Weed control in organic cereals and pulses

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INTRODUCTION

Weeds remain one of the most significant agronomic problems associated with organic arable crop production. It is recognised that a low weed population can be beneficial to the crop as it provides food and habitat for a range of beneficial organisms (Millington *et al*., 1990; Clements *et al*., 1994; Aebischer, 1997; Fuller, 1997; Patriquin *et al*., 1998). However, above critical population thresholds, weeds can significantly reduce crop yield and quality in conventional (Cussans, 1968; Hewson *et al*., 1973; Cousens, 1985; Cudney *et al*., 1989) and organic (Bulson, 1991) crops alike. The challenge for organic farmers is to manage weeds in such a way as to accommodate their beneficial effects whilst still producing an acceptable crop.

PREVENTATIVE WEED CONTROL TECHNIQUES

The aim of weed management strategies in organic farming is to maintain weed populations at a manageable level through a range of husbandry approaches throughout the rotation, which means that direct control actions within the individual crop have a greater surety of success. It is important to consider weeds as part of the biodiversity of the farm, so management is the general philosophy rather than eradication. Biodiversity is seen as both an indicator of ecological health, and the weeds themselves are an important food source, both directly and indirectly, for a whole range of beneficial fauna. There may be a few situations in crop seed production where the avoidance of spreading weed seeds is required; notably difficult to control or clean-out weed seeds such as wild-oat, couch-grass and perennial broad-leaved weeds. It is important that seed is not produced in fields with such weeds where they cannot be readily rogued-out. Aside from the key strategy of not growing seed crops in seriously weedy fields, there is a wide range of weed suppressing strategies that have to be considered in an organic rotation:

- Crop rotation
- Choice of crop species
- Choice of variety/cultivars
- Use of stale and false seedbeds
- Time of sowing
- Seed quality
- Seed rate
- Cultivations in darkness
- Crop architecture
- Direction of sowing
- Crop vigour
- Undersowing in cereals and mixed cropping
- Inter-cropping
- Clean harvesting
- Allelopathy

Crop rotation

Crop rotation is a key factor in determining the absolute levels of weeds in crops in the rotation, as well as having an effect on the relative abundance of different weed species. Results from rotational plot trials at SAC at two Scottish sites clearly show the impact of increasing the proportion of arable crops in the rotation on the weed seedbank (Table 1).

Table 1. Effect of percentage of arable crops in preceding years on the weed seedbank populations (No seeds m^{-2} to 20cm depth) (Younie et al., 1996).

% Arable Crops	Tulloch	Woodside
0	16,800	-
25	32,875	19,200
50	29,360	38,867
75	56,700	44,967

Davies *et al.* (1997), surveying the farm rotations at one of the same farms (Woodside) and another farm in Fife, and comparing local conventional fields, confirmed the beneficial impact of grass in the rotation (Table 2).

Table 2. Impact of grass in the rotation on mean numbers of weed seeds m^{-2} to 20cm depth over 4 seasons (Davies et al., 1997).

	Year 1	Year 4
Jamesfield		
Conventional rotation *	5,710	12,167
Rotations with grass	26,092	17,782
Rotations with no grass	25,276	42,141
Woodside		
Conventional rotation*	10,500	16,000
Rotations with grass for <2years	22,140	45,857
Rotations with grass for >2years	21,688	40,438
Rotations without grass	29,500	153,999

*Conventional arable rotation, with herbicides.

Grass in the rotation for two or more years reduced weed seedbanks at Jamesfield, and weed seedbank changes over early years after conversion at Woodside were greatly reduced. This was reflected in weed numbers in the crops (Table 3), with significant reductions in weed numbers where there was more than two years of grass in the rotation.

Table 3. Impact of number of seasons of grass in organic rotations on weed numbers (log + 1)/$0.25m^{-2}$ (Davies et al., 1997).

	Number of Seasons in grass		Significance
Year	**0**	**3+**	
1	3.89	2.02	*
4	3.51	1.68	**
1 → 4	-0.38	-0.35	*

≤0.05; ** ≤0.01

Further observations from these farms have shown improved weed management as both farms increased the grass component of the rotation.

Grass leys are feasible where stock plays a part in the rotation, either direct grazing or through hay or silage use. However, on many farms grass leys cannot be considered except possibly for fertility building during periods of set-aside. On such farms breaks in the arable rotation are often only one- to two-year-long green manure crops, with undersowing acting as one season. In these cases the influence of other crops in the rotation will affect weed population increases. Bulson *et al*. (1996) showed that, after an initial red clover break, successive wheat crops gave the highest weed increase, whereas including potatoes, in which weed control can be very successful, and the more competitive oat crop in the rotation with wheat improved weed management (Table 4). Winter beans in the rotation did not have a beneficial effect on weed number build-up.

Table 4. Weed dry matter at harvest (g m^{-2}) as affected by course of rotation (Bulson *et al*., 1996).

Course of rotation	Weed dry matter (dm, g m^{-2})
RC/WW	151
RC/WW/WW	178
RC/WW/WW/SO	115
RC/POT/WW	115
RC/POT/WW/WO	79
RC/WW/WBN/WW	129
Significance	***

Note: RC= red clover, WW= winter wheat, SO= spring oats, POT=potato, WO=winter oat, WBN=winter beans

Nevertheless, the long-term control of weed density within stockless rotations is difficult, and further work is required into undercropping and break crops as aids in both annual weed management and fertility development. The control of perennial weeds appears to be a particular problem in such rotations in comparison with long grass-break rotations (Cormack, 1997). Furthermore, later crops in long runs of arable cropping will tend to be less vigorous, and therefore less competitive against weeds, allowing annual weed seed banks to build up.

Individual species population changes have been compared by Davies *et al*. (1997), and grass in the rotation appeared to increase meadow-grass (*Poa spp*) and possibly mayweed (*Matricaria spp*) numbers, but most annual weed species were encouraged by no grass in the rotation; notably *Polygonum spp*, fat-hen (*Chenopodium album*) and spurrey (*Spergula arvensis).*

Choice of Species

The choice of crop species is usually dictated by economic factors. However, where selection can be made, the suppressive effect on weeds is an important factor. Amongst the cereals, the most competitive are probably oats and winter rye, followed by triticale, barley and wheat. Bertholdson and Jonsson (1994; vide Taylor *et al*., 2001) noted that barley appears to compete with weeds mostly for below ground resources, whereas in oats and wheat competition for light seems more important (Eisele and Kopke, 1997, Lemerle *et al*., 1996; Gooding *et al*., 1997). However, even in barley, above ground canopy development and shading will play an important part in weed growth suppression. Nevertheless, trials at Elm Farm Research Centre (EFRC) in 2000 clearly showed the value of triticale and oats in terms of weed suppression (Figure 1). Winter wheat, spring wheat and spring barley were less competitive and experienced higher weed levels. In Figure 1, winter wheat is shaded dark; triticale and oats are light.

Although it is sometimes considered that spring varieties are more competitive, later sown well-established winter crops can give good suppression of spring emerging weeds. Nevertheless, the short, upright growth habit of many modern winter wheats is not suited to good weed suppression.

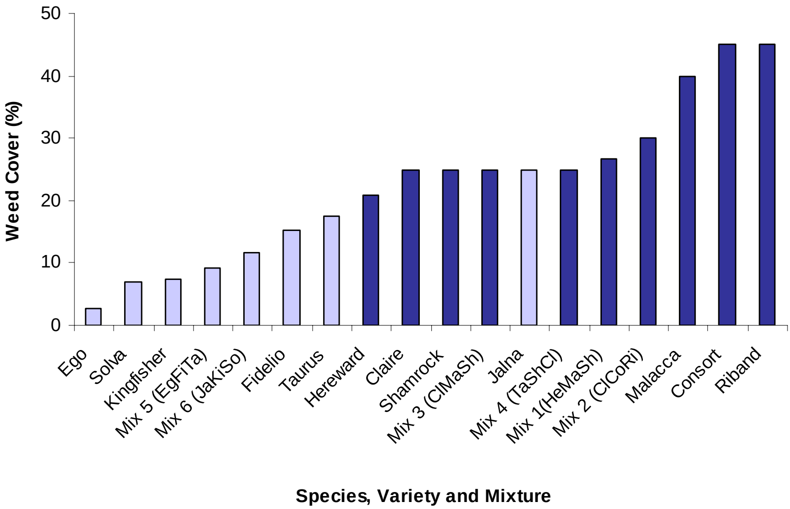

Figure 1. The effect of winter cereal species, variety and varietal mixture on weed cover (%) (Assessed Jul 2000).

Amongst the pulses, field beans, once early weed competition is controlled, tend to grow over later emerging weeds and smother them out. Peas, being much shorter, are more likely to succumb to weeds. The semi-leafless nature of many modern varieties allows more light to penetrate through to the weeds.

Choice of Variety

Richards and Davies (1991), amongst others, have shown that, in conventional systems, increased early prostrate ground cover in wheat and spring barley cultivars reduced weed emergence and early growth. Eisele and Köpke (1997) confirmed that in organic systems, wheat with planophile rather than erectrophile leaves gave increased ground shading during growth, which could significantly decrease weed biomass.

It has been shown that older, taller cultivars of wheat such as Maris Widgeon also reduced the penetration of photosynthetically active radiation into the crop (Cosser *et al.*, 1997). Reducing the plant height of Maris Widgeon through introduction of dwarfing genes, increased weediness (Cosser *et al.*, 1995). However, further trials (Cosser *et al.*, 1997) also showed that tall Maris Widgeon was not always the best variety at suppressing weeds compared with some shorter modern varieties. Eisele and Köpke (1997) also indicate that tallness is not the only or prime character, and that good overall shading ability is more important.

The new European Union funded WECOF project will attempt to evaluate the relative importance of early and later leaf angle development and height and speed of development on light penetration and weed suppression in wheat, so that farmers will be able to make better choices amongst available varieties, and breeders will more readily be able to select characteristics that favour weed suppression. It must be accepted, however, that such characteristics in practice may prove secondary to yield benefits and disease protection, so an economic analysis of such benefits will also be undertaken within WECOF (Davies and Hoad, personal communication). In the WECOF core trial first season, at the main UK site in East Lothian, the varieties showing greatest weed suppression are firstly a German variety used on organic farms, Pegassos, and secondly the UK variety, Rialto. These varieties show the best crop ground cover and crop biomass throughout the growth stages of the crops. Pegassos is marginally taller than Rialto. Yield assessments had just been taken at the time of writing this paper, and these varieties also gave the best yield. There are further trials in progress with a wider range of varieties.

There has been less work on other cereal crops, but it must be assumed that the principles that apply to wheat are likely to apply throughout cereal types. Notably that ground cover and shading are key features. Identifying and comparing suitable cultivar types amongst other cereal species will be examined within projects at SAC associated with WECOF. It is clearly evident from various workers that cultivar architecture is closely related to aspects of crop architecture in terms of weed suppression and the WECOF project also seeks to integrate these two areas.

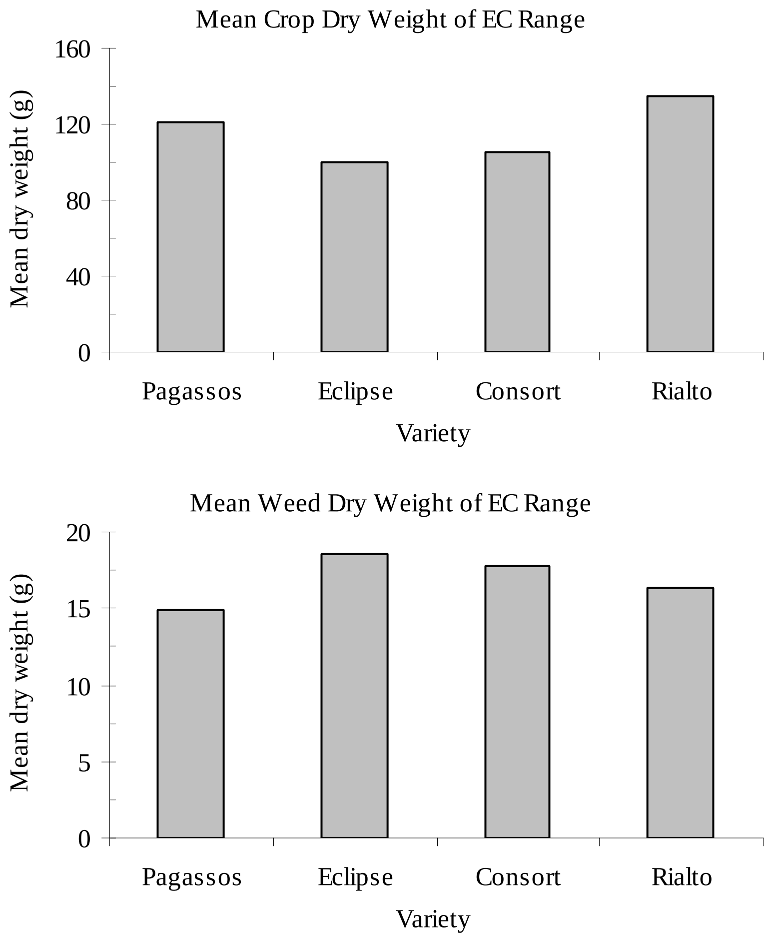

Figure 2. Wheat variety and weed biomass dry weights throughout the Growth Stages (EC) at WECOF Core Trial, Colstoun Mains 2001.

The possibility of using mixtures of varieties for weed suppression is less well researched, but work at EFRC is showing that mixtures can work as well as the best component (Figure 3).

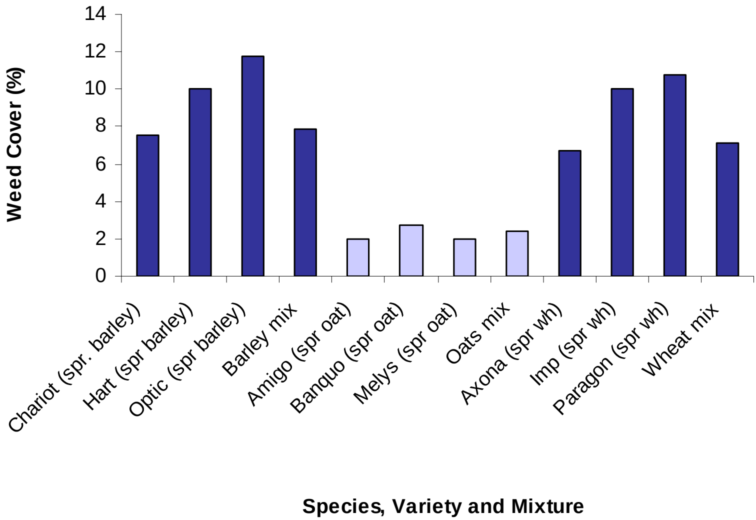

Figure 3. The effect of spring cereal species, variety and varietal mixture on weed cover (%) (Assessed Jun 2000).

There has been less work on varietal differences amongst pulses, but Grevsen (2000) in Denmark has found significant differences between pea cultivars in weed suppression (Table 5). The most competitive types were larger peas, and not semi-leafless.

Stale and False Seedbeds

This technique involves preparing the seedbed several weeks before sowing in order to stimulate a flush of weeds, so reducing the weed seedbank likely to affect the crop. Moist conditions are essential to encourage weed emergence. The small weeds can then be removed with a very shallow harrow, or with a flame-weeder or infra-red burner.

It is preferable if this is linked with later sowing in the spring as use too early may coincide with low soil temperatures and miss important weed emergence periods. In winter crops delayed sowing is preferred because major weed problems can be greatly reduced, and this also gives an opportunity for stale seedbed approaches. The small loss in yield possible from delayed sowing is balanced by the reduced losses due to weeds.

Table 5. Dry weight of weeds and number of weed plants at harvest in pea cultivars (from Grevsen, 2000)

Cultivar	Dry weight weeds (gm^{-2})		No of weeds (m^{-2})	
Dinos	160	a	348	a
Argona	154	a	274	ab
Kermit[1]	140	a	228	ab
Bella[1]	136	a	261	ab
Rani	117	ab	273	ab
Ambassador	88	b	180	b
Greenshaft	80	b	237	ab
Jaguar	80	b	186	b

Means followed by the same letter are not significantly different (P = 0.05); -[1] semi-leafless types.

Time of Sowing

Early sowing of winter cereals and pulses increases weed populations significantly (Lesser *et al.*, 1996), and it is generally advised that in the UK drilling after mid-October is optimum for wheat to minimise weed competitiveness. There will be local differences, and early October may be preferred for beans for weather reasons where soil types are heavy, and generally in northern and western regions.

In spring cereals and pulses, allowing time for a stale seedbed approach (see above) assists in reducing weed problems in the crop. Otherwise it is difficult to avoid weed emergence with the crop.

Seed Quality

It is clear that good crop establishment and early vigour, important for weed suppression, is linked to the quality of seed used. Currently, undressed conventional seed can be used with derogation (up to 31 December 2003) because of the limited organic seed availability, although that is changing. If farmers use their own seed, there may be a problem. A small trial at Elm Farm Research Centre (EFRC) has shown lower germination and vigour in home-saved spring wheat than in untreated brought-in conventional seed.

The fact that seed remains untreated has presented problems where head diseases are widespread. In season 2000, German and French seed producers found high levels of *Fusarium* in wheat seed, which entailed more conventional seed being used than expected. Seed testing for diseases is critical so that best selections between stocks can be made, even at the farm level. Meanwhile, EFRC has set up Seeds for the Future Initiative to improve breeding and production to overcome these problems.

Cultivations in the Dark

Hartmann and Nezadal (1990; vide Ascard, 1993) found that weed populations were considerably reduced when all soil cultivations were done at night. The theory behind this is that many weeds need light signals to germinate. This has been re-examined by a number of workers, and others, such as Ascard (1993) and in Sweden. EFRC in England (Welsh *et al.*, 1999) have looked at putting a light-proof cover over a power harrow/drill combination. The results are variable, with on occasion up to 70% reduced germination, but sometimes, in dry soils, little difference with cultivation in the light. Furthermore, there can be increases in species not affected by the light.

The value of the reductions has been shown by Welsh *et al.* (1999) to be transitory, with little final biomass or yield benefit from the treatment. A more consistent result from the practice has to be proven before it can be considered for widespread use.

Seed Rates and Sowing Pattern

It has been recognised for a long time through observation that crops grown at higher seed rates tend to compete more effectively with weeds. However, there is not always a matching yield benefit, and the extra seed cost then has to be matched with the extra weed control benefit.

Examples include Younie and Taylor (1995), who found that increasing seed rate in spring oats from 150 to 300kg/ha had a significant impact on weed growth, greater than that of narrow row spacings (Figure 4; Table 6). The effect was apparent as early as late May, with 94% and 22% more weed biomass in the 150kg/ha and 225kg/ha seed rate respectively than in 300kg/ha. There was no yield difference between 225 and 300kg/ha seed rate, but it was reduced at the lower rate.

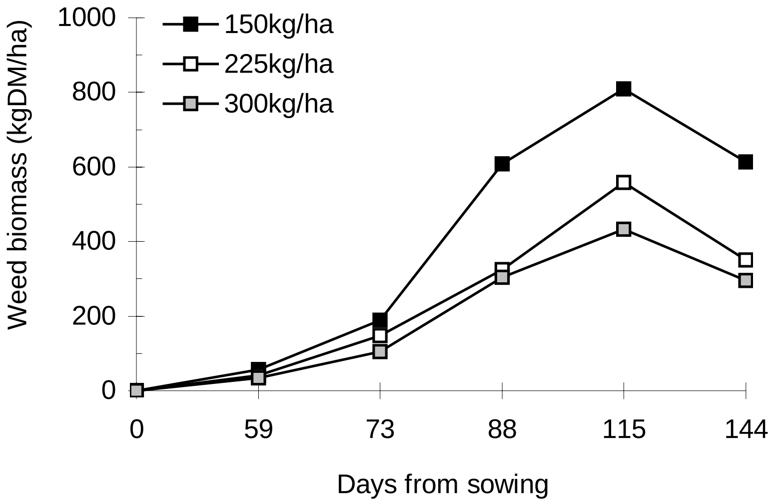

Figure 4. The effect of oat seed rate (mean of 2 sites, 1994) on weed development (Younie & Taylor, 1995)

Table 6. Effect of seed rate and row spacings (mean of 2 sites) on spring oat grain yield (Younie and Taylor, 1998)

	Tonnes/ha @ 85% dry matter
Seed rate (kg/ha)	
150	5.32
225	5.65
300	5.66
Row spacing (cm)	
9	5.54
13.5	5.68
18	5.43

Increased weed suppression with higher seed rates is reflected in increased leaf area index and light infiltration of the canopy (Table 7).

Table 7. Effect of seed rate on crop leaf area index and percentage of incident light infiltrating oat canopy in early June (Mean of two sites) .

Seed rate (kg/ha)	Leaf Area Index	Percentage light infiltration to 10cm above ground
150	4.68	58.3
225	5.66	56.1
300	6.54	49.9

In wheat, Dover and East (1990) found that increasing seed rates from 300 up to 450 seeds m^{-2} (250kg/ha) reduced pre-harvest weed populations slightly, without any yield variation.

Griepentrog *et al*. (2000) also found that increasing wheat seed rates from 200-660/m^2 greatly increased weed suppression. However, sowing in a cross pattern at 12-8cm, compared with a normal row pattern at the same width, suppressed weed biomass by a further 30%. Yield also increased by 60% over normal row pattern at 400 seeds/m^2.

Work under the European Union WECOF project, started in 2000, includes row width in organic wheat as a key factor in weed suppression. Provisional Scottish results indicate that row width of about 16cm gives better weed suppression than narrower or wider row widths, but these trials are being repeated over two further seasons. (Davies and Hoad, personal communication).

Amongst the pulses, Grevsen (2000) in Denmark found that increasing seed rate of pea cultivars from 90 to 150 seeds m^{-2} reduced the dry weight of weed plants by 40%. Seed weight and leaf type were important, as was early growth vigour of cultivars. (Table 5). Vine length was not, however, correlated with weed weight, conflicting with results from Canada by Wall and Townsley-Smith (1996; vide Creusen, 2000). Early growth is likely to be critical in other pulses, but possibly, in beans, canopy development over a longer period may be of importance.

Direction of Sowing

Eisele and Kopke (1997) noted that increased shading ability in taller wheat varieties could only be seen when sown in an E-W direction, compared with a N-S direction. The importance of direction, hypothesised by a number of workers, may be dependent on variety. However, its importance may also be dependent on latitude. As a consequence the EU WECOF project has integrated direction of sowing into the core work on variety type and row width, with sites from Spain to Scotland to resolve the issues involved. Initial results from a Scottish site do not show a clear response to direction of sowing in terms of crop growth and weed suppression. There is a complex interaction with row width and variety, and only a tendency for E-W sowing to show benefits at narrow row widths at GS49 in ¾ varieties, but at wide row widths, N-S sowing may have given better response (Table 8).

However, this varies with variety and growth stage, and further trials are planned to confirm these trends.

Table 8. Impact of direction of sowing on percent weed ground cover under wheat varieties at GS49 (Davies & Hoad; unpublished).

	Row Width			
	Narrow	Medium	Wide	Mean
E-W Sowing				
Pegassos	8.4	20.6	16.3	15.1
Eclipse	18.1	19.1	26.9	21.4
Consort	20.3	17.8	41.6	26.6
Rialto	13.4	14.7	23.1	17.1
			Overall	20.1
N-S Sowing				
Pegassos	13.0	12.8	6.9	10.9
Eclipse	28.4	24.5	24.5	25.8
Consort	14.6	12.3	19.1	15.3
Rialto	18.0	12.4	16.3	15.6
			Overall	22.5

We have no evidence for peas and beans, but beans sown in drills may also show a benefit to E-W drilling in terms of weed control in the row.

Crop Vigour

Crop vigour has been noted by several workers as being of importance in early competition with weeds. This is in part a varietal factor, as noted by Creusen (2000) for peas, and in terms of early prostrate ground cover as noted for cereals by Richards and Davies (1991). In part, it is also related to the quality of the seed, as has been noted earlier in this paper.

However, continuing crop vigour is related to soil, weather factors, and nutritional status. Weather factors are not controllable, but good seedbed conditions will assist in good crop establishment and long-term root growth. Nutritional status of the soil affects both the growth of the crop and the weeds. It is evident that crops further from the nutrition building phase of the rotation will have less available nitrogen, and such crops will be less vigorous (e.g. Table 9) and potentially less competitive against weeds.

Table 9. Effect of years after clover break on yield of wheat (from Cormack, 1997)

Rotation	Yield (t/ha) @ 85% DM
Clover/Clover/Potatoes/Wheat (1)	6.3
Clover/Clover/Wheat	9.8
Clover/Clover/Potatoes/Wheat (2)	6.7

Although not from organic systems research, Grundy *et al*. (1993) clearly showed the impact of nitrogen availability on weed growth in wheat crops (Table 10), as a result of increased crop vigour and growth.

Table 10. Weed density in response to additions of nitrogen in wheat (from Grundy *et al*., 1993)

Kg N/ha	Weed density m^{-2}
0	143.2
40	124.4
160	36.0
SE	15.3
P	$P<0.001$

Grundy *et al*. (1993) also found that the reduction in weeds was greater where high N availability was linked with high sowing densities.

It is clear that certain weed species are highly nitrophilic, and others much less so. This will probably have an impact on the mix of weed species present in fully converted systems. By observation, nitrophilic species such as cleavers and brome species are much less of a problem in organic than conventional systems. But those apparently less dependant on high nitrogen levels over winter and early spring such as deadnettles, knot-grass, fat-hen and mayweeds, are at least as great a problem, and with less vigorous crops, probably more of a problem than in conventional systems. In Denmark, Jørnsgård *et al*. (1996) have confirmed these observations by showing that some weeds, including fat-hen and deadnettles, have lower nitrogen ‘optima’ than the crop, indicating that they would be relatively more competitive at lower nitrogen status. The importance of timely weed control is organic crops is clear, with some evidence that control measures as nitrogen becomes available in the spring are crucial.

Undersowing and Mixed Cropping

Intersowing wheat crops with subterrananean clover in Italy and undersowing with clover in France has been shown to reduce weed biomass (Barberi *et al*., 1998, vide Taylor *et al*., 2000; Lambin *et al*., 1994, vide Taylor *et al*., 2000). In practice in the UK it is usually spring barley or oats that are undersown with clover or grass/clover, and these are less weedy before and after harvest than when there was no undersowing (Younie, 2001).

Mixed cropping with pulses may also reduce weed growth, but Eisele (1998; vide Taylor *et al*., 2000)) showed that *Vicia hirsuta* (hairy tare) can severely reduce crop yields, so care must be taken to miminise competition with the cereal. Recent work at SAC with vetch and spring barley showing similar results (Younie, personal communication). However, where mixed crops are grown to provide high protein feeds, such mixtures appear to be good at reducing weed growth. Clements *et al*, (1997) are developing a conventional whole-crop silage system with clover and wheat, and found that herbicides were not needed for broad-leaved weed control.

Bulson *et al*. (1991) inter-cropped organic autumn sown field beans and wheat, found yield benefits, and significant reductions in weed biomass, with the optimum being around 75% recommended density of beans and 75-100% of wheat (Table 11).

Table 11. Weed biomass (g m^{-2}) as affected by bean and wheat density (from Bulson *et al*., 1991).

		Wheat %				
		0	25	50	75	100
Beans %	0	434	302	146	97	124
	25	398	168	148	96	124
	50	346	162	133	80	100
	75	284	138	151	75	36
	100	169	117	72	83	62

Pe, vetch, bean barley and oat mixtures have long been a common feature of arable/livestock rotations. These are generally less weedy than individual component crops.

Sowing of crops into prepared stands of a legume (i.e. bi-cropping) has been examined by a number of workers, with the legume primarily present as a nitrogen donating part of the rotation. In these situations annual weeds do not present a problem, although long established ground cover can develop perennial weed problems.

Allelopathy

Many plant species produce chemicals that affect the development of plants growing in their immediate environment. This is called allelopathy. A wide range of species have been found to produce such effects, but as yet are not widely used in agriculture. The use of rye, cut and left, prior to sowing soyabean has been used in the USA. Morris and Parish (1991) found that sunflower residue can inhibit weed growth, but also wheat growth in minimum-till situations. This is being examined further in the current EU WECOF project. However, in much of the UK sunflowers have no potential as a break crop before wheat, and other crops require further investigation.

Cleanliness

A number of hygiene practices are recommended to reduce weed problems. In general equipment should be washed down after operation in particularly weedy fields, whether harrows or harvesters. Weeds should not be allowed to flower and blow seed onto cropping areas.

REACTIVE WEED CONTROL

Reactive weed control mainly relates to some form of mechanical intervention in the growing crop. Mechanical weed control in organic cereal and pulse crops can be split broadly into two methods; selective (e.g. inter-row hoeing or brush weeders) and non-selective (e.g. spring-tine weeding or harrowing). A survey of EFRC's arable farmer group members found that the use of spring-tine weeders, such as the Harrowcomb or Einbock, was the most widely practiced form of mechanical weed control in organic cereal crops in the UK, whilst inter-row hoeing was very uncommon (EFRC, 1997). The survey also highlighted that mechanical weed control tended to be conducted in the spring rather than in the autumn period.

When deciding on a reactive weed control strategy, it is important to consider a number of key factors:

1. *Weed threshold*. Is the weed infestation of sufficient size to affect significantly the current crop in terms of grain yield and quality and consequently crop gross margin and net farm income? If I decide not to control the weeds, will the seed that they produce significantly affect future crops?

2. *Timing*. If the weed population is of sufficient size to warrant control, what is the best time to implement control to achieve the maximum benefit to the crop?

3. *Method*. Which method of weed control is likely to be the most effective at removing weeds at the appropriate time?

Weed thresholds

Orson (1990) emphasised the difficulties in developing a weed threshold system due to the highly complex nature of quantifying crop-weed interactions. Each species will vary in its competitiveness, which in turn will be influenced by the competitiveness of the crop, date of emergence in relation to the crop, weather conditions, soil type and nutrient status. It is recognised that the competitiveness of weeds and the dormancy of their seeds depend to a large extent on soil type and the weather conditions that follow the time when weeds have to be removed in order to prevent or minimise yield loss.

There has been a considerable research effort over the last few years to identify weed threshold levels in non-organic crops, however, very few studies have aimed to do the same for organic crops. It is clear that conditions in organic crops are different from those encountered in non-organic crops and, for the reasons give above, it is likely that weed threshold levels will also be different. This remains an area where further research is needed, although Bond and Lennartsson (1999) commented that for most organic crops, weed control would be justified.

Timing

To identify the most appropriate time to control weeds it is important to know when weeds are likely to exert their greatest competitive effect on the crop and/or when the crop can least tolerate the presence of weeds. As a rule of thumb, in autumn/winter-sown crops, it is the autumn germinating weeds that pose the most serious problems and, likewise, in spring-sown crops, weeds that germinate at a similar time to the crop are likely to be the most problematic. Therefore, in general, ensuring the crop is kept as weed free as possible during its early growth stages is likely to be the most beneficial strategy. Once crops become established, they should then be able to compete effectively with emerging weeds. Clearly, as has been shown already, some crop species are better competitors than others. This rule of thumb has been reinforced by another approach that can address this question, the identification of the critical weed-free period, first suggested by Nieto *et al*. (1968).

The critical weed-free period represents the time interval between two separately measured components: the maximum weed-infested period or the length of time that weeds which have emerged with the crop can remain before they begin to interfere with crop growth; and the minimum weed free period or the length of time a crop must be free of weeds after planting in order to prevent yield loss (Weaver *et al.*, 1992). These components are experimentally determined by measuring crop yield loss as a function of successive times of weed removal or weed emergence respectively.

Very few studies have considered this in organic farming systems. Welsh *et al*. (1999) reported some initial results for the critical weed-free period in organically grown winter wheat (Figure 5).

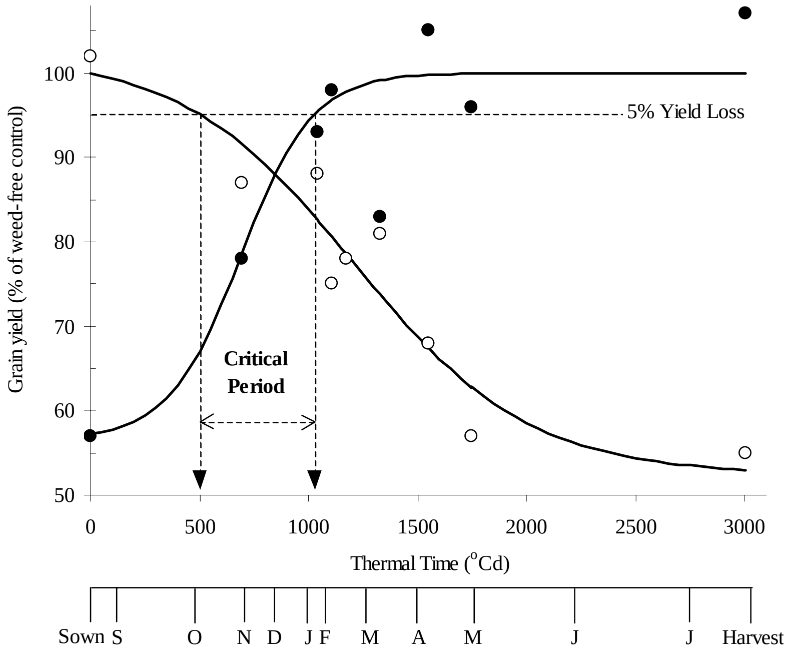

Figure 5. Observed and fitted wheat grain yield (% of predicted weed-free control) as affected by the duration of the weed-infested period (○, ——) (SE = 17.3) and weed-free period (●, ——) (SE = 17.4) in 1995/96.

The results suggested that with a mixed weed infestation of blackgrass and mayweed the critical weed-free period would begin at 645 °C days after sowing (December) and end at 1223 °C days after sowing (March). Therefore, in the case of winter wheat, keeping the crop free of weeds from shortly after sowing to the early spring is the most effective strategy. This is in contrast to current practice, where most weeding operations start in the spring period, by which time the crop will have already suffered a significant yield penalty (20-25% reduction). It should be noted, however, that this was the result from only one season at one site.

Unfortunately, there has not been a similar study for field beans or peas, but it is anticipated that weed control should be focused at the start of the growing season whilst the crop becomes established.

Method of weed control

Experiments conducted by Jones *et al*. (1996) investigated the most effective ways of killing annual weeds mechanically. The experiments comprised a range of cutting and burial treatments. Their findings indicated that the most effective means of control was achieved either by cutting weed stems at the soil surface or by totally burying them with soil. The moisture content of the soil was also shown to be an important factor in determining the effectiveness of treatment such that control was better under dry soil conditions. This is supported by Terpstra and Kouwenhoven (1981) who reported that under dry soil conditions hoeing resulted in 96% weed control whilst under moist conditions the level of control decreased to 84%.

Spring-tine weeders

Spring-tine weeders (e.g Einbock or Harrowcomb) rely on numerous spring-tines to create a tilth to bury weeds but also to rip weeds out of the soil resulting in desiccation (Kouwenhoven and Terpstra, 1979; Terpstra and Kouwenhoven, 1981; Rasmussen and Svenningsen, 1995).

Spring-tine weeders are available in a range of working widths (typically from 6m to 24m), although they are all basically the same design. They comprise modular frames, which are suspended from the main frame by means of chains. Suspending the modular frames in this way allows each of them to follow the contours of the ground independently of the main frame. Each of the modular frames is equipped with rows of "L " shaped spring-tines. The tines are available in a range of diameters, depending on the intensity of treatment required, with the larger diameter tines resulting in a greater intensity of treatment.

The angle of the tines can also be adjusted to increase or decrease the intensity of weeding treatment. Angling the tines forward increases the pressure on the tine, consequently increasing the intensity of treatment, whilst angling the tines backward has the opposite effect.

Inter-row hoes

As the name implies, cultivation only occurs between the crop rows, in contrast to spring-tine weeding where the entire area is cultivated. Weed control results from undercutting the weed plants and either leaving them on the soil surface to desiccate or burying them in soil (Terpstra and Kouwenhoven, 1981).

There are numerous types of inter-row hoe available, although their mode of action is principally the same. Generally, the inter-row hoe comprises a tool bar to which the inter-row hoeing units are attached. The units have independent suspension to allow the hoe blades to follow the surface contour, resulting in a consistent depth of cultivation. The hoe blades are mounted to the units via either a rigid or sprung leg. There is also a variety of cultivating tools for inter-row weeding, from standard A-blades to rolling cultivators.

Both the depth and angle of the hoe blade can be adjusted. Both increasing the blade angle (from the horizontal) and increasing its depth of cultivation result in more soil movement and consequently more aggressive weed control. The angle of rotary cultivators can also be adjusted to give more or less soil movement.

Key factors influencing mechanical weed control

Böhrnsen (1993) cited eight key factors that influenced the efficacy of mechanical weeding techniques:

1. Soil type
2. Soil moisture
3. Soil surface structure
4. Working principles of the weed control machinery
5. Driving speed
6. Weed species specific robustness
7. Growth stage of weeds and cultivated plants
8. Weather after the mechanical weed control treatment

Soil type and condition

Soil type and condition are expected to affect any weed control technique that relies on tillage. There is, however, currently little data in the literature that relates the efficacy of mechanical weed control to these factors although it is possible to speculate on the likely affects that soil type/condition will have. Spring-tine weeding will tend to be more severely constrained by soil type/condition than inter-row hoeing (Rasmussen, 1993c; Stöppler-Zimmer, 1994). For example, the relatively light tines of the spring-tine weeder are less likely to penetrate the soil if it is crusted or hard than the more robust and heavier hoe blades.

Driving speed and direction

A study by Rydberg (1994) investigated the influence of driving direction and driving speed of harrowing on weeds and cultivated plants. The study was conducted in an oat crop and treatments were implemented at the 3-4 leaf stage. The level of weed control was found to be dependent on driving speed although most of the reduction in weed levels was achieved at 5 km h^{-1}. Harrowing across the crop rows did not provide significantly better levels of weed control than harrowing along the rows. Neither speed nor direction of harrowing significantly affected oat grain yield.

The major limitation of inter-row hoeing is its speed of operation. Because the hoe has to be guided accurately between the crop rows, forward speed is limited to ensure accuracy. There is, however, some very recent work that has looked at developing automated guidance systems for inter-row hoeing (Tillett and Hague, 1999). The first commercial version of this machine has recently been released and it promises to allow significantly greater speeds of operation, greater accuracy and increased workable hours as the tractor driver will be less fatigued from having to concentrate on accurate driving.

Weed species and growth stage

Weed species and growth stage are also important factors in determining the efficacy of mechanical weed control. Berry (1994) found that different weeders removed some species more readily than others. Similarly, a review by Stöppler-Zimmer (1994) found that individual weed species demonstrated differing responses to mechanical weed control. Cleavers (*Galium aparine*) and common hemp-nettle (*Galeopsis tetrahit*) were controlled more effectively than either mayweed (*Matricaria recutita*) or red dead-nettle (*Lamium purpureum*) by harrowing. Also, harrowing generally offers poor control of grass weeds (Blair *et al*., 1997). In contrast, the efficacy of inter-row hoeing is less sensitive to weed species than harrowing due to its more robust nature.

Böhrnsen (1993) reported that small weeds (< 3-leaf stage; 60-85% reduction) were controlled much more effectively by harrowing than large weeds (> 3-leaf stage; 33-63% reduction), whilst inter-row hoeing controlled weeds effectively (90% density reduction) at a wide range of growth stages. Both Wilson *et al*. (1993) and Welsh *et al*. (1997) found that tap rooted weeds, e.g. field poppy (*Papaver rhoeas*) and shepherds purse (*Capsella bursa-pastoris*), were controlled most effectively at an early weed growth stage before their tap-roots established. Shallow rooted weeds, however, e.g chickweed (*Stellaria media*) or cleavers, with a more scrambling or climbing habit were controlled best at later growth stages when they could be “raked” out of the crop.

Weather after treatment

Weather after the weeding operation is also likely to have a large effect on its efficacy. Wet weather after treatment, especially with those weeders relying on desiccation as a means of weed kill, will decrease the effectiveness of control, as weeds may re-root (Terpstra and Kouwenhoven, 1981).

Selectivity

Rasmussen (1990) introduced the concept of selectivity as a means of evaluating a range of harrows, where selectivity was defined as the ratio between weed control and crop burial in soil. Selectivity is the key factor that determines the possibilities for achieving high degrees of weed control without serious crop damage. Theoretically, spring-tine weeding can control weeds completely if it is done with adequate intensity during early crop growth stages, but this is rarely possible without causing significant reductions in crop yield (Rasmussen, 1991, 1992).

Rasmussen (1991) found that the selectivity of harrowing was influenced by the composition of the weed flora, site characteristics and degree of weed control, whilst there were no differences in selectivity between the harrows used. Rasmussen (1993b) also highlighted that inter-row hoeing was a highly selective method of weed control in comparison to harrowing.

Efficacy of mechanical weed control

Spring-tine weeding

Spring-tine weeding can be carried out at three stages during the growing season: pre-crop emergence, early post-crop emergence and late post-crop emergence. Although Rasmussen (1996) suggested that pre-emergence soil cultivation after crop planting has the potential to control early germinating weeds, it may create weed problems by stimulating subsequent weed seed germination (Roberts and Potter, 1980; Mohler and Galford, 1997).

Early post-crop emergence weed control is performed a few weeks after crop emergence. For cereals, the recommendation would be to harrow once the crop gets to the 3-leaf stage. At this time, the main problem is the low selectivity of control between crop and weeds. Weeds at this stage are mainly controlled by burial with soil, however, the crop is also vulnerable to soil coverage at this time (Rasmussen, 1996). Wilson *et al*. (1993) who found that autumn weeding treatments with a tine harrow reduced crop cover from 80% to 70% supports this.

Rasmussen (1995) reported that spring-tine weeders could be used at later crop growth stages than other types of harrow. When weeding is conducted parallel to the crop rows in the late stages of cereal development, the tines tend to be forced into the inter-row spaces due to the resistance offered by the crop rows. If the tines are long enough, inter-row spring-tine weeding can be carried out from late tillering until crop maturity. The use of spring-tine weeders in this way has been defined as selective harrowing and works by uprooting weeds, tearing them apart and burying them in soil, without the associated crop damage.

Reductions in weed density as a result of spring-tine weeding range from 5% to 90% depending on the weed species present (Rasmussen, 1991, 1992, 1993b; Wilson *et al*., 1993; Peruzzi *et al*., 1993; Rasmussen and Svenningsen, 1995).

It is clear, therefore, that harrowing with a spring-tine weeder has the potential to reduce weed levels but its impact on crop yield is more ambivalent. For example, Popay *et al*. (1992) working in wheat and barley in New Zealand reported that spring-tine weeding reduced weed density and weed dry matter but had no effect on crop yield. Similarly, Samuel and Guest (1990) found that harrowing in the spring reduced the population of speedwell (*Veronica hederifolia)* by as much as 90% but there was no benefit in terms of crop yield. Peruzzi *et al*. (1993) also reported a 40% reduction in weed density as a result of spring-tine weeding but again crop yield was not significantly affected.

Therefore, although spring-tine weeding can significantly reduce weed density, it rarely produces significant and positive crop yield responses. Rasmussen (1993b) suggested that this might be due to a number of factors:

1. Initial weed infestation below a competitive level.
2. Insufficient level of weed control.
3. Damage to the crop by the mechanical weeding operations.

Other factors, however, such as the timing of weed removal in relation to the critical weed free period and subsequent weed emergence following mechanical control are also likely to affect crop yield response to weeding.

Inter-row hoeing

In contrast to spring-tine weeding, inter-row hoeing is a selective method of mechanical weed control (Rasmussen, 1993a, 1993c). Also, inter-row hoeing is particularly effective at controlling mature weeds (Böhrnsen, 1993; Morrish, 1995), whereas spring-tine weeding is most effective when weeds are small and consequently more vulnerable to soil cover (Wilson *et al*., 1993; Böhrnsen, 1993).

Work by Hammarström *et al*. (1993) demonstrated that hoeing winter wheat with ducks-foot blades at a 25 cm row spacing could reduce the density of weeds between the rows by 82% and weed biomass by 35%. The weed density in the crop row was reduced by 25%. He also found that it was possible to hoe at a normal crop row spacing of 12.5cm using a rotary hoe. At this row spacing, weed density was reduced by approximately 45% between the rows and 25% in the rows. Crop yields were slightly increased as a result of hoeing with both the ducks-foot blades and the rotary hoe when compared with the unweeded control sown on 12.5cm rows, although the increases were not statistically significant.

Similarly, Böhrnsen *et al*. (1993) reported that inter-row hoeing could reduce weed density by 90%, whilst spring-tine weeding only resulted in a 35% reduction in weed density. Crop yield, however, was only slightly improved by inter-row hoeing in comparison with the unweeded control.

A limitation of inter-row hoeing is that the crop generally has to be planted on a wide row spacing, which might be expected to increase the level of intra-specific competition within the crop and consequently limit grain yield. Hammarström *et al*. (1993), however, found no significant difference in grain yield between the unweeded controls at a crop row spacing of 12.5cm and 25cm. Also, Rasmussen (1993a) reported that crop yields at a 20cm row spacing were significantly higher than crop yields at a 12cm row spacing although he thought this could be due to the higher density of plants established at 20cm row spacing as a result of higher seed rates. Weed dry matter was found to be higher in crop sown on 20 or 25cm rows compared with 12 or 12.5cm rows (Rasmussen, 1995; Hammarström *et al*., 1993). This is probably as a consequence of the decreased competitive ability of the crop at the wide row spacing.

In contrast to spring-tine weeding, inter-row hoeing tends to result in greater reductions of weed density and its efficacy is less affected by the growth stage of the weeds. Yield responses to inter-row hoeing, however, are still variable with few reports of statistically significant positive yield responses.

Problematic Weeds

Perennial weeds (couch, creeping thistle, docks etc) are probably the most problematic for organic agriculture. In-crop mechanical weed control is generally poor at controlling this type of weed. Perennial weeds are best controlled on a rotational basis, making use of cover crops as well as the cultivations between different phases of rotation. In extreme cases it may be necessary to fallow the field to allow a series of rigid-tined cultivations.

Of the annual species, wild-oats can also be difficult to control and are certainly a potentially serious problem for those engaged in organic seed production. However, there have been some very innovative solutions to minimising the problem. For example, the use of a converted rape swather, with the cutter-bar set above the height of the crop, to remove wild oat seed heads (Steele, 1997).

Secondary effects of mechanical weed control

Soil

Mattsson *et al*. (1990) reported a number of advantages of inter-row weeding, other than weed control. Inter-row weeding breaks up the soil crust allowing aeration of the soil and possibly improves the water holding capacity of some soils. Also, soil tillage, through mechanical weed control, may lead to an increased nitrogen concentration in the soil by exposing less accessible substrates to mineralisation by microbes (Dowdell *et al*., 1983; Böhrnsen, 1993; Smith *et al*. 1994). It is likely that inter-row hoeing will be more effective than spring-tine weeding at producing this effect due to the greater soil movement that occurs with this method.

Fauna

Mechanical weeding may also have detrimental side effects such as damage to populations of beetles, other soil fauna, and ground-nesting birds (Jones *et al*., 1996). Careful consideration must, therefore, be given to the timing and frequency of weeding operations to minimise the impact on the environment.

SUMMARY

- Crop rotation is the key to long-term management of weeds. In particular grass breaks give the best results. Clover breaks and crops in which weeds are easy to manage are important for stockless rotations.
- Amongst cereals, triticale and oats are more competitive than wheat or barley.
- Cereal and pea varieties vary in ability to shade out weeds. Which are the best shading attributes is still being resolved, but either early or late shading may be acceptable.
- Use of stale seed-beds is a very useful way of reducing weed emergence in the following crop.
- Early sowing in autumn increases weed pressures. In the spring allow time for stale seed-bed approaches.
- Good seed quality gives good crops. The new EFRC Seeds for the Future Intiative will improve breeding and production of organic seed.
- A more consistant result from cultivations in the dark to reduce weed emergence is required before it can be widely advised.
- Increasing seed rates improves competition with weeds, but check the cost against that of extra cultivations.
- Sowing in an E-W direction may give extra weed suppression in taller varieties, but this may vary with latitude and row width, and further research is needed.

- Good crop vigour improves weed suppression. Crops further from the nutrition building phase tend to be less competitive.

- Inter-sowing or undersowing crops gives good suppression of annual weeds. Mixed cropping of cereals and pulses are also more competitive than each crop alone.
- The use of allelopathy for weed suppression still requires further research for UK conditions. Sunflower and rye residues have shown benefits in other countries, but inhibition of the crop is also possible.
- If you have been working in a weedy field, wash off equipment before moving to other fields.
- The identification of weed thresholds should help to rationalize weed control (i.e. to weed or not to weed). At present, however, there is little information available.
- Weed control in the growing crop should be timed to remove weeds during the early part of the growing season, to allow the crop to become established and competitive against emerging weeds.
- Spring-tine weeding is most effective on friable soils where it can produce sufficient tilth to bury weeds. In general, weeds should be controlled at an early growth stage before they become established. Control of mature broad-leaved weeds, perennial weeds and grasses is poor.
- Inter-row hoeing, due to its more robust mode of action, is less sensitive to soil type and conditions and can work well on heavier soils or on soils that tend to cap. Also, it can control annual broad-leaved and grass weeds at a wide range of weed growth stages. The control of perennial weeds is still difficult and these weeds should be dealt with during the primary and secondary cultivations before drilling. The major limitation of inter-row hoeing is its work rate, although this has recently been addressed by automated guidance hoeing systems.
- Mechanical weed control may also have the added benefit of stimulating the mineralisation of soil-bound nitrogen, which, if timed with the crops peak demand for nitrogen, could help to improve crop yield and quality.

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