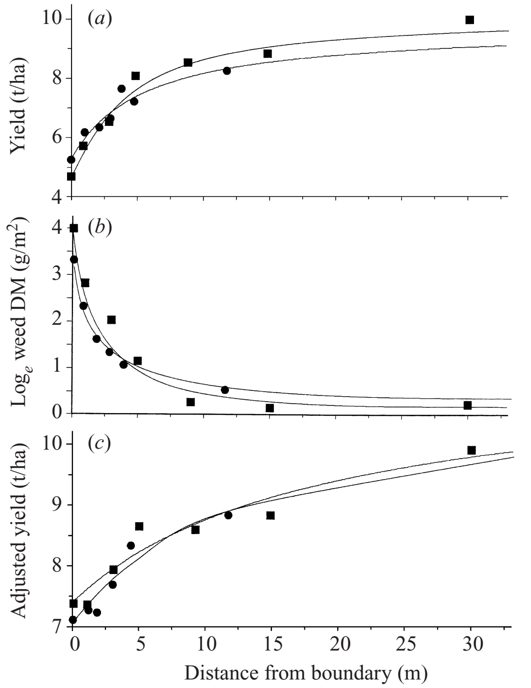

Fig. 1. Effect of distance from the boundary (m) on (*a*) mean grain yield (t/ha) (1994, $r^2 = 0{\cdot}97$ and 1995, $r^2 = 0{\cdot}99$), (*b*) weed DM (g/m^2) (1994, $r^2 = 0{\cdot}98$ and 1995, $r^2 = 0{\cdot}98$) and (*c*) adjusted yields (1994, $r^2 = 0{\cdot}83$ and 1995, $r^2 = 0{\cdot}93$) based on field surveys performed in 1994 (●) and 1995 (■). Fitted lines are inverse polynomial regressions. See Table 3 for parameter values.

variable did not produce good fits, accounting for only 29 % (1994) and 45 % (1995) of the variation respectively (Table 4). In 1994, it was necessary to fit the model separately using different parameter values (i.e. *a*, *b* and *d*) for each site in order to account for a significant proportion of the variation. However, in 1995, fitting the model to each site using separate asymptotes of maximum yield (i.e. different *a* parameters) only was enough to account for much of the overall variation and emphasized the importance of individual site differences in terms of yield potential (Table 4). Maximum yields ranged from 0·8 t/ha to 10·2 t/ha. Using separate *b* and *d* parameters at each site significantly increased the fit of the model for the 1995 data, but only accounted for a further 8 % of the variation.

Fitting the non-linear regression with constant parameter values (*a*, *b* and *d*) to log$_e$ WDM using distance from the boundary as the explanatory variable accounted for only a small proportion of the variation in 1994 (14·6 %), but substantially more in 1995 (38·8 %). The optimum model fit in 1994 was obtained by adding separate *a* and *b* parameters for each site and this explained (60 %) of the variation. In 1995, adding separate *a* and *b* parameters at each site accounted for a similar amount of variation (69·4 %), but was significantly improved when separate non-linear parameters (*d*) were added (88·5 %).

There was a negative linear relationship between yield (y) and square root WDM (x) in both 1994 ($y = 7{\cdot}63 - 0{\cdot}31x$, $R^2 = 0{\cdot}24$) and 1995 ($y = 8{\cdot}42 - 0{\cdot}33x$, $R^2 = 0{\cdot}24$). This association was used to remove the effects of weed on yield and to produce adjusted yields for non-linear analysis. Once the effects of weed dry matter had been eliminated, the fit of the inverse polynomial regression model with constant *a*, *b* and *d* parameters over all sites was reduced when compared to unadjusted yields and accounted for only 11 % of the variation in 1994 and 14 % of the variation in 1995 (Table 4). Fitting separate asymptotes (*a* parameters) to adjusted yields at each site, significantly improved the fit of the model in both years and for 1994, the percentage variation accounted for exceeded that of the corresponding unadjusted yields by 10 %. Inspection of all the adjusted yield data *v.* distance from the boundary for each site individually, confirmed that the relationship was of the inverse polynomial form. In 1994, the optimum model was obtained by fitting all parameters separately (*a*, *b* and *d*), accounting for 65 % of the variation compared to 81·2 % for unadjusted yields. For the 1995 adjusted yields, simply adding separate asymptotes (*a* parameters) improved the fit to 67·3 %, approximately 10 % less than for corresponding unadjusted yields, but this increased to 75·8 % by also adding separate *b* parameters (Table 4).

Table 3. *Mean* a, b *and* d (±1 S.E.M.) *parameters for yield* (*t/ha*), *log$_e$ weed DM* (*g/m^2*) *and adjusted yield* (*t/ha*) *survey data averaged over all sites in 1994 and 1995*

	1994			1995		
Parameter	Yield (t/ha)	Log$_e$ weed DM (g/m^2)	Adjusted yield (t/ha)	Yield (t/ha)	Log$_e$ weed DM (g/m^2)	Adjusted yield (t/ha)
a	9·82 (±0·23)	0·37 (±0·42)	11·86 (±7·75)	10·29 (±0·51)	−0·23 (±0·24)	11·31 (±1·83)
b	−4·53 (±1·15)	2·96 (±0·46)	−4·85 (±7·56)	−5·53 (±0·52)	4·21 (±0·28)	−3·90 (±1·17)
d	0·20 (±0·13)	0·60 (±0·29)	0·05 (±0·12)	0·23 (±0·07)	0·36 (±0·24)	0·06 (±0·06)

Table 4. *Results from inverse polynomial regression analysis for survey data collected in 1994 and 1995. See text for model description*

		Crop yield (dry weight)			$\log_e$ weed DM			Adjusted crop yield (dry weight)		
	D.F.	Mean square	% variation accounted for	*F*-value	Mean square	% variation accounted for	*F*-value	Mean square	% variation accounted for	*F*-value
1994										
All parameters constant	2	46·42	29·0	77·14**	9314·4	14·6	20·95**	14·57	11·0	17·58**
+separate *a* parameters	15	3·05	33·7	5·06**	2352·0	35·9	5·29**	6·15	43·5	7·43**
+separate *b* parameters	15	1·02	35·5	1·69	1982·4	60·0	4·46**	1·41	44·2	1·70
+separate *d* parameters	15	8·09	81·2	13·44**	587·2	62·9	1·32	2·94	65·2	3·55**
residual	48	0·60			444·7			0·82		
1995										
All parameters constant	2	221·04	45·1	276·23**	62663·0	38·8	287·91**	45·70	14·0	57·89**
+separate *a* parameters	23	15·24	78·8	19·04**	1633·6	42·8	7·51**	18·12	67·3	19·17**
+separate *b* parameters	23	2·61	83·4	3·26	3611·5	68·4	16·59**	3·36	75·8	3·56**
+separate *d* parameters	23	1·63	86·2	2·04*	2196·3	88·5	10·09**	1·52	78·4	1·61
residual	96	0·80			217·6			0·94		

* Significant at $P < 0{\cdot}05$, ** significant at $P < 0{\cdot}01$.

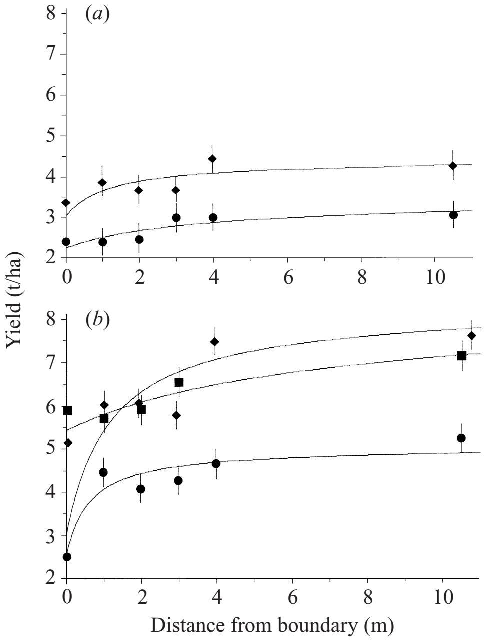

Fig. 2. Relationship between mean grain yield (t/ha) (±S.E.M.) and distance from the boundary (m) for the (*a*) Shropshire and (*b*) Leicestershire sites in 1994 (■), 1995 (◆) and 1996 (●). Fitted lines are inverse polynomial regressions. See text for details.

Field experiments

Grain yield

Plots of mean grain yield against distance from the boundary for the Shropshire and Leicestershire sites between 1994 and 1996 are shown in Fig. 2*a*, *b*. Grain yield increased towards an asymptotic maximum, but the inverse polynomial relationship was not as evident as for the survey data. For the Leicestershire site in 1994 (Table 6) and the Shropshire site in 1995 (Table 5) particularly poor model fits (< 11 % of variation) were obtained. However, for the remaining years, between 28–39 % of the variation was explained using constant (*a*, *b* and *d*) parameters and this was comparable to the survey analyses (Table 4). In 1996, at the Leicestershire site, the model fit was significantly improved by fitting separate *a* parameters accounting for each treatment type (fully sprayed and conservation headlands), but this only accounted for a further 1 % of the variation.

The 3 sets of non-linear parameters (*a*, *b* and *d*) produced from the 12 treatment plots at each site in each year were analysed separately using a sequential analysis of variance. The absence of data from Shropshire in 1994 prevented a fully balanced factorial analysis. Using this approach meant that there was no appropriate estimate of error variance for the effects of year, site or the year-site interaction and conse-

Table 5. *Results from inverse polynomial regression analysis for experimental data collected at the Shropshire site in 1995 and 1996. See text for model description*

		Crop yield (dry weight)			Adjusted crop yield (dry weight)		
	D.F.	Mean square	% variation accounted for	*F*-value	Mean square	% variation accounted for	*F*-value
1995							
All parameters constant	2	4·48	7·6	3·72*	4·17	9·3	4·49*
+ separate *a* parameters	1	1·54	8·1	1·27	2·17	11·2	2·34
+ separate *b* parameters	1	0·02	8·1	0·02	0·01	11·2	0·01
+ separate *d* parameters	1	0·14	8·1	0·11	0·63	11·2	0·68
residual	66	1·21			0·93		
1996							
All parameters constant	2	1·10	3·0	0·87	—	—	—
+ separate *a* parameters	1	0·09	3·3	0·07	—	—	—
+ separate *b* parameters	1	0·14	3·3	0·11	—	—	—
+ separate *d* parameters	1	0·22	3·3	0·17	—	—	—
residual	66	1·27					

* Significant at $P < 0\cdot05$.

Table 6. *Results from inverse polynomial regression analysis for experimental data collected at the Leicestershire site between 1994 and 1996. See text for model description*

		Crop yield (dry weight)			Adjusted crop yield (dry weight)		
	D.F.	Mean square	% variation accounted for	*F*-value	Mean square	% variation accounted for	*F*-value
1994							
All parameters constant	2	6·67	10·4	4·39*	3·52	6·0	2·85**
+ separate *a* parameters	1	2·08	11·0	1·37	1·84	6·9	1·48
+ separate *b* parameters	1	0·56	11·2	0·39	0·43	6·9	0·35
+ separate *d* parameters	1	1·59	11·5	1·04	0·24	7·0	0·20
residual	54	1·52			1·24		
1995							
All parameters constant	2	14·62	29·2	15·45**	—	—	—
+ separate *a* parameters	1	1·58	29·7	1·67	—	—	—
+ separate *b* parameters	1	1·84	30·2	1·95	—	—	—
+ separate *d* parameters	1	0·63	30·4	0·67	—	—	—
residual	66	0·95			—		
1996							
All parameters constant	2	23·32	38·4	19·73**	2·64	5·5	3·30*
+ separate *a* parameters	1	9·44	39·2	7·99*	2·95	8·9	3·69
+ separate *b* parameters	1	2·22	39·7	1·88	0·03	8·9	0·05
+ separate *d* parameters	1	0·59	41·4	0·49	3·43	11·8	4·29*
residual	66	1·18			52·7		

* Significant at $P < 0\cdot05$, ** significant at $P < 0\cdot01$.

quently classical significance tests were not available for these effects. However, comparison of the relative magnitude of the mean squares suggests that the *a* parameter for yield varied significantly between sites and years with little indication of any significant interaction between the two factors. However, there was evidence of a significant year-headland-site effect and also a significant year-headland-site effect on the *b* parameter (Table 7). This suggests that both yield at the boundary and asymptotic yield showed interactions with headland type and the location and year of the experiment. There was no evidence of any year or site effects on the *d* parameter and this suggests that a common *d* parameter over all sites was

Table 7. *Sequentially fitted ANOVA showing effect on yield of year of cropping, location of site and headland management on fitted* a, b *and* d *values for each treatment plot in field experiment*

		a		*b*		*d*	
	D.F.	Mean square	*F*-value	Mean square	*F*-value	Mean square	*F*-value
Year (Y)	2	48·51	—	9·77	—	18·23	—
Site (S)	1	50·04	—	0·44	—	15·41	—
Y × S	1	1·92	—	6·05	—	26·93	—
Block	10	0·80	1·55	2·70	0·40	32·71	1·88
Headland (H)	1	1·30	2·53	8·25	1·21	48·91	2·81
Y × H	2	0·93	1·81	16·6	2·44	37·27	2·14
H × S	1	0·92	1·80	11·59	1·70	14·15	0·81
Y × H × S	1	2·37	4·62*	27·05	3·97*	45·72	2·63
Error	40	0·51		6·81		17·38	

* Significant at $P < 0·05$.

Table 8. *Overall mean yield parameter values* (a, b *and* d) *for experimental data between 1994 and 1996. Standard errors of regression parameters are shown in brackets and are based on 342* D.F.

a	*b*	*d*
5·20 (0·29)	−0·33 (0·36)	1·9 (4·63)

Table 9. *Mean weed DM* (g/m^2) *and grain yield* (t/ha) *at harvest for fully sprayed headlands* (*FSH*) *and conservation headlands* (*CH*) *between 1994 and 1996*

		Shropshire			Leicestershire		
	Year	FSH	CH	S.E.	FSH	CH	S.E.
Grain	1994	—	—	—	6·43	6·06	0·20
	1995	4·13	4·46	0·17	6·28	5·98	0·15
	1996	2·71	2·77	0·18	4·39	3·67	0·19
Weed	1994	—	—	—	1·20	3·32	0·21
	1995	1·42	1·30	0·24	0·51	3·81	0·12
	1996	0·56	0·82	0·20	1·37	2·29	0·22

appropriate. The parameters from fitting a single overall model are shown in Table 8.

Overall yield across the headland for each site in each year is shown in Table 9. Generally, yields were marginally higher for fully sprayed headlands when compared to conservation headlands in Leicestershire, though not in Shropshire.

Weed DM

Comparison of the relative magnitude of the $\log_e$ WDM mean square also suggested that the *a* parameter for yield varied significantly between sites and years, but there was no significant interaction between the two factors (Table 10). There was no significant effect of any other factors on the parameters tested.

Weed–yield relationships

There were negative linear relationships between grain yield and square root weed dry matter for Shropshire in 1995 and in Leicestershire in all three years of the experiment. The model regression parameters are listed in Table 11.

Adjusted yields

Once the effects of weeds had been eliminated, the fit of the inverse polynomial regression model was marginally improved when compared to unadjusted yields at Shropshire in 1995 (Table 5) using constant parameters (*a*, *b* and *d*), but still remained low (< 10%). At Leicestershire (Table 6) in 1994 and 1996, analysis of adjusted yields provided a poorer overall model fit (6% of the variation). Further inspection of the data suggested that the relationship between adjusted yield and distance from the boundary remained non-linear. Adjustment of yield for weed effects eliminated asymptotic (*a* parameter) differences between conservation and fully sprayed headlands in 1996 (Table 6). No adjusted yields were calculated for the Leicestershire site in 1995 due to the weak relationship between grain yield and square root weed dry matter.

Fertilizer distribution

Fertilizer deposition over the headland area in 1995 ranged from 87·43 to 150·17 kg N/ha at the Shropshire site and from 19·04 to 55·06 kg N/ha at the Leicestershire site. Regression analysis showed that there was no significant relationship between grain yield and fertilizer distribution or between fertilizer distribution and distance from the edge of the crop at either site. However, it should be noted that the measured dose formed only part of the total fertilizer N applied at each site (see Table 1).

Table 10. *Sequentially fitted ANOVA showing effect on* $\log_e$ *weed DM of year of cropping, location of site and headland management on fitted* a, b *and* d *values for each treatment plot in field experiment*

	D.F.	*a*		*b*		*d*	
		Mean square	*F*-value	Mean square	*F*-value	Mean square	*F*-value
Year (Y)	2	17·40	—	9·77	—	18·23	—
Site (S)	1	23·45	—	0·44	—	15·41	—
Y × S	1	0·04	—	6·05	—	26·93	—
Block	10	1·981	0·49	2·70	0·40	32·71	1·88
Headland (H)	1	3·669	0·90	8·25	1·21	48·91	2·81
Y × H	2	8·948	2·20	16·60	2·44	37·27	2·14
H × S	1	3·893	0·96	11·59	1·70	14·15	0·81
Y × H × S	1	1·638	0·40	27·05	3·97	45·72	2·63
Error	40	4·074		6·81		17·38	

Table 11. *Parameters* (± 1 S.E.) *for linear regression of grain yield* (y) *against square root weed dry matter* (x) *at the Leicestershire* (*Leics.*) *and Shropshire* (*Shrops.*) *sites between 1994 and 1996. Standard errors of regression parameters are shown in brackets and are based on 58* D.F. (*1994*) *and 70* D.F. (*1995 and 1996*). F *value shows significance of linear regression coefficient*

Site and year		μ	β	*F*-value	Probability	% variation accounted for
Leics.	1994	6·89 (0·21)	−0·15 (0·04)	17·59	< 0·001	22
	1995	6·48 (0·19)	−0·09 (0·03)	7·00	0·01	8
	1996	4·74 (0·14)	−0·17 (0·02)	78·93	< 0·001	52
Shrops.	1995	4·80 (0·17)	−0·60 (0·15)	16·27	< 0·001	18
	1996	2·70 (0·15)	0·04 (0·07)	0·57	NS	1

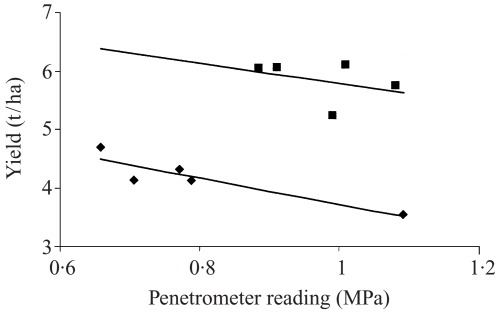

Fig. 3. Relationship between grain yield and soil compaction for the Shropshire (◆) ($y = 5{\cdot}92 - 2{\cdot}17x$, $R^2 = 0{\cdot}82$) and Leicestershire (■) ($y = 7{\cdot}48 - 1{\cdot}66x$, $R^2 = 0{\cdot}13$) sites.

Soil compaction

Soil compaction, measured as penetrometer readings at 15 cm depth, had a significant negative effect on grain yield ($P < 0{\cdot}05$) at the Shropshire site in 1995, and accounted for 82% of the variation (Fig. 3). However, at the Leicestershire site there was no significant relationship between soil compaction and grain yield. There was no significant relationship between soil compaction and distance from the crop edge at either site.

DISCUSSION

Several studies have shown that, on average, yields from crop margins or headlands are lower than the rest of the field, though in most cases exceptions have been reported where headland yields were either similar or higher than midfield yields (Boatman & Sotherton 1988; de Snoo 1994, Speller *et al.* 1992; Sparkes *et al.* 1994; Cook & Ingle 1997; see also Boatman 1992*b*). Furthermore, where yields have been measured at different distances into the field, no consistent pattern has emerged other than a general trend for yields to increase with distance (Speller *et al.* 1992; Sparkes *et al.* 1994; Cook & Ingle 1997). In the present study, distance from the field boundary affected yield in both years of the survey and yield increased in a non-linear manner with distance to approach an asymptotic maximum. In 1995, the yield data appeared not to have reached an asymptote within the range of distances measured, up to 30 m from the crop edge, suggesting that the ‘headland effect’ may typically extend at least this far into the field.

Fitting the inverse polynomial model to the yield-distance relationships generated by the survey was undertaken for two main reasons. The first was that it simulated a biologically realistic response of fine-scale yield change across a headland and could potentially allow rapid assessments of yield loss to be made when headlands were left uncropped for conservation or other purposes. In another survey, Cook & Ingle (1997) suggested that the relationship between yield and distance from the boundary is linear, but their initial measurements were only taken at 2·5 m from the boundary and the overall yield response generated was consequently much flatter. The second was that it allowed a detailed analysis of the effect of site differences on yields. Asymptotic yields differed between sites in the range 3·3–12·4 t/ha and formed a complex interaction with distance from the boundary and the non-linear component of the model. In both years, fitting separate parameters for the inverse polynomial model at each site improved the fit of the model suggesting that there were significant interactions between site effects and the fitted models. Cook & Ingle (1997) reported a similar range of yield differences between sites, ranging between 2–11 t/ha in their survey of headland yields. Model fits were generally better with the 1995 survey data compared to 1994. This was, in some part, due to the inclusion of additional quadrats at different positions from the crop edge (up to 30 m in 1995), allowing better estimates to be made of model parameters.

The survey also showed that $\log_e$ weed DM was negatively related to distance from the boundary and that this relationship was also non-linear. Furthermore, there was a negative linear relationship between yield and square root weed DM, an association that has been the subject of other studies (e.g. Boatman, 1992*b*; Christensen *et al.* 1994).

It is tempting to conclude that the higher prevalence of weeds at crop edges is at least partly responsible for lower yields. However, competition from the crop itself can be an important factor affecting weed development and high seed rates have been shown to reduce weed dry matter production (Grundy *et al.* 1993; Christensen *et al.* 1994).

When the inverse polynomial regression model was fitted to yields mathematically adjusted for the effects of weed biomass, overall model fits of yield *v.* distance from the boundary were reduced in both years when compared to unadjusted yields. However, fitting separate asymptotes at each site accounted for amounts of variation that were comparable to corresponding unadjusted yields and inspection of the data showed the pattern of yield response across the headland at each site to be of inverse polynomial form. This provides the strongest evidence from the current study that factors other than weed infestation affect yield response across the headland. The extent of the boundary effect can also be investigated by examining the d parameter from the model. The distance from the boundary at which the yield is midway between the boundary yield (i.e. $[a+b]$ at $x=0$) and the asymptotic yield (a) is $1/d$ and thus $1/d$ can be interpreted as a measure of the range of the boundary effect. Consequently, the smaller the value of d, the larger the range of the boundary effect and the further the boundary effect spreads into the field. For both years of the survey, the d parameter was reduced from approximately 0·2 for unadjusted yields to 0·05 for adjusted yields (Table 3). As a result, the range of the headland effect ($1/d$) is much smaller for unadjusted yields, suggesting that the weed effects are important close to the boundary and that the remaining effects, after eliminating the weed effects, extend further into the field.

In the designed experiments, non-linear relationships between yield or weed dry matter and distance from the headland were observed that were similar to those obtained by the survey. However, on analysis, the inverse polynomial models from the designed experiments had less explanatory power than those from the survey data. This can, in part, be attributed to the shorter maximum distance sampled from the boundary (11·5 m) compared with the 1995 survey data. The inverse polynomial model did not have good explanatory power at the Shropshire site in 1995, possibly because the crop lodged and the yield increase with distance from the boundary was less apparent. Lodging was also a problem at Shropshire in 1996, but the effect was more uniform and yields, although low, showed a more distinct increase with distance from the boundary. Consequently, the non-linear regression model fits for yield had generally better explanatory power at the Leicestershire site.

The model parameters for yield based on both experimental sites in all years (Table 8) differ from those produced from the survey data (Table 3). In the experiment, continuous cereal cropping accounted for the lower asymptotic yield (a) but the yields on the boundary (i.e. $[a+b]$ at $x=0$) where similar, approximately 5 t/ha, suggesting that there was a proportional decline in the b parameter. The headland effect ($1/d$) was much smaller for the experimental data (0·53) compared to the survey data (≈ 5) and this is particularly apparent at the Shropshire site when the headland yield profiles are compared (Figs 1*a* and 2*a*).

There was no significant difference in asymptotic yield between fully sprayed and conservation headland types despite yield reductions of between 4·8 to 16·4% for conservation headlands at the Leicestershire site. These reductions are within ranges reported by other authors using similar treatments (Boatman & Sotherton 1988; Boatman 1992*b*; de Snoo 1994).

Previous studies have only examined effects of conservation headland management on cereal yield in a single year. In a ploughing system, such as that used at both experimental sites in the present study, it might be expected that weed infestations would increase in the third year of conservation headland management, as weed seeds ploughed down in the first year would be ploughed back to the surface (Moss & Cousens 1990). The yield reduction on the Leicestershire conservation headland plots was certainly greater in 1996 than in either of the preceding years, though differences in weed dry matter were greatest in 1995. Consideration of weed dry matter alone however, does not take account of differences in competitive ability and timing of senescence between weed species. Guidelines for conservation headland management suggest that they be rotated round the farm to avoid excessive weed build-up. It may be particularly advisable to avoid treating a crop margin as a conservation headland in the second year after conservation headland management in the previous year.

Asymptotic $\log_e$ weed DM (a parameter) varied significantly between year and site but was increased by the conservation headland treatment. There was a significant negative relationship between yield and square root weed DM at harvest, except for the Shropshire site in 1996. At Shropshire, the low yields following crop lodging reduced the correlation between yield and square root weed DM.

Some movement of weed seeds between plots could have taken place during harvesting and cultivation operations, but the effect of this was minimised by sampling only from the centres of the plots. Horizontal movement as a result of cultivations is less than one metre for the majority of seeds (Fogelfors 1985; Howard *et al*. 1991; Rew & Cussans 1997). Combine harvesters can move a larger proportion of seeds over a greater distance (Howard *et al*. 1991; Rew *et al*. 1996), but this only applies to seeds not shed by harvest time and of these, only a proportion are removed by the combine. Of seeds moved by the combine, $< 5\%$ were moved more than 5 m from the source (Howard *et al*. 1991). Seed movement between plots is therefore unlikely to have greatly influenced the results.

At the Shropshire and Leicestershire sites, inverse polynomial models fitted to yields adjusted to take account of weed DM, gave a weaker relationship than corresponding models fitted to unadjusted yields. Adjusted yield for Leicestershire in 1995 was not calculated since the regression of yield *v*. square root weed DM only accounted for 8% of the variation and this was not considered to be a significant relationship. The inclusion of separate asymptotes (a parameters) for adjusted conservation and fully sprayed headlands did not significantly improve model fits. Detailed inspection of adjusted yield data *v*. distance from the boundary showed evidence of an inverse polynomial trend, but the high degree of scatter also allowed a linear interpretation. One reason for the loss of the non-linear response for the experimental data could be attributed to the maximum distance sampled. In 1995, the survey extended to 30 m and clearly provided the best fit of the inverse polynomial model to adjusted yield in the entire study. The experimental data only sampled up to 11 m; in retrospect this was probably inadequate as the boundary effects extended further than 11 m into the field.

There was a significant relationship between soil density and yield in one experiment. In the other experiment where soil density was measured, there was little variation between samples. Sparkes *et al*. (1994) also measured soil density at different distances from the field boundaries, and found that yield was reduced in the tramlines where penetrometer cone resistance was high. The effect of soil compaction on crop yields is well known (e.g. Eriksson *et al*. 1974; Soane *et al*. 1982; Håkansson *et al*. 1988), but more work is needed to establish its importance relative to other factors in crop margins.

The limited measurements of fertilizer distribution pattern made in this study showed the wide variation in application rates that can occur under normal agricultural conditions, previously demonstrated by Rew *et al*. (1992). Despite this, no effect on yield was observed. Although the application measured only supplied part of the total nitrogen fertilizer dressing, it was assumed that the same pattern would apply during the second application. However, this may not have been the case and further work on this aspect is also needed.

In summary, it appears that there is evidence for a non-linear relationship between cereal yield and distance from the boundary at least up to 30 m from the crop edge. Although there is a negative linear relationship between cereal yield and weed DM, it is unlikely that weed presence alone is entirely responsible for the observed relationship, since yield adjusted for weeds also showed evidence of a response related to distance from the boundary. Allowing greater weed survival by selective herbicide use on conservation headlands did not significantly reduce yields. There was a significant relationship between soil compaction and yield at one site.

The models developed in this paper quantify the relative importance of weeds versus other factors such as soil compaction and seed bed quality on yield at field margins. However, our work also shows that the parameters of the fitted model can be very dependent on site effects and further work is needed to elucidate the nature of these site-specific effects.

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