DEPARTMENT for ENVIRONMENT, FOOD and RURAL AFFAIRS **CSG 15**

Research and Development

Final Project Report

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Project title	A REVIEW OF KNOWLEDGE: INTER-ROW HOEING AND ITS ASSOCIATED AGRONOMY IN ORGANIC CEREAL AND PULSE CROPS
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Executive summary (maximum 2 sides A4)

The aim of this project was to establish the "state of the art" for inter-row hoeing and its associated agronomic practices in organic cereal and pulse crops. To achieve this a detailed review of literature was undertaken.

- To facilitate inter-row cultivation in cereal and pulse crops, some adjustment of row spacing may be required. For cereals, drilling crops in 25 cm rows can reduce yield compared with normal drilling practice, primarily due to greater intra-specific competition amongst the crop (i.e. competition between crop plants). Yield reductions of up to 10 % have been reported, although the reductions in organic systems tended to be less than in conventional systems. However, the financial implications of this reduction could be similar for both systems given the higher value of organic crops. There is some evidence that weed levels may also increase when wide rows are used, but the data were inconsistent.
- The yield penalty resulting from widely spaced crop rows can be minimised using a number of approaches, depending on the drill:
  1. Reducing the seed rate in widely spaced crop rows can help to minimise excessive intra-specific competition. The exact reductions are uncertain for organic systems, but they could be in the order of 10 – 20 % compared with a standard seed rate for 12.5 cm rows.
  2. Band sowing the crop in wide rows can also help to minimise intra-specific competition as the seed is distributed over a greater area. This approach would require a shoe or plate to be fitted to the drill coulter to spread the seed.
  3. Using a twin-row arrangement can completely overcome the yield penalty. This approach requires that the coulters on the drill be moved to form a series of narrow twin rows with a wide gap between for inter-row hoeing.
- The recommended row spacing for peas (up to 20 cm) and beans (up to 35 cm) does not require any further adjustment for inter-row hoeing.

- Recent developments in automated guidance of inter-row hoeing equipment mean that weeding operations can now be conducted a much higher speeds (10 km h^{-1}). This has highlighted the limitations of some of the cultivators currently used (e.g. 'A' blades), as excessive soil throw can occur at this high speed. Unfortunately, this subject area has received little attention so firm recommendations cannot be made. However, rolling cultivators may prove to be the most suitable at high forward speeds. For manually guided hoes working at slower speeds (5 km h^{-1}), 'A' and 'L' blades offer an effective low cost solution. Whilst the addition of guidance systems can increase the cost of basic hoeing equipment, this can be more than compensated for by the higher workrate, assuming the equipment is used at full capacity.
- In terms of the timing of inter-row hoeing, it is suggested that weeding operations should be conducted at an early stage in the growing season, as the weeds that emerge with or shortly after the crop are the ones that pose the most significant threat for crop yield. Delaying weeding can result in a significant yield penalty. However, weeding later in the season may also be required to stop any later emerging weeds or weeds that were not controlled earlier from setting seed. Weeding on two occasions can provide better levels of weed control than weeding once, but weeding more frequently offered little additional benefit. Overall, inter-row hoeing can control a broad range of annual broad-leaved and grass weed species at a wide range of weed growth stages and under a wide range of soil conditions. Reductions of weed biomass of up to 99 % have been reported as a result of inter-row hoeing, although this has not always resulted in a positive crop yield response. This is probably due to crop damage resulting from inaccurate hoeing, a problem that can be overcome with automated guidance.
- There is some evidence to suggest that mechanical weeding operations can mineralise soil bound nitrogen, but this may only equate to approximately 5 kg N ha^{-1}. Nevertheless, this small quantity of additional nitrogen could be beneficial to organic crops, where nitrogen can be limiting.
- The impact of inter-row hoeing on ground nesting birds is uncertain. Early indications suggest that skylarks prefer to nest directly adjacent to or in the crop row rather than between rows. If this is confirmed then inter-row hoeing is unlikely to significantly disrupt nesting. For autumn sown crops, weeding should have been completed before the nesting season, for spring-sown crops, optimum weeding and nesting times coincide. The practice of sowing cereal crops in wide rows may be beneficial to skylarks as they prefer an open crop canopy.

The information contained within this review should enable farmers to make best use of inter-row hoeing in their arable crops. This will assist in overcoming some of the current production constraints in organic systems, namely weeds. The information is also of relevance to non-organic farmers who may be considering mechanical weeding as a partial alternative to herbicides. This will result in an environmental benefit through reduced crop protection inputs.

There are a number of areas that require further research and development:

- The interaction of seed rate and row spacing needs to be confirmed in organic systems since the absolute level of crop response is likely to be different compared with that observed in conventional systems. More generally, recommendations for optimum seed rates in organic systems are based on very little data and would benefit from additional investigation.
- Relatively little is known about the mechanisms of weed kill and the detailed interaction between the cultivator blade, the weed and the soil. This is particularly important with the new automated guidance equipment that allows weeding at high forward speeds. The efficacy and efficiency of mechanical weed control could be improved if the underlying science was better understood.
- The timing and frequency of inter-row hoeing has received very little attention. The optimum weed control timings are based on small-plot crop:weed competition studies and need to be verified under field scale management with inter-row hoeing equipment.
- Finally, the impact of inter-row hoeing and widely spaced crop rows on ground-nesting birds has not been looked at directly, but is of importance.

This report could form the basis of a short synthesis publication, aimed at farmers, to ensure research findings are presented in a user-friendly format. This could be circulated through various channels including web sites, technical events, trade shows, and EFRC Bulletin. In addition, presentations will be made at farmer group meetings. A review paper will be prepared for publication in a refereed scientific journal.

Scientific report (maximum 20 sides A4)

1. INTRODUCTION

Weeds present one of the most significant agronomic problems for organic arable crop production. Organic farmers rely on a wide range of preventative and reactive methods to control weeds including, crop rotation, timing of sowing and mechnanical techniques (Davies & Welsh, 2002). Whilst spring-tine weeding remains the most common direct method for weed control in organic cereal crops, it is clear that there are a number of problems relating to its efficacy and selectivity. Inter-row hoeing can overcome many of these problems but, at present, there are no established agronomic guidelines for its rational implementation. This, to some extent, has prevented organic farmers in persuing inter-row hoeing as a method of weed control. Therefore, to address this, it is important that all available information relating to inter-row hoeing and its associated agronomy is reviewed and disseminated to provide farmers and their advisors with the necessary information to first, make an informed decision on the most appropriate method of weed control for their specific situation and second, to establish, where possible, agronomic guidelines for its use.

2. AIMS & OBJECTIVES

The aim of this project was to establish the "state of the art" for inter-row hoeing and its associated agronomic practices in organic cereal and pulse crops. To achieve this, a detailed review of literature was undertaken, focusing on the following objectives:

1. To review the interaction of seed rate and row spacing with respect to weed suppression, crop yield and crop quality for a range of autumn and spring sown cereal and pulse crops. The economics of seed rate adjustment will also be considered.
2. To review the effect of timing and frequency of inter-row hoeing in relation to weed control, crop yield response and crop quality. Where possible, a cost/benefit economic analysis will be conducted.
3. To review the potential for mineralisation of soil-bound nitrogen through cultivations and identify robust methodologies of sufficient resolution to measure this effect when cultivations are conducted at hoeing depth.
4. To review information relating to cultivations at hoeing depth with respect to choice of cultivation tool, speed of operation, soil type and soil condition.
5. To review the environmental impact of inter-row hoeing and growing crops on a wide row spacing with respect to ground-nesting birds.
6. To produce a final report that will, where possible, identify guidelines to assist organic farmers in the use inter-row hoeing equipment in cereal and pulse crops. In addition, areas that require further research will be highlighted.
7. To disseminate the resulting information to researchers, advisors and industry.

3. SUMMARY OF REVIEW

3.1 Seed Rate & Row Spacing

Alterations in the sowing arrangement of both cereal and pulse crops can significantly affect crop yield and weed development.

Within limits, increasing seed rate serves to increase yield and, through improved competition, restrict weed development, weed biomass and weed seed return (e.g. Godel, 1935; Carlson & Hill, 1985; Bulson *et al*., 1997; Champion *et al*., 1998; Taylor & Younie, 2002). This is particularly important for organic agriculture as the farmer must not only consider the effect of weeds in the current crop, but must also take account of weed seed return which will affect future weed populations and thus yield of subsequent crops in the rotation.

Recommended seed rates for organic arable crops are typically higher than those recommended for non-organic systems for the reasons cited above (Lampkin & Measures, 2001). Also, higher rates are recommended to compensate for damage that may be incurred through mechanical weed control, which, at this time, mainly comprises some form of harrowing. Table 1 provides the current recommendations for a range of organically grown arable crops (Lampkin & Measures, 2001).

Table 1. Recommended seed rates for organic arable crops. After Lampkin & Measures (2001).

Crop Species	Recommended seed rate	
	(Seeds m^{-2})	(Kg ha^{-1})
Winter wheat	400 - 450	180 – 220
Spring wheat	500 - 550	225 – 275
Winter oats	500 - 550	175 – 225
Spring oats	650 - 700	220 – 270
Winter barley	350 - 400	160 – 200
Spring barley	375 - 425	180 – 220
Triticale	-	160 – 220
Rye	-	160 – 200
Winter field bean	25	-
Spring field beans	45	-

From the experimental data reported in this review, it is difficult to establish any absolute recommendations as to the optimum seed rate for arable crops grown in organic systems, since there have been relatively few studies that have considered this question directly. It is perhaps misleading to use data gathered in conventional systems, as the competitive interactions of crop and weed are likely to vary under the very different environment of high fertility (e.g. Grundy *et al*., 1993) and herbicides. However, it is likely that the trends observed in conventional systems will be repeated under organic management and so the use of higher seed rates in organic systems is justified.

For cereal crops, with the exception of rye, increasing crop row spacing from normal practice (10 – 12.5 cm row) to wide rows (20 – 30 cm) can result in a significant reduction in yield of the order 5 – 10 % (e.g. Holliday, 1963; Finlay *et al*., 1971; Cussans & Wilson, 1975; Bishnoi, 1980; Andersson, 1986; Koscelny *et al*., 1990; Champion *et al*., 1998; Taylor & Younie, 2002) (Figure 1). The data from organic systems offers some support for this but, in general, the yield reductions were less marked (e.g. Dierauer, 1990; Daly *et al*., 1990). Although there was only limited data, rye appeared to be more sensitive to increases in row spacing with a yield reduction of 16 % resulting from an increase of row spacing from 12.5 cm to 25 cm (Bishnoi, 1980). In terms of the effect on weeds, the data were more ambivalent, but weed biomass was less affected by increases in crop row spacing than crop yield (Andersson, 1986; Dierauer, 1990; Koscelny *et al*., 1990; Champion *et al*., 1998; Taylor & Younie, 2002).

For pulse crops, the implications are less important as the recommended row spacings would allow inter-row hoeing to take place without any need for adjustment (PGRO, 1991 & 1996). However, for winter beans, it is unlikely this crop will be inter-row hoed due to the yield penalty from drilling compared with broadcasting and shallow ploughing (Bowerman & Cook, 1991).

The implications of this for organic farmers considering inter-row hoeing for weed control are clear. Increases of crop row spacing to accommodate inter-row hoeing are likely to result in some yield penalty, particularly at the high seeds rates that are commonly employed in organic systems. However, these row width increases are unlikely to contribute to significantly increased weed levels. There is no consistent data relating to the interaction of cultivar response to adjustments in seed rate and row spacing.

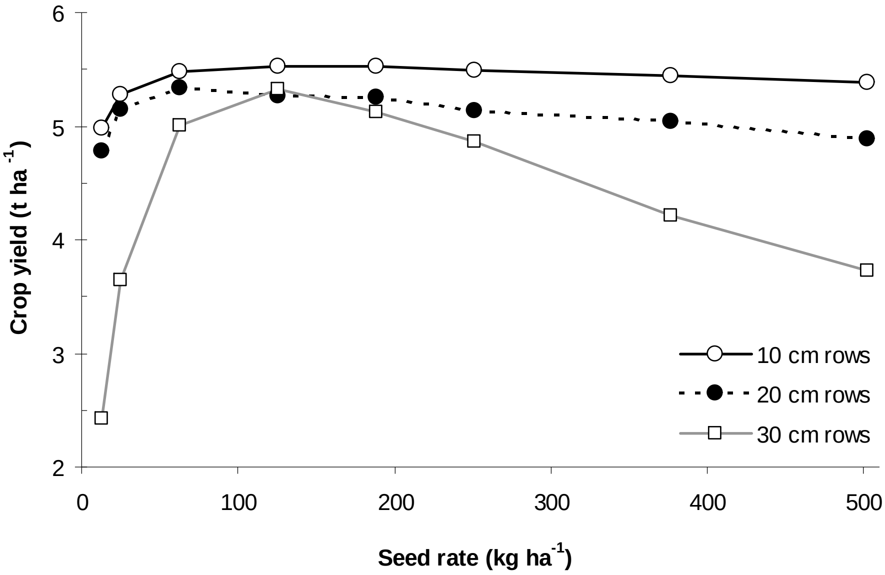

Figure 1. The effect of seed rate and row spacing on winter wheat yield. After Holliday (1963).

To minimise any yield penalty from sowing cereals in wide rows, it may be worth considering the spatial arrangement of the crop. There is some evidence that by avoiding the extreme rectangularity that occurs when sowing on wide rows at high seed rates can help to maintain crop yield and improve weed competition. This may be achieved in a number of ways:

1. **Reduce seed rates when sowing in wide rows (20 – 25 cm).** The evidence would suggest that the optimum seed rate in wide rows is less than that in narrow rows. For example, Champion *et al*. (1998) found that the optimum seed rate in 15 cm rows was 250 plants m^{-2}, whilst in 9 cm rows, 350 plants m^{-2} resulted in the highest yield. Clearly, this will result in a considerable saving in seed costs as well as improved yield. If this response were mirrored in organic systems there would be an economic benefit of approximately £30 ha^{-1} from savings in seed (this assumes a 28 % reduction in standard seed rate of 250 kg ha^{-1}; organic seed at £460 t^{-1}) and £71 ha^{-1} from improved yield at reduced seed rate (this assumes 12 % yield increase over average organic yield of 3.2 t ha^{-1}; grain value at £185 t^{-1}). Therefore, the total economic benefit of reducing seed rates in widely spaced crops could be approximately £100 ha^{-1}.

2. **Band-sowing**. Depending on the drill, shoes can be fitted to the coulters to give a broadcast effect rather than sowing in rows (Fig. 2D). Whilst this is probably not as effective as sowing in twin rows (Fig. 2C), it may offer benefits over drilling in widely spaced rows due to a reduction in intra-specific competition amongst the crop (Andersson, 1986).

3. **Maintain seed rates and row number, but alter the positions of the rows.** Moving the coulters on the drill to sow in twin rows with a wide gap between (e.g. Fig 2C) can help to minimise the problems of high intra-specific competition that occurs when sowing in wide rows. Evidence would suggest that this arrangement does not lead to any yield penalty compared with sowing at a normal row spacing of 12.5 cm (Blair *et al*., 1997).

For those farmers not considering inter-row hoeing as a method of weed control, there could be some benefit from broadcast sowing rather than drilling (Fig. 2A). Reductions in weed biomass of up to 30 % have been reported with corresponding improvements in crop yield (Griepentrog *et al*., 2000; Olsen *et al*., 2002). However, broadcasting must not be undertaken at the expense of achieving a uniform planting depth, as crop establishment can be adversely affected, thus negating any benefits of a more even crop distribution.

In terms of grain quality, there is very little information reported concerning the effects that sowing arrangement has on these parameters. One experiment did report some benefit for grain protein levels with a wider row spacing (Germeier, 2000), but this was at the expense of yield and may just have been a result of a nitrogen dilution effect in the grain (Greenwood *et al*., 1991).

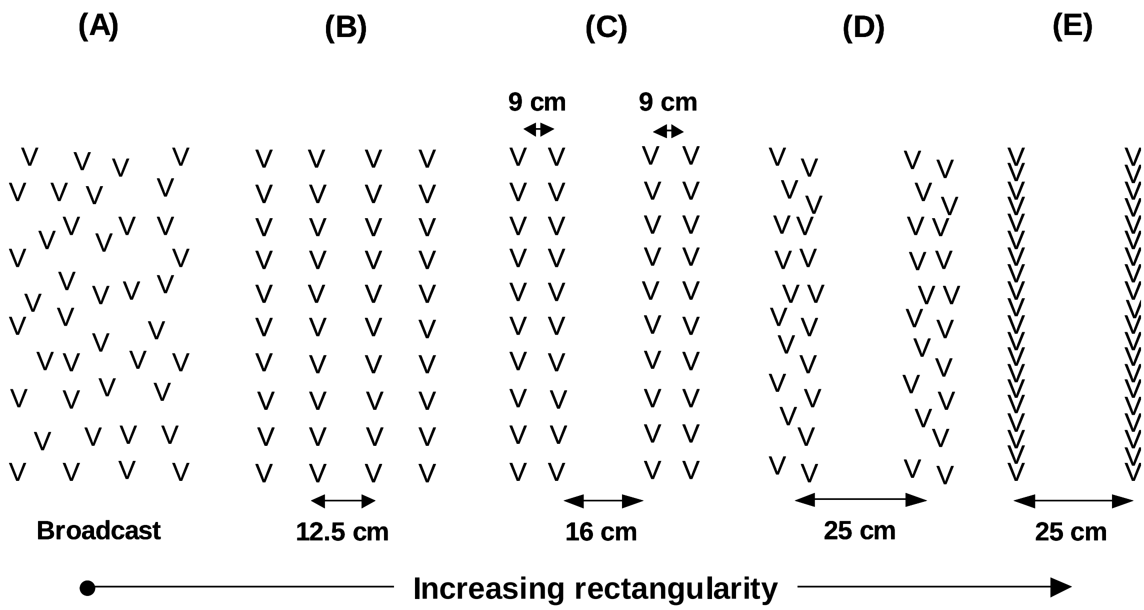

Figure 2. Different planting arrangements for cereals

3.2 Timing & Frequency of Inter-Row Hoeing

Data from crop:weed competition studies suggest that it is the weeds that emerge with or shortly after the crop that are the ones that pose the most significant threat for crop yields (Cousens *et al*., 1987; Kropff *et al*., 1993). However, a range of factors affects the absolute level of competition and, of these, weed population density is probably one of the most important (Cousens, 1985; Cudney *et al*., 1989; Wilson & Wright, 1990; Kropff *et al*., 1992).

In terms of the optimum timing for mechanical weeding operations, it would appear that weeding at an early stage in the lifecycle of the crop is likely to produce the greatest yield response to weeding. If weeds are not controlled at an early stage, significant reductions in crop yield may result. For organic winter-sown cereals, the data, albeit rather limited, would suggest that weeding should commence in the autumn or early spring depending on when the crop is sown (Welsh *et al*., 1999). However, the ability to weed in the autumn can be severely constrained by soil conditions. For spring-sown crops, mechanical weeding should commence as early as possible after the crop and weeds have emerged. Unlike harrowing, inter-row hoeing can be conducted at very early crop growth stages if crop protectors are used, such as those shown in Plate 1.

It may also be necessary to control weeds later in the growing season to prevent them from shedding seed. Data from inter-row hoeing in winter wheat indicated that weeding could be conducted at a late stage in the season (GS 55 = ¾ ear emerged) without incurring any yield penalty (Welsh *et al*., 1997). For pea crops, weeding cannot be continued after the tendrils have met across the rows as crop.

It is clear from the literature that inter-row hoeing using ducksfoot blades is capable of controlling a wide range of weeds, including both annual broad-leaved and grass species, at a wide range of growth stages. There is no information on the control of perennial weeds such as docks and couch grass, but it is anticipated that inter-row hoeing will not be effective against these types of weeds.

In terms of the overall efficacy of inter-row hoeing, reductions of weed density and biomass of up to 99 % have been reported (Böhrnsen, 1993; Rasmussen, 1993; Morrish, 1995; Welsh, 1998). However, yield benefits are typically much smaller, in the region of 4 - 5 % and only when crop damage is minimal (Böhrnsen, 1993; Hammarstöm *et al.,* 1993).

Plate 1. Inter-row hoeing using crop protectors at an early growth stage in sugar beet.

3.3 Cultivations at Hoeing Depth

Each tillage operation influences and often controls weed populations by covering, cutting and uprooting (Kouwenhoven, 1982). The differing root structure and growth habit of weeds means that the effectiveness of mechanical weed control will vary depending upon the type and size of weed. Jones *et al*. (1996) conducted pot experiments to investigate the effectiveness of these three modes of weed kill on grass and broad-leaved weeds. Four species of weed were chosen for their different root and growth habits: chickweed (a fibrous rooting prostrate broad-leaf weed); field poppy (a tap rooted broad-leaved rosette forming weed); annual meadow-grass (a prostrate annual grass) and rough-stalked meadow-grass (*Poa trivialis* L.) (an upright grass). Each treatment was conducted with a soil-based compost under dry and wet conditions. Cutting was done at either 1 cm above the surface, at the surface or 1 cm below the surface. There was also a treatment in which all leaves were removed and stems left intact. Burial was either partial or complete to a depth of 1 cm. Uprooting was done with the roots laid on the surface and with reburial after uprooting. Results showed that for broad-leaved weeds, uprooting (leaving the roots on the surface) and cutting at or below ground level were the most effective treatments, giving approximately 90% reductions in dry weight. The efficacy of these treatments was improved in dry conditions. Uprooting and reburial was also effective in dry conditions but poor (65 % reduction) in the wet, indicating the importance of ground conditions at or immediately after treatments. Relatively poor results (35 % - 70 % reduction) from cutting above ground and stripping indicate the importance of cultivation, as opposed to a mowing operation in controlling these weeds.

The results obtained by Jones *et al.* (1995) in grass weeds were broadly similar to those in broad-leaved weeds. One exception was that complete burial was always more effective (98 – 100 % reduction) irrespective of moisture. Uprooting grass on the other hand was even more sensitive to moisture than in broad-leaved weeds. Typically, reductions were 55 % for uprooting in wet conditions and 100 % in the dry.

Terpstra & Kouwenhoven (1981) investigated the depth of soil coverage necessary to kill weeds. They found 1.5 cm was lethal for small weeds and 2 cm for larger weeds. Their studies showed that increasing working depth from 2.5 cm to 4.0 cm gave only an 8 % increase in weed kill. Their experiments were conducted under laboratory conditions using only garden cress (*Lepidium sativum* L.) as a model weed.

Taken together, these results show the potential for improved weed control by selecting an appropriate tool to treat specific types of weed at particular moisture levels. For example, a tool that primarily has a below soil level cutting action may be appropriate to control broad-leaved weeds in dry conditions, but grass weeds in the wet may favour a tool that will result in a higher proportion of burial. However some caution is needed in the interpretation of these laboratory results conducted with a limited number of species.

Throughout the review and in industry it is apparent that there is much confusion over the names associated with hoe blades. Generally the soil-engaging component of the hoe is referred to as the blade, but this covers a wide range of designs. Reviewing literature has enabled us to draw together the various names and identify the design features that ensure each blade is consistently associated. Figure 3 identifies the important design features for blade classification.

Rake angle (α) is the angle of lift that the hoe blade has from the horizontal. A low rake angle will cause the blade to cut cleanly, with minimal soil disturbance. Increased rake angle generates more soil movement and mixing of the soil.

The sweep angle (γ) is the angle of the cutting face to a line perpendicular to the direction of travel. A compromise is needed between self-cleaning, effective cutting and draught force. A blade with a sweep angle of 30-50 degrees with a low rake angle, just enough to prevent scrubbing, (typically 2-5 degrees) is classified as a sweep.

When viewed in plan form sweeps either have ‘L’ or ’A’ blade profiles. Figure 3 shows an ‘L’ blade, illustrating the sweep angle and leg mounting. Often two ‘L’ blades of opposite hands are used as a pair and staggered with a trailing and leading blade so that trash or stones can flow between without causing blockages. It also enables the overall width to be adjusted to suit the crop growth stage and soil conditions.

‘A’ blades have a centrally mounted leg, with a swept cutting face on each side, with a low rake angle.
Variations of the ‘A’ blade come in the form of the ‘ducksfoot’. The difference is an increased rake angle, typically 20 degrees, that tends to displace more soil from between rows into the row.

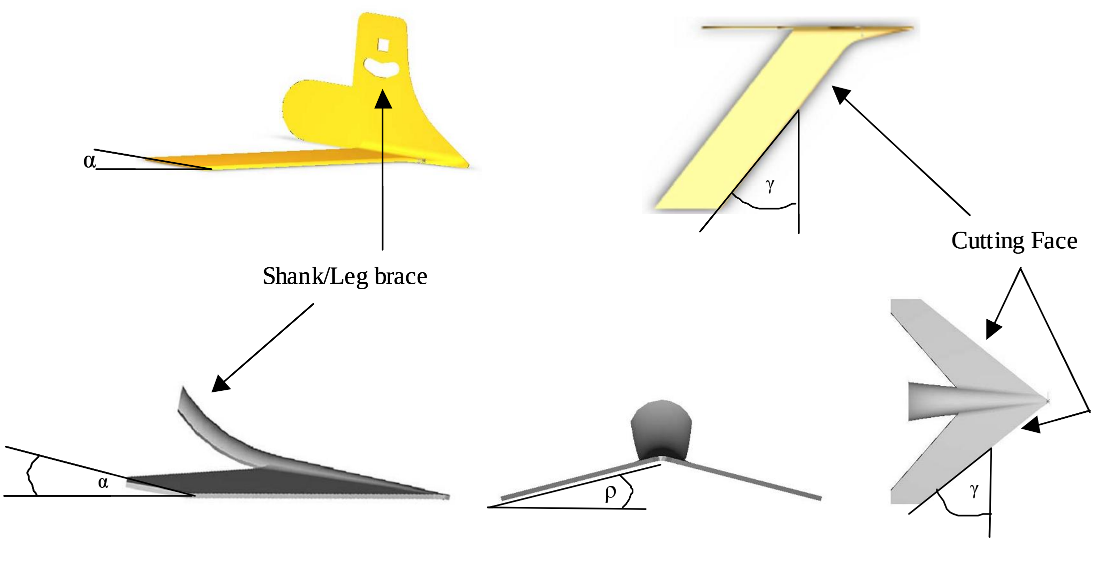

Figure 3. Hoe blade classification.

The tractor hoe is a generic name given to a tractor and toolbar mounted weeding mechanism (Plate 2).

Plate 2. Tractor hoe.

The important aspect of the tractor hoe is the weeding device itself, the soil engaging part of the hoe. Many different types of blades can be fitted to the hoe and this section gives an overview of the common types (Table 2 & Plates 3 – 12).

Table 2. Summary of commercial equipment

Hoe Device	Av. Speed	Depth mm	Weed Control	Mode of action	Weed size
Harrow	7 km h^{-1}	20-30 mm	Inter & Intra Row	Uprooting/burial	< 50 mm
Brush weeder	< 3.5 km h^{-1}	15-45 mm	Inter & Intra Row	Uprooting/burial	< 25mm
Split hoe	3 km h^{-1}	50 mm	Inter Row	Uprooting/burial	< 50 mm
Finger weeder	10 km h^{-1}	12-19 mm	Intra Row	Uprooting	< 25 mm
Torsion weeder	<10km h^{-1}	25 mm	Intra Row	Uprooting/burial	< 25 mm
Hoe ridger	7 km h^{-1}	25–40 mm	Inter & Intra Row	Burial/cutting/uprooting	Large
Subsurface tiller	8 km h^{-1}	100 mm	Inter Row	Cutting	Large
Powered rotary	6 km h^{-1}	120mm	Inter Row	Cutting/burial/uprooting	<150
Rotary cultivator	10 km h^{-1}	20-50 mm	Inter Row	Cutting/mixing	< 25 mm
Basket weeder	8 km h^{-1}	25 mm	Inter Row	Scrubbing, uprooting	< 20 mm
Sweep	6 km h^{-1}	20-40 mm	Inter Row	Cutting/burial/uprooting	Large
Ducks foot	6 km h^{-1}	20-40 mm	Inter Row	Cutting/burial/uprooting	Large

Plate 3. Sweep Blade

Plate 4. Ducksfoot

Plate 5. Basket weeder

Plate 6. Finger weeder

Plate 7. Torsion weeder

Plate 8. Split hoe

Plate 9. Horizontal brush weeder

Plate 10. Vertical brush weeder

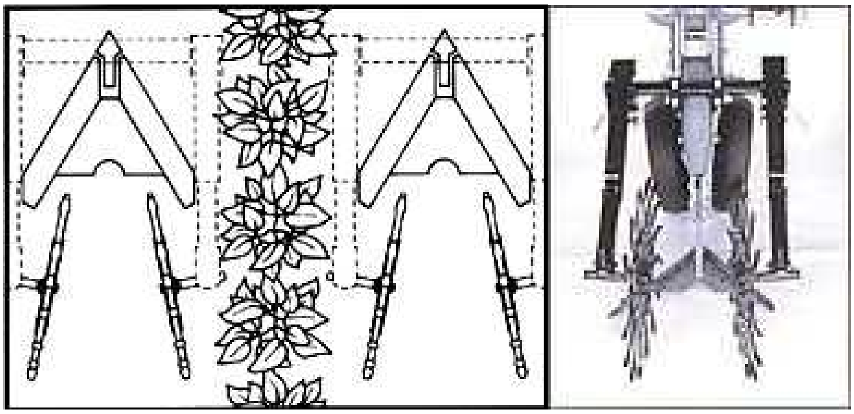

Plate 11. Rotary hoe

Plate 12. Powered rotary inter-row weeder

With a few exceptions much of the research on inter-row cultivation techniques for weed control, as reviewed above, has been of the form of field tests of one system against another. Whilst providing some valuable practical indications of efficacy and limitations they can only draw definite conclusions about the specific circumstances of the trial. That is, the weeds present, crop type, weather conditions etc. Such studies do little to further the scientific understanding of the detailed interactions that build up to provide the overall system. There would seem to be some merit in improving the detailed knowledge of each component of these systems. This would allow more analytical techniques to be used in designing weed control systems and in providing advice on how and when they should be used. Areas of interest might include: mechanisms of weed kill; influence of cultivation on the crop; improved understanding of the precision achieved in inter-row systems and soil/blade interaction as it relates to soil movement. Reducing draught force and design to avoid blockages formed by weeds or stones will also merit consideration as implements become larger and work rates higher.

Raising the level of science in mechanical weed control to a level closer to that already achieved in chemical control would advance the technology available to organic growers and make it more attractive to conventional farmers as part of an integrated strategy.

3.4 Mineralisation of Soil Bound Nitrogen

The factors described in the previous sections will potentially be influential upon the nutritional effects of the weeding operation, over and above that of simply reducing inter-plant competition. The effects will be mainly on the nitrogen dynamics of the soil/crop system, via greater oxidation of soil organic matter upon disturbance (Silgram & Shepherd, 1999). This should be most noticeable for clayey soils where a greater degree of physical protection is afforded organic matter in aggregates (until overcome by tillage) (Hassink, 1992). However, minor effects may also come from the recycling of nitrogen from the cut and buried weeds themselves, depending upon their size. The timing of the weeding operation will be of prime importance in determining whether any nitrogen flush from the operation is beneficial to the neighbouring crop, or merely adds to soil losses by leaching.

Both effects would contribute to a long-term net loss of soil nitrogen reserves through crop offtake, though mineralised nitrogen would be seen as a net gain to the annual crop system. In an organic crop production system, mineralised soil organic nitrogen would have to be replaced by returns of nitrogenous organic resources from outside the system, such as livestock manure or leguminous green manure. Returns of crop residues and weeds grown on site do not constitute such an input, as they merely recycle nitrogen taken from the soil on site, and a fraction of the nitrogen would once again enter physically protected long-term pools in the soil. Leaching losses are an accelerated extra loss, which would entail increased returns to compensate for the following crop.

Very few studies report any measurements of soil nitrogen to support and quantify this theoretical effect. Böhrnsen (1993) reported an increase in nitrate-nitrogen of the surface soil at 10-20 cm depth after weeding (4 & 18 days) with three types of harrow and tined weeders, but this was most noticeable after inter-row hoeing (but still only of the order of 4.5 kg ha^{-1} NO_3^- N). The effect was not statistically significant, however, but probably contributed to a small yield increase (2 %) due to the use of mechanical weeding. The effect was noticed on both silty loam and heavier alluvial clay loam soils, though a stiffer tined implement proved more effective on clay soils with a crusting surface.

Another study that focussed specifically on the potential of soil nitrogen mineralisation following mechanical weeding was that of Smith *et al.* (1994). In this study, soil mineral nitrogen concentrations (to 30 cm depth) and plant nitrogen concentrations were measured at the time of weeding, and at weekly intervals afterwards, in first and second wheat crops during 1993 & 1994. Harrowing with a spring tine weeder was carried out on five occasions from mid February to late April in 1993 in a winter wheat crop, which had been sown using non-inversion methods, and on two occasions in mid April in 1994, in spring wheat sown after conventional ploughing. In both years, measurements were compared with those taken from non-harrowed plots in the same crops. In 1993, the earlier harrow events produced little soil disturbance, though soil mineral nitrogen levels were marginally higher after these events compared to non-harrowed areas, by between 4 and 8 kg ha^{-1}. The later harrowings in March and April produced more soil disturbance but contributed little extra nitrogen. In fact, less soil nitrogen was measured after the later harrowings compared with non-harrowed plots after 41 kg ha^{-1} N (as fertiliser) was applied at the beginning of March (from 4 to 20 kg ha^{-1} N). There was, however, a tendency to maintain plant nitrogen concentrations around 3.8 - 4.1 % in the harrowed plots compared with a steady decline to about 3.1 % in the non-harrowed plots, though the difference in plant N offtake is not recorded. In 1994, no differences in soil or plant nitrogen contents, that could be attributed to harrowing events, could be detected. This difference between years was attributed to the tendency of non-inversion tillage methods to concentrate soil organic matter and nutrient reserves in the surface 10 cm of soil, where weeder tines would exert their maximum effect. However, it should also be noted that the 1993 crop followed oilseed rape, which leaves high nitrogen residues in the soil (Smith *et al.* 1994).

The above study did not record yields or grain nitrogen offtake, so any definite yield advantage cannot be ascribed to mineralised nitrogen from soil sources following weeding. However, a study by Welsh *et al.* (1997), which compared the weed suppression efficiency of spring tine and inter-row “ducksfoot” hoe weeders, used at various times in a crop’s early growth stages, did find a yield enhancement on a sandy clay loam soil. Statistically significant at P = 0.07, this enhancement (7.0-7.6 t ha^{-1} compared to 5.9 t ha^{-1} in unweeded plots, SED = 0.49) was found at levels of weed burden which should not have resulted in a competitive yield reduction. The effect was attributed to extra mineralised soil nitrogen mainly because grain nitrogen concentrations were similarly enhanced (1.66 - 1.78% compared to 1.58 % in unweeded plots, P = 0.322, SED = 0.076). However, the effect was not large, consisting of a total N offtake increase of only 3.5 kg ha^{-1} at the most, and was not evident at other sites.

From the limited amount of scientific literature available, it is apparent that any additional nitrogen derives from mineralised soil organic nitrogen, rather than recycled plant nitrogen from weed material incorporated into the soil. The difference in weed dry matter in May between weeded and unweeded plots in the work of Welsh *et al.* (1997) was of the order of 20-30 kg ha^{-1} dry matter which, even at an assumed N concentration of 2 % represents only 0.5 kg ha^{-1} N! On the other hand, several studies reviewed by Silgram & Shepherd (1999) pointed to a nitrogen flush of between 5 and 25 kg ha^{-1} N after ploughing or similar cultivation impact. If carried out in the autumn, much of this increased mineralisation results in increased leached nitrogen (Goss *et al.,* 1993).

3.4 Impact of Inter-Row Hoeing on Ground-Nesting Birds

It has been reported that mechanical weeding might have detrimental side effects such as damage to populations of beetles, other soil fauna, and ground nesting birds *(*Jones *et al*., 1996; Fuller, 1997). There has been very little work that has looked directly at this question. However, research has shown that organically-cropped fields supported significantly higher skylark densities throughout the breeding season than intensively cropped fields or grazed pasture (Wilson *et al*., 1997).

Whilst it might be anticipated that harrowing would disrupt ground-nesting birds, since the entire soil surface is cultivated, the impact of inter-row hoeing is less certain, where only 70 – 80 % is cultivated.

The level of disruption will be influenced by two factors:

1. The time at which skylarks nest in relation to the lifecycle of crop and weeds.
2. The position of skylark nests in relation to the crop row.

Skylarks (*Alauda arvensis*) nest between April and August (Gibbons *et al*., 1993). Wilson *et al*. (1997) suggest that skylarks must complete 2 - 3 nestings per season in order for populations to be self-sustaining. For winter-sown cereals, weeding should already have been completed before nesting takes place. The main problem is with spring sown crops as optimum weeding and nesting times coincide. However, inter-row hoeing may be less detrimental than harrowing due to its greater efficacy (Davies & Welsh, 2002) requiring less weeding treatments to maintain adequate control. Also, since inter-row hoeing can control mature weeds (Böhrnsen, 1993; Rasmussen, 1993; Morrish, 1995), weeding could be delayed to allow skylarks to achieve at least 2 successful nestings. However, this delay could be at the expense of crop yield.

If weeding must take place during the nesting season, the level of disruption will depend on where the birds nest in relation to the crop row. If skylarks nest in or next to the crop row then inter-row hoeing should not destroy the nest, although soil coverage may result. Clearly, if skylarks nest in between the crop rows, then hoeing is likely to be significantly more detrimental, although the absolute levels of damage are unknown and will depend on the type of cultivator used. There is some evidence from Leake (*pers comm*.) that suggests skylarks prefer to nest directly adjacent to crops rows rather than in the open tramline spaces (Plates 13 & 14).

Plate 13. Skylark chicks nesting in narrowly spaced winter barley crop rows.
Photograph by Katheryn Murray.

Plate 14. Skylark nest with eggs next to the winter wheat crop row adjacent to a tramline. Photograph by Katheryn Murray.

Sowing in wide rows might, in itself, encourage more skylarks to nest in the crop. Wilson *et al*. (1997) concluded that skylark density was lowest in fields with dense vegetation cover. Winter cereals in both conventionally and organically managed fields will typically have reached complete ground cover during the early part of the skylark nesting period. Sowing crops in a wide row spacing, such as those required for inter-row hoeing, may open up the crop canopy sufficiently to provide a better habitat for skylarks and other ground nesting bird species. The Allerton Research & Educational Trust at Loddington in Leicestershire is currently addressing this question (Leake, pers comm.).

4. CONCLUSIONS

4.1 Seed Rate and Row Spacing

- The yield of both cereal and pulse crops can be significantly affected by the spatial arrangement of the crop.
- Within limits, increasing seed rate can improve crop yield and reduce weed development in the crop when sowing at normal row spacings (e.g. 12.5 cm).
- Sowing cereal crops at row spacings greater than 12.5 cm can result in a reduction of yield of the order 5 – 10 %. This effect is particularly acute when high crop seed rates are used, such as those employed in organic systems. Selecting an appropriate sowing arrangement and/or reducing seed rate in widely spaced crop rows can overcome this negative effect. Weed development was generally unaffected by row spacing.
- Pulse crops such as field beans, combining and vining peas can be successfully grown at row spacings that facilitate inter-row cultivation for weed control without any need for adjustment over normal practice.

4.2 Timing and Frequency of Inter-Row Hoeing

- The weeds that emerge with or shortly after the crop can be the most serious in terms of the competitive effect against the crop. However, the time of onset of competition and its duration are affected by a large number of factors. Later emerging weeds, whilst not affecting yield as seriously, may still require control to stop seed shedding. Therefore, mechanical weed control should be targeted at an early stage in the growing season to control early germinating weeds.

- Inter-row hoeing using ducksfoot blades can control a wide range of broad-leaved and grass weeds at a wide range of growth stages.

- Crop damage can result from inter-row hoeing, but the latest developments in automated guidance and careful cultivation tool selection can overcome this problem.

- Reductions of weed density and biomass of up to 99 % can be achieved with inter-row hoeing, but crop yield response is generally much smaller. Hoeing on two occasions can provide significantly better reductions in weed biomass than hoeing once, but hoeing more frequently than this offers little additional benefit. In terms of the control of weeds, the exact timing or frequency of weeding was unimportant, but, at certain times, inter-row hoeing can stimulate a flush of weed emergence.

4.3 Cultivations at Hoeing Depth

- Simple blades such as the “ducksfoot” offer effective low cost solutions, but tend to cause excessive soil disturbance at high speed. Flatter A or L shaped sweep blades cause less soil disturbance and maybe, therefore, appropriate at higher speeds and at earlier crop growth stages.

- Rolling cultivators may provide improved performance at early growth stages and at high speed but at an increased cost.

- Relatively little is known about the mechanisms of weed kill and the detailed interaction between the blade, the weed and the soil.

- The efficacy and efficiency of mechanical weed control could be improved if the underlying science was better understood.

4.4 Mineralisation of Soil Bound Nitrogen

- Cultivation to depths of 15-30 cm can lead to 5-25 kg ha^{-1} more nitrogen mineralised than soil management by zero-tillage methods.

- Weeders disrupt the soil surface to depths of less than 10 cm (typically 2-5 cm), and possibly release about 5 kg ha^{-1} N.

- Much of the mineralised N from autumn cultivation is lost to over winter leaching.

- Increases in soil organic nitrogen mineralisation upon physical disruption are larger on clays and clay loams than sandy material soils.

- Mineralisation rates are higher at higher soil temperatures and lower soil moisture deficit levels.

4.5. Impact of Inter-row Hoeing on Ground-Nesting Birds

- At present, there is very little information about the effects of inter-row hoeing and its associated agronomic practices on ground nesting bird populations. A lot will depend on where these bird species nest in relation to crop rows, but the timing and frequency of weeding may need to be altered to minimise impact, particularly in spring-sown crops. It is conceivable that there may also be beneficial effects from the agronomic practices associated with inter-row hoeing, if widely spaced crop rows provide a good habitat for nesting.

5. RECOMMENDATIONS FOR FARMERS

5.1 Seed Rate and Row Spacing

- To minimise any yield penalty, consider reducing seed rates when sowing cereals at a wide row spacing (20 – 25 cm). The exact reduction is uncertain for organic systems, but it may be in the order of 10 – 20 % compared with a standard seed rate. Alternatively, band sow the crop at a wide spacing to minimise the competitive effects.

- If the drill configuration permits, consider sowing a twin row arrangement leaving a wide gap between twin rows for inter-row hoeing.

- For pulse crops, sow at 20 cm for peas and 17 to 35 cm for spring-sown field beans.

5.2 Timing and Frequency of Inter-Row Hoeing

- Consider early weeding treatments to control weeds that emerge with or shortly after the crop, as these are the ones that are likely to have the most significant effect on crop yield. Weeding later in the season may also be required to prevent weeds setting seed.

- Weeding on two occasions with ducksfoot blades appears to provide good levels of weed control. Weeding more frequently than this offers very little additional benefit. However, this will depend on the success of each weeding operation.

5.3 Cultivations at Hoeing Depth

- Accurate guidance is the key to the efficiency and efficacy of inter-row cultivation. Automatic guidance systems provide high accuracy at relatively high workrates, but well designed manual systems operated by skilled operators are capable of adequate precision.

- Ducksfoot hoe blades mounted on spring tines provide a relatively low cost and robust general purpose tool for arable inter-row cultivation in a variety of soil types.

- For early hoeing, side guards can be used to protect the crop from burial. An alternative lighter option is to use L or A blades with low rake angles that create less lateral soil movement.

6. RECOMMENDATIONS FOR FUTURE RESEARCH

- The interaction of seed rate and row spacing has not been determined under organic conditions for any of the arable crops reported here. It is recommended that studies be conducted under organic management to confirm the findings reported for non-organic systems.

- Very few studies have looked at the timing and frequency of inter-row hoeing in organically managed arable crops. Whilst the theory would suggest that early weeding treatments would provide the greatest benefits, there is very little practical evidence for this, as crop damage has tended to mask the benefits from weed control. It is recommended that research should evaluate the latest automated guidance hoeing equipment to determine the optimum timing and frequency for weed control, when crop damage is minimal. Also, the research should determine the range of operating timings for this equipment in terms of the earliest and latest growth stages that it can be safely used, without causing unnecessary crop damage.

- It is recommended that future research should be aimed at improving the understanding of the mechanisms by which different weed types can be killed mechanically under different soil and moisture conditions and at different growth stages. Also, further research is required to improve the understanding of the physical interaction between cultivation tools, soil, crop, and weeds under a range of operating conditions. Progress in these two areas needs to be linked and would lead to improved tool/implement design and better advice for farmers on how to use them. This would in turn improve efficacy, increase workable days, give higher workrates, reduce energy consumption and generally make mechanical weed control a more practical option.

- It is suggested that further research is required to identify the direct impact of inter-row hoeing on ground-nesting birds, taking account of both the position of skylark nests in relation to crop rows and the timing and frequency of weeding. Research in this area should be built on the findings from The Allerton Research & Educational Trust project as they are reported.

7. OUTPUT FROM THE PROJECT

WELSH JP, TILLETT ND, HOME M & KING JA (2002) A Review of Knowledge: Inter-row hoeing and its associated agronomy in organic cereal and pulse crops. Final report from DEFRA Funded Project OF0312.

WELSH JP, TILLETT ND, HOME M & KING JA (In Preparation) A Review of Knowledge: Inter-row hoeing and its associated agronomy in organic cereal and pulse crops. *Weed Research*.

WELSH JP, TILLETT ND, HOME M & KING JA (In Preparation) Executive Summary of A Review of Knowledge: Inter-row hoeing and its associated agronomy in organic cereal and pulse crops. *EFRC Bulletin*.

8. REFERENCES

ANDERSSON B (1986) Influence of crop density and spacing on weed competition and grain yield in wheat and barley. In: *Proceedings European Weed Research Society Symposium on Economic Weed Control*, Wageningen, The Netherlands, 121-128.

BISHNOI UR (1980) Effect of seeding rates and row spacing on forage and grain production of triticale, wheat and rye. *Crop Science* **20**, 107-108.

BLAIR AM, JONES PA, ORSON JH & CASELEY JC (1997) Integration of row widths, chemical and mechanical weed control and the effect on winter wheat yield. *Aspects of Applied Biology* **50**, 385-392.

BÖHRNSEN A (1993) Several years' results about mechanical weed control in cereals. In: *Proceedings of the Fourth International Conference IFOAM – Non Chemical Weed Control*, Dijon, France, 93-99.

BOWERMAN P & COOK SK (1991) Winter beans – effect of sowing date, plant population and method of establishment on two soil types. *Aspects of Applied Biology* **27**, 85-88.

BULSON HAJ, SNAYDON RW & STOPES CE (1997) Effects of plant density on intercropped wheat and field beans in an organic farming system. *Journal of Agricultural Science, Cambridge* **128**, 59-71.

CARLSON HL & HILL JE (1985) Wild oat (*Avena fatua*) competition with spring wheat: Plant density effects. *Weed Science* **33**, 176-181.

CHAMPION GT, FROUD-WILLIAMS RJ & HOLLAND JM (1998) Interactions between wheat (*Triticum aestivum* L.) cultivar, row spacing and density and the effect on weed suppression and crop yield. *Annals of Applied Biology* **133**, 443-453.

COUSENS R (1985) An empirical model relating crop yield to weed and crop density and a statistical comparison with other models. *Journal of Agricultural Science* **105,** 513-521.

COUSENS R, BRAIN O, O'DONOVON JT & O'SULLIVAN A (1987) The use of biologically realistic equations to describe the effects of weed density and relative time of emergence on crop yield. *Weed Science* **35,** 720-725.

CUDNEY DW, LOWELL SJ, HOLT JS & REINTS JS (1989) Competitive interactions of wheat (*Triticum aestivum*) and wild oats (*Avena fatua*) grown at different densities. *Weed Science* **37,** 538-543.

CUSSANS GW & WILSON BJ (1975) Some effects of crop row width and seedrate on competition between spring barley and wild oat *Avena fatua* L. or common couch *Agropyron repens* (L) Beauv. In: *Proceedings of the European Weed Research Society Symposium on the Status and Control of Grassweeds in Europe*, 77-86.

DALY JM & STEVENSON KR (1990) Weeds in organic cereal crops in New Zealand: Some preliminary findings. In: *Proceedings 3rd International Conference on Non-Chemical Weed Control*, Linz, Austria, 55-64

DAVIES DHK & WELSH JP (2002) Weed control in organic cereal and pulses. In: *Organic Cereals and Pulses* (Eds) D Younie, BR Taylor, JP Welsh & Wilkinson JM. Chalcombe Publications, Lincoln, UK, 77-114.

DIERAUER HU (1990) Efficiency of different implements in combination with variation of seed distance in mechanical weed-control. In: *Proceedings 3rd International Conference on Non-Chemical Weed Control*, Linz, Austria, 79-90.

FINLAY RC, REINBERGS E & DAYNARD TB (1971) Yield response of spring barley to row spacing and seeding rate. *Canadian Journal of Plant Science* **51**, 527-533.

FULLER RJ (1997) Response of birds to organic arable farming: Mechanisms and evidence. In: *Proceedings of the 1997 Brighton Crop Protection Conference – Weeds*, Brighton, UK, 897-906.

GERMEIER CU (2000) Wide row spacing and living mulch: New strategies for producing high protein grains in organic cereal production. *Biological Agriculture and Horticulture* **18**, 127-139.

GIBBONS DW, REID JB & CHAPMAN RA (1993) *The New Atlas of Breeding Birds in Britain and Ireland: 1988-1991*. Poyser, London. 520 pp.

GODEL GL (1935) Relation between rate of seeding and yield of cereal crops in competition with weeds. *Scientific Agriculture* **16**, 165-168.

GOSS MJ, HOWSE KR, LANE PW, CHRISTIAN DG & HARRIS GL (1993) Losses of nitrate-nitrogen in water draining from under autumn-sown crops established by direct drilling or mouldboard ploughing. *Journal of Soil Science* **44**, 35-48.

GREENWOOD DJ, GASTAL F, LEMAIRE G, DRAYCOT A, MILLARD P & NEETESON JJ (1991) Growth rate and %N of field grown crops: theory and experiments. *Annals of Botany* **67**, 181-190.

GRIEPENTROG HW, WEINER J & KRISTENSEN L (2000) Increasing the suppression of weeds by varying sowing parameters. In: *Proceedings 13th International Scientific Conference IFOAM,* Basel, Switzerland, 173.

GRUNDY AC, FROUD-WILLIAMS RJ & BOATMAN ND (1993) The use of cultivar, crop seed rate and nitrogen level for the suppression of weeds in winter wheat. In: *Proceedings Brighton Crop Protection Conference – Weeds*, Brighton, UK, 997-1002.

HAMMARSTRÖM L, GILLBERG B & PETTERSSON H (1993) Inter-row cultivation in cereals. In: *Proceedings 4th International Conference IFOAM on Non-Chemical Weed Control*, Dijon, France, Theme 5 Posters.

HASSINK J (1992) Effects of soil texture and structure on carbon and nitrogen mineralisation in grassland soils. *Biology and Fertility of Soils* **14**, 126-134.

HOLLIDAY R (1963) The effect of row width on the yield of cereals. *Field Crop Abstracts* **16**, 71-81.

JONES PA, BLAIR AM & ORSON JH (1995) The effect of different types of physical damage to four weed species. In: *Proceedings 1995 Brighton Crop Protection Conference - Weeds,* Brighton, UK, 653-658.

JONES PA, BLAIR AM & ORSON (1996) Mechanical damage to kill weeds. In: *Proceedings of the Second International Weed Control Congress*, Copenhagen, Denmark, 949-954.

KOSCELNY JA, PEEPER TF, SOLIE JB & SOLOMON SG (1990) Effect of wheat (*Triticum aestivum*) row spacing, seeding rate, and cultivar on yield loss from cheat (*Bromus secalinus*). *Weed Technoogy* **4**, 487-492.

KOUWENHOVEN JK (1982) Weed control by Tillage Tools. In: *Proceedings 9th Conference of the International Soil Tillage research Organisation,* Istro, Socialistic Fedral Fepublic of Yougoslavia, Osijek, *262-268*

KROPFF MJ, LOTZ LAP & WEAVER SE (1993) Practical Applications. In: *Modelling Crop-Weed Interactions*, (Eds) MJ Kropff & HH van Laar, CAB International, Oxford, 149-166.

KROPFF MJ, WEAVER SE & SMITS MA (1992) Use of ecophysiological models for crop-weed interference: Relations amongst weed density, relative times of weed emergence, relative leaf area, and yield loss. *Weed Science* **40**, 296-301.

LAMPKIN N & MEASURES M (2001) *2001 Organic Farm Management Handbook (4th Edition).* (Eds) N Lampkin and M Measures. University of Wales, Aberystwyth, UK & Elm Farm Research Centre, Newbury, UK.

LEAKE AR (pers. Comm..) Allerton Research & Educational Trust, Loddington House, Main Street, Loddington, Leicestershire LE7 9XE, UK.

MORRISH CH (1995) Aspects of mechanical and non-chemical weed control in forage maize. *Unpublished PhD thesis, Wye College, University of London*.

OLSEN JM, KRISTENSEN L, GRIEPENTROG HW & WEINER J (2002) Effects of crop density, spatial uniformity and weed species on competition with spring wheat (*Triticum aestivum*). In: *Proceedings of the 5th European Weed Research Society Workshop on Physical Weed Control*, Pisa, Italy, 45.

PGRO (1991) *Information Sheet No. 155 Plant density & Row width recommendations for vining peas, green beans and broad beans*. Processors & Growers Research Organisation, Peterborough, UK.

PGRO (1996) *Information Sheet No. 156 Plant density & Row width recommendations for combining peas and field beans*. Processors & Growers Research Organisation, Peterborough, UK.

RASMUSSEN J (1993) Can high densities of competitive weeds be controlled efficiently by harrowing or hoeing in agricultural crops? In: *Proceedings 4th International Conference IFOAM on Non-Chemical Weed Control*, Dijon, France, 83-87.

SILGRAM M & SHEPHERD MA (1999) The effects of cultivation on soil nitrogen mineralization. *Advances in Agronomy* **65**, 267-311.

SMITH SP, ILES DR & JORDAN VWL (1994) Nutritional implications of mechanical weeding intervention for weed control in integrated farming. *Aspects of Applied Biology* **40**, *Arable farming under CAP reform*, 403-418.

TAYLOR BR & YOUNIE D (2002) The effects of cultural practices on crop and weed growth in organic spring oats. In: *Proceedings 5th European Weed Research Society Workshop on Physical Weed Control*, Pisa, Italy, 57-66.

TERPSTRA R & KOUWENHOVEN JK (1981) Inter-row and intra-row weed control with a hoe ridger. *Journal of Agricultural Engineering Research* **26,** 127-134.

WELSH JP (1998) Developing strategies for weed control in organic arable systems. *Unpublished Ph.D. Thesis, Departments of Agricultural Botany and Agriculture, University of Reading*.

WELSH JP, BULSON HAJ, STOPES CE, FROUD-WILLIAMS RJ & MURDOCH AJ (1997) Mechanical weed control in organic winter wheat. *Aspects of Applied Biology,* **50***: Optimising cereal inputs: Its scientific basis. Part 2: Crop protection systems,* 375-384.

WELSH JP, BULSON HAJ, STOPES CE, FROUD-WILLIAMS RJ AND MURDOCH AJ (1999) The critical weed-free period in organically-grown winter wheat. *Annals of Applied Biology* **134**, 315-320.

WILSON JD, EVANS, J, BROWNE SJ & KING JR (1997) Territory distribution and breeding success of skylarks (Alauda arvensis) on organic and intensive farmland in southern England). *Journal of Applied Ecology* **34**, 1462-1478.

WILSON BJ & WRIGHT KJ (1990) Predicting the growth and competitive effects of annual weeds in wheat. *Weed Research* **30**, 201-211.