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Pre-harvest glyphosate for weed control and as a harvest aid in cereals

by

J H Orson[1] and D H K Davies[2]

[1]The Arable Group, The Old Rectory, Morley, Wymondham, Norfolk, NR18 9DB
[2]Scottish Agriculture College, Pentland Building, Bush Estate, Penicuik, Midlothian, EH26 0PH

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Abstract

Pre-harvest glyphosate application for cereals was introduced in the UK in 1980 to control perennial weeds, notably common couch (*Elytrigia repens* syn. *Elymus* or *Agropyron repens*). The application time enables very effective perennial weed control without delaying subsequent field operations. This recommendation has been so successful and that now only a small crop area needs to be treated.

Currently a much greater area of wheat is treated with glyphosate pre-harvest in order to aid harvesting. A survey of the scientific literature and experiments carried out by The Arable Group (TAG) and Scottish Agricultural College (SAC) suggest that the benefits of the treatment are variable and that careful targeting of this application is necessary. This may reduce the concern expressed in a recent report for the Food Standards Agency over the level of incidence of residues of glyphosate in UK bread.

The pre-harvest application of glyphosate as a harvest aid is easier to justify in barley than in wheat. It appears to reduce both grain and straw moisture content in a range of circumstances in barley and experimental data suggest that this reduces sieving and threshing losses and increases the throughput of the combine.

It is not clear why the treatments have different effects in wheat and barley. Barley grains may be more exposed to the spray and possibly treated wheat grains and straw may more readily reabsorb moisture from the atmosphere.

Further investigations are needed on the effect of post-application humidity and rainfall on the moisture content of grain and straw (including green stems of wheat ears that contain grain that is 'harvest dry') of wheat and barley treated with pre-harvest glyphosate. Early studies on harvester performance were undertaken in the 1980's. Further studies are needed on the effect of current agronomy and harvesting machinery in evenly-maturing and weed-free spring barley treated with pre-harvest glyphosate. Experiments on the effect on the wheat harvesting operation of pre-harvest glyphosate are not needed unless it can be shown that treated wheat grain and straw do not more readily reabsorb moisture from the atmosphere than untreated grain and straw.

Background

A study recently commissioned by the Food Standards Agency (FSA) has highlighted the fact that residues from the pre-harvest application of glyphosate are the second most commonly occurring residues in cereals; chlormequat being the most common (Berry, 2005). However, bread grists consist of both UK and imported wheat and therefore the derivation of the residues cannot be attributed with absolute confidence.

The residues are consistently below the Maximum Residue Levels (MRLs), which suggests that farmers are adopting good practice in terms of dose and time of application. Usage has been relatively stable over recent years. It was initially adopted for the control of perennial weeds but this now represents a relatively small percentage of the area treated. Table 1 suggests that the major reason for the usage of glyphosate pre-harvest of wheat is as an aid to the harvesting operation. However, care has to be taken when interpreting the data because desiccation could involve applying it to desiccate both crop and weeds.

Concern over residues, as expressed by the FSA report, appears to relate to the incidence of residues rather than to the levels of the residues. Data from Monsanto and Cessna *et al*. (1994 & 2002) suggest that the level of residues is associated with dose but that even the lower doses used for harvest aid will leave detectable levels at harvest. Hence, any initiative to reduce the incidence of residues must be to reduce the proportion of the crop sprayed rather than to reduce the dose of the individual applications.

The pre-harvest application of glyphosate for the control of perennial weeds has brought tremendous benefits to the UK farmer. When compared to post-harvest application, it generally increases the control of perennial weeds and, in addition, its time of application does not result in a delay in cultivation after harvest. Indeed, it can be argued that the pre-harvest application has resulted in an overall reduction in glyphosate usage for perennial weed control.

The case for the pre-harvest application of glyphosate as a harvest aid is more contentious, particularly in the absence of weeds and secondary tillers. In many cases, research has indicated no advantage in evenly-maturing and weed free wheat crops. However, there is experimental evidence to support the pre-harvest application of glyphosate in order to aid the harvest of the barley crop, particularly spring-sown. Hence, a more precise identification of situations where this application is justified could result in a reduction in the incidence of residues.

Reasons	Area treated (ha)		
	2000	2002	2004
Black-grass/wild-oat	2,026	779	-
Common couch	-	4,620	11,067
Rye-grass	-	455	-
Grass weeds (unspecified)	11,065	506	-
Cleavers	1,660	-	-
Thistles	-	-	468
Broad leaved weeds (unspecified)	1,731	-	-
General weed control	15,767	2,164	17,677
Volunteers	1,951	489	4,373
Desiccant	49,837	35,840	69,699
Reasons unspecified	227,742	204,613	150,130
Total glyphosate use (ha)	311,780	249,465	253,414
Total wheat area	2,078,908	1,989,417	1,981,661

Table 1. Area (ha) of wheat in Great Britain treated with pre-harvest glyphosate according to reason for application (Source: Pesticide Usage Survey Group, CSL).

Glyphosate

Perennial weeds have always been a problem in UK arable production, notably common couch (*Elytrigia repens* syn. *Elymus* or *Agropyron repens*) and the common thistle (*Cirsium arvense*). Prior to the adoption of herbicides, the control of these weeds would often involve leaving the land as bare fallow or relying on hand removal. Perennial weeds benefit from shallow cultivations because a higher proportion of their perennating organs remain undisturbed and intact and so effective chemical control of these weeds can contribute to reducing the energy requirement for crop establishment.

Glyphosate was discovered by Monsanto and first described in 1971 (Baird *et al*., 1971). It is absorbed primarily through plant foliage, typically by diffusion, and is translocated throughout the whole plant. Unusually for herbicides, it has the ability to move down the plant with the photo-assimilates in the phloem to 'sinks' caused by the growth of perennating organs (Caseley & Coupland, 1985). Its slow mode of action assists this process by ensuring that damage to plant tissue that might otherwise prevent its movement does not occur until after there has been sufficient transport to the perennating organs. By the same token, the slow impact on the plant means that penetration of the plant cuticle is not impaired by local damage. This results in the higher concentrations that occur with low volume application being more toxic to the plant (Merritt, 1982).

Unusually, it is a water soluble herbicide. This results in its activity being very responsive to the weather conditions being experienced by the target plants at around the time of application (Orson, 1982). The reason for this is that water-based compounds have more difficulty in penetrating the outer layers of the plant than 'oil-based' compounds. Hence, changes in the outer layers of the plants as a result of weather conditions have a more significant impact on efficacy. This issue resulted, along with its high cost in the 1970s and 1980s, in significant levels of interest and research on the influence of weather conditions (Caseley & Coupland, 1985) and the impact of adjuvants (Turner, 1985) on the dose of glyphosate required to kill weeds.

Glyphosate was first introduced into the UK in 1974 for the control of perennial weeds, notably common couch. It replaced other herbicides with higher doses of active ingredient which were often used in conjunction with repeated cultivation to control common couch.

The pre-harvest application for perennial weed control was introduced in 1980 (O'Keeffe, 1980) and the harvest aid recommendation followed a few years later. The pre-harvest recommendation for perennial weeds resulted in more effective control at a time of application that does not delay subsequent field operations. This has provided the farmer with more flexibility of cropping and more timely sowing dates in the autumn, so providing the basis for improved soil structure.

Hence glyphosate, particularly the pre-harvest application for perennial weed control, has resulted in the potential to reduce significantly the energy involved in crop production and has improved soil management and flexibility in cropping.

Theoretical basis for the pre-harvest application for perennial weed control

Stage of weed

Pre-harvest application typically enables perennial weeds to be treated at the optimum stage of development for control. They have to be relatively advanced for control with glyphosate due to the need for sufficient foliage to intercept the herbicide and also because the perennating organs act as a significant 'sink' only at relatively advanced growth stages (Caseley & Coupland, 1985). In perennial broad-leaved weeds in particular, optimum control is achieved from applications at the flowering stage (Lee, 1973; Banks & Santelmann, 1976); this often coincides with the timing of the pre-harvest application. The advanced growth stages required for the effective control of perennial broad-leaved weeds are rarely achieved post harvest in the autumn. In addition, perennial broad-leaved weeds do not reliably re-grow after harvest and are in any case relatively sensitive to frost which damages the foliage and reduces photo-assimilate movement and thus glyphosate penetration and movement within the plant.

Growth of weed

The growth and development of common couch is delayed by crop competition (Cussans, 1968). The growth of new rhizomes is more impaired by crop competition than that of above-ground growth (Cussans, 1970). Common couch starts to grow rapidly, particularly the rhizomes, once the crop starts to ripen, provided that the soil is moist (Cussans, 1968, 1970). This results at the time of the pre-harvest application in the ideal situation of sufficient and actively growing stems and leaves to intercept the spray but a restricted mass of rhizomes that is growing rapidly and so providing a very positive 'sink'.

Weather conditions

The warmer weather associated with pre-harvest application is more suitable for the movement of glyphosate into and around the plant than after harvest. However, there needs to be sufficient soil moisture to ensure that weed growth is not severely restricted. At the time of spraying, humidity is of key importance because high levels facilitate penetration of the outer layers of the plant by glyphosate (Caseley & Coupland, 1985). It is for this reason that weed control with glyphosate under marginal conditions of soil moisture could be enhanced by early morning spraying (Jensen & Kudsk, 1988).

Crop safety

Cereal grains reach their maximum dry matter content when their moisture content is about 37% and from this stage, the grain matures and exists independently of the rest of the plant (Mitchell *et al*., 1980). When the bulk moisture content of an evenly-maturing crop is 30%, 95% of the grains, by weight, will be less than 34%

moisture content (O'Keeffe, 1980). Grain yields are not affected by doses of glyphosate between 0.36 to 4.32 kg ae/ha provided that the bulk grain content on an evenly-maturing crop is at or below 30% at the time of application (O'Keeffe, 1980; O'Keeffe, 1981b, O'Keeffe *et al.*, 1981, O'Keeffe & Makepeace, 1985).

Efficacy of pre-harvest application on perennial weeds

There have been many experiments assessing the efficacy of pre-harvest application of glyphosate on common couch (e.g. O'Keeffe, 1980; O'Keeffe 1981a; O'Keeffe *et al*., 1981; Orson, 1982; Sheppard *et al*., 1984; Richards & Shepherd, 1984), and some experiments on perennial broad-leaved weeds and volunteer potatoes (O'Keeffe & Makepeace, 1985). A few experiments compared pre-harvest application with that of post-harvest application. These generally confirm that the pre-harvest application provides very effective control and/or an opportunity to achieve the same level of control as post-harvest applications from lower doses (Tables 2 & 3).

Dose (kg ae/ha)	Year and site					
				1980		
	SW1	SW2	SE	HM	N1	N2
1.44	1	0	0	0	0	1
0.72	12	5	0	1	5	2
0.36	17	3	11	1	8	15
				1981		
	SW	HM	N1	N2	N3	
1.44	11	0	0	4	0	
0.72	13	0	5	1	0	
0.36	22	1	23	5	45	
0.18	49	1	75	18	100	

Table 2. Survival (%) of viable rhizome buds of common couch from the pre-harvest application of a range of doses of glyphosate (kg ae/ha) in England (Source; Orson, 1982)

Site	Pre-harvest		Post-harvest	
	0.72 kg ae/ha	1.44 kg ae/ha	0.72 kg ae/ha	1.44 kg ae/ha
1	99.7	99.7	95.1	97.8
2	98.8	98.4	64.5	89.6
3	99.4	99.2	31.6	93.7
4	-	90.0	-	60.0

Table 3. Reduction (%) of common couch shoots in the following season after pre-harvest or post-harvest application of a range of doses (kg ae/ha) of glyphosate in 1979 in Scotland (Source; O'Keeffe *et al*., 1981)

Glyphosate as a harvest aid

Crop yield

Wheat The introduction of strobilurins increased the interest in pre-harvest glyphosate as a harvest aid on evenly-maturing and weed-free crops. This is because these fungicides prolong green leaf and straw retention. TAG carried out several trials relating to this particular situation. Eleven of the twelve TAG trials carried out at different locations between 1999 and 2006 and taken to yield demonstrated that the pre-harvest application of glyphosate gave similar yields when applied when the bulk grain moisture content was at or below 30%. Astbury & Kettlewell (1992) had similar results in six wheat trials in evenly-maturing and weed-free crops taken to yield but these were carried out before the strobilurins were introduced. This agrees with the findings of O'Keeffe (1981b).

The only negative impact on yield was recorded in a TAG trial carried out in 1999. This result indicated the possible impact of applying glyphosate to 'even up' a variable crop where a significant proportion of the grain had a moisture content well above 30%. Overall, there was a significant benefit from the application of pre-harvest glyphosate in terms of moisture content of the grain, regardless of whether fungicides had been used or not. Unfortunately, there was also a consistent trend in reduced yields of grain particularly where strobilurins had been used in the fungicide programme.

The explanation for these results was that the trial was carried out on a second wheat that was suffering from a significant take-all infection. Within and between plots there was considerable variation in maturity and moisture content at the time of glyphosate application but the bulk moisture content of the grain was assessed over the whole site to determine when the application should take place. It is likely that the moisture content of the grain in the parts of the trial not prematurely ripened by take-all would have been higher in the strobilurin treated plots. This may explain the increased trend to yield loss from the pre-harvest application of glyphosate in the strobilurin treatments (Table 4).

Fungicide programme (doses at l/ha)					
T1 (GS 32)	T2 (GS 39)	T3 (GS 65)	1.0 l/ha Roundup @ 30%MC	Yield (t/ha)	%MC
-	-	-	-	6.52	18.23
-	-	-	Yes	6.32	14.96
0.25 Opus + 1.0 Bravo	0.75 Opus + 1.0 Bravo	0.5 Folicur	-	7.31	17.34
0.25 Opus + 1.0 Bravo	0.75 Opus + 1.0 Bravo	0.5 Folicur	Yes	6.81	14.91
0.25 Opus + 1.0 Bravo	0.75 Landmark	0.3 Amistar	-	7.89	17.74
0.25 Opus + 1.0 Bravo	0.75 Landmark	0.3 Amistar	Yes	7.17	15.26
0.25 Opus + 1.0 Bravo	1.0 Landmark	1.0 Amistar	-	8.98	16.28
0.25 Opus + 1.0 Bravo	1.0 Landmark	1.0 Amistar	Yes	8.19	15.64

Table 4. Yield (t/ha @ 85% MC) and moisture content (%MC) of grain at harvest of Consort wheat, treated or not treated with 1.0 l/ha Roundup (360 g ae/l glyphosate) when the bulk grain content of the site was 30% moisture content (MC). Opus contains 125 g/l epoxiconazole; Bravo, 500 g/l chlorothalonil; Folicur, 250 g/l tebuconazole; Landmark 125 g/l kresoxim-methyl and 125 g/l epoxiconazole

Barley The Scottish Agricultural College **(**SAC) carried out a total of 11 field trials between 1979 and 1981 in order to investigate the impact of pre-harvest glyphosate on both yield and ease of harvest of barley. The results from six sites (five spring barley and one winter barley) are published in O'Keeffe *et al*., 1981 and Sheppard *et al*, 1984. The sites were infested with common couch but no impact on crop yield was recorded except in one trial where the crop lodging occurred between treatment and harvest. Lodging was more severe on the plots where pre-harvest glyphosate was applied, possibly because the treated couch was less able to keep the crop standing. The crop may have been more vulnerable to lodging because of the couch competition reducing straw strength directly or by reducing crop tiller numbers, resulting in large ears of barley (Table 5).

Grain moisture content at harvest

Wheat There was no impact on grain moisture content at harvest from the pre-harvest application of glyphosate, at 30% moisture content of the grain on evenly-maturing and weed-free wheat crops, in the six experiments described by Astbury & Kettlewell (1992) and in 11 of the 12 TAG trials, the exception being the trial described in Table 4. The TAG trials included triazole and strobilurin based fungicide programmes, whilst those programmes quoted in Astbury & Kettlewell (1992) were based on triazoles.

Hence, it can be concluded that the application of pre-harvest glyphosate to weed-free and evenly-maturing crops has little or no advantage in terms of moisture content of the grain. In their trials Monsanto recorded reductions in grain moisture content but only within a week of application. The conditions of approval state that crops should not be harvested for at least seven days after the application of pre-harvest glyphosate.

In contrast, in North America, significant reductions in the subsequent grain moisture content of wheat at harvest were recorded when glyphosate had been applied at moisture contents above 25%, provided that the post-application weather was overcast. Climate may explain the different results; consistently overcast but dry and low humid conditions appear to favour the reduction of grain moisture content of wheat at harvest as a result of the application of pre-harvest glyphosate (Darwent *et al.*, 1994; Wiersma & Holen, 2006).

Application of pre-harvest glyphosate in order to control weeds or secondary tillers is more likely to reduce grain moisture content by ensuring that any green matter is partly desiccated. This may be of benefit in two ways: faster drying in the field and/or less green matter passing through the combine with the grain. It was noted by O'Keeffe & Makepeace (1985) in the pre-harvest trials for weed control that the moisture content of grain was lower at harvest when crops infested with common couch were treated. However, in two trials carried out by SAC on sites infested with common couch in Scotland in 1989, there was no significant impact from pre-harvest glyphosate on the moisture content of grain. However, on one site there was a trend for grain from the treated plots to be about 2% (25.5 vs 27.5 % MC, SED 1.43) drier eight days after treatment but there were no differences five, 12 and 14 days after treatment (Sheppard *et al.*, 1989).

Barley In the barley trials carried out by SAC in 1980, 1981 (Table 5) and 1985 (Richards & Sheppard, 1987), there was a reasonably consistent trend for pre-harvest glyphosate treatments to result in the moisture content of grain to be around 1% lower at harvest. This was both in weedy and non-weedy sites. This advantage was not noted in a total of six trials carried out in 1983 and 1984 (Richards & Sheppard, 1987). The harvest weather was wetter in the years where there was a trend towards pre-harvest glyphosate slightly reducing moisture content (Table 6).

This suggests a difference in the impact of the pre-harvest application of glyphosate on the grain moisture content of barley and wheat. Unlike wheat, there appears to be reasonably consistent reductions of barley grain moisture content under high humidity conditions. This more consistent trend for pre-harvest glyphosate to reduce the moisture content of barley rather than wheat may be due to the morphology of the grain. In wheat, the grain is more effectively shielded from the spray by the glumes. However, the results from North America suggest that there may only be an advantage in the pre-harvest application of glyphosate on grain moisture content of wheat in slow maturing conditions and low levels of humidity. It can be hypothesised that in high humidity conditions the wheat grains in treated crops are unlikely to lose moisture more rapidly or that they reabsorb moisture more readily than the untreated crop.

Kg ae/ha	Crop	Year	Couch	Straw throughput (t/ha)			Separation losses (% yield)			Wheeling losses (% yield)			MC grain at harvest (%)			Yield (t/ha)		
				0	*0.72*	*1.44*	*0*	*0.72*	*1.44*	*0*	*0.72*	*1.44*	*0*	*0.72*	*1.44*	*0*	*0.72*	*1.44*
1 Dunbar	SB	80	No	3.7	3.2	2.9	1.7	1.0	0.9	0.0	4.5	3.5	*20.8*	*19.8*	*19.6*	4.10	4.20	4.20
2 Haddington	SB	80	No	5.7	4.1	4.6	4.8	1.6	1.6	0.0	3.1	1.9	*25.3*	*23.5*	*23.1*	4.20	3.60	2.80
3 Musselburgh	SB	80	No	3.5	2.8	2.5	1.4	0.8	0.8	0.0	5.3	4.6	*20.2*	*18.6*	*18.6*	4.20	3.90	4.00
4 1980 2	SB	80	No	8.7	7.3	7.5	1.0	0.8	1.3	0.0	3.4	2.0	*21.7*	*19.7*	*19.2*	3.60	3.80	4.00
5 1980 5	SO	80	Yes	7.5	6.2	6.2	3.6	5.7	2.9				*18.5*	*18.2*	*17.9*	4.39	4.97	5.15
6 1981 1	WB	81	No	6.6	4.9	5.5	4.5	3.1	2.8	0.0	4.7	5.3	*19.2*	*17.6*	*17.6*	5.00	5.80	5.10
7 1981 3	SB	81	No	8.7	7.3	7.5	1.0	0.8	1.3	0.0	3.4	2.0	*17.3*	*16.8*	*17.4*	3.39	3.59	3.14
8 1981 4	SB	81	No	8.0	6.3	6.0	3.6	2.4	2.6	0.0	3.3	1.3	*17.6*	*15.9*	*17.5*	4.96	6.66	6.39
9 Kedslie	WB	81	Yes	6.4	4.6	5.7	7.3	3.0	2.8	0.0	4.7	5.3	*21.7*	*19.7*	*19.2*	3.50	3.70	3.90
10 Biel 81A	SB	81	Yes	3.6	3.1	3.2	1.0	0.8	1.2	0.0	3.4	2.0	*19.2*	*17.6*	*17.6*	5.00	5.70	5.10
11 Biel 81B	SB	81	Yes	5.7	4.5	4.2	3.8	2.4	2.5	0.0	3.3	1.3	*17.3*	*16.8*	*17.4*	3.60	3.60	3.10

Sites 1-3 - O'Keefe, M G; Richards M C; Sheppard, B W (1981): The effects of crop safety and weed control from applications of the isopropylamine salt of glyphosate pre-harvest of cereals; *Proceedings Crop Protection in Northern Britain*, pp. 51-56
Sites 4-8 - SAC unpublished data (SCAE/ESCA, 1982)
Sites 9-11 - Sheppard, B W; Richards, M C; Pascal, J A (1984): Agronomic effects from the control of *Agropyron repens* in barley by pre-harvest application of glyphosate; *Proceedings Crop Protection in Northern Britain*, pp. 51-56.

Table 5. Scottish Agricultural College (East of Scotland College of Agriculture) and Scottish Centre of Agricultural Engineering (Scottish Institute of Agricultural Engineering) results with Winter Barley (WB), Spring Barley (SB) and Spring Oats (SO), 1980 and 1981

	July	August	Total
1980	66.5	105.7	172.2
1981	69.1	7.3	76.4
1982	45.0	62.4	107.4
1983	9.8	36.5	46.3
1984	17.1	28.9	46.0
1985	177.1	114.2	291.3
1986	60.2	70.3	130.5
1987	85.9	101.3	187.2
1988	165.9	83.6	249.5
1989	15.1	113.8	128.9

Table 6. Rainfall at Penicuik in the harvest periods of the Scottish trials 1980-89 (mm)

Straw moisture content at harvest

Wheat The adoption of the strobilurin fungicides can increase the moisture content of wheat straw at harvest, particularly at cutter bar height (Wacker, 2000). Jorgensen & Olesen (2002) also demonstrated that fungicides, particularly the strobilurins, can significantly increase the moisture content of wheat straw at harvest. The extent of the increase varied according to the dose of strobilurins adopted and also between seasons. However, there was little additional moisture content of the straw when strobilurins, at the doses close to those that are being used commercially today in the UK, were added to a triazole based fungicide programme.

Trials in crops infested by common couch by the Scottish Centre of Agricultural Engineering (SCAE) and SAC showed a reduction in moisture content of matter other than grain (MOG) in 1989 in one of two trials (Sheppard *et al.*, 1989). In the other trial rain fell two days before harvest and there was no reduction in the moisture content of the MOG. TAG carried out six trials between 2004 and 2006 on the impact on straw moisture content of pre-harvest application and recorded no beneficial effects in evenly-maturing and weed-free crops. In some cases, the pre-harvest application resulted in straw with a higher moisture content at harvest, particularly at cutter bar height. This may be due to the fact that the characteristics of the straw were changed by the glyphosate in such a way that it may have more readily reabsorbed moisture from the atmosphere.

Barley There was a significant reduction in the moisture content of straw following pre-harvest glyphosate treatment in four Scottish spring barley trials in 1985 by SCAE/ESCA(SAC) (Richards & Sheppard, 1987). All the trials had either secondary tillers or wheat plants as weeds. In addition, 1985 was a particularly wet and humid harvest. In 1984, when there was a very dry harvest, only at one of the three sites was there a significant reduction in straw moisture content from glyphosate treatment. Data from earlier trials did not include moisture content analysis. However, the reduction in weight of MOG combined, following glyphosate pre-harvest use in 1979-81 trials by the same group, probably reflects reduced moisture content of the straw. These trials were also reported by O'Keeffe & Makepeace (1985). Literature searches have not found any other public domain research in this area.

Harvesting of the crop

Wheat In general, pre-harvest glyphosate applied to evenly-maturing weed-free wheat crops in experiments in the UK appears to have no beneficial effect on the moisture content of grain and straw.

However, survey information (Monsanto, 2007) based on the opinions of drivers of modern Claas combines in Britain suggests large financial benefits when harvesting a 'fully dry harvest managed crop' (i.e. crop treated with pre-harvest glyphosate) compared to a 'partially dry conventional crop' containing green stems and nodes.

Reductions in green matter other than grain (MOG) may increase the speed of combining, reduce the moisture content of the grain and straw and also reduce separation and header losses (O'Keeffe & Makepeace, 1985).

SAC and SCAE investigated this in 1989 in two field trials infested with common couch (Sheppard *et al.*, 1989). As mentioned earlier, the impact on grain moisture was limited to a non-statistical reduction, eight days after treatment, in one of the trials. No effect was noted five, 12 or 14 days after application. The level of desiccation of the couch was determined by both the dose and formulation of the glyphosate and the moisture content of the MOG (including straw) on one site was reduced. It is interesting to note that on the other site, harvested two days after rain, there was no difference in the moisture content of the MOG. This again suggests that rain or conditions of high humidity after application may negate the impact of pre-harvest glyphosate in wheat. In the trial where the moisture content of MOG was reduced, there was a consistent trend to a higher grain yield due to reduced separation, shedding and header losses. In addition, a significant increase in combine throughput was recorded.

Since the Scottish trials no experimental studies have been published in the public domain on the impact on combining efficiency.

Barley The impact of the pre-harvest application of glyphosate on the harvesting operation of weed infested barley was investigated by ESCA (SAC) and SCAE in a total of 10 trials in 1983, 1984 and 1985 (Sheppard *et al.*, 1984; Richards & Sheppard, 1987). Overall, there was no advantage in terms of separation and header losses but in the wet harvest of 1985, there was a significant reduction in the moisture content of the straw in all four trials and there was also a trend to reductions in grain moisture content. All trials in 1985 were infested with either wheat or secondary tillers. These 'weeds' did not feature in the trials carried out in earlier years.

An 11-31% improvement in combine efficiency, which will give some combining time benefits, was found by Sheppard *et al* (1984) in the earlier Scottish trials in barley. However, these trials were undertaken over 20 years ago, and advances in combine technology may have improved their ability to cope with high matter other than grain (MOG).

The Scottish trials also indicated that wheeling losses from the late pass through the crop averaged about 3.5% of yield. However, there have been changes in sprayer and tractor equipment and in widths of sprayer wheelings since the 1980s which makes the current value of this loss difficult to assess.

Hagberg falling number

There have been advantages recorded from increased Hagberg Falling Number (HFN) because of the reduction in green grains achieved with pre-harvest glyphosate (Lunn *et al*., 1998). This is because in the initial stages of grain development alpha-amylase activity is very high. However, SAC and the SCAE did not measure an increase in HFN in the two couch infested trials carried out in 1989 to measure the impact on pre-harvest glyphosate on the harvesting operation (Sheppard *et al.*, 1989).

Gale *et al*. (1983) hypothesised that a slow grain drying rate could trigger pre-maturity alpha-amylase formation in wheat. Astbury & Kettlewell (1992) suggested that as the drying rate of grain appears to be a determinant of (HFN) in their experiments then, in theory, pre-harvest glyphosate may reduce any harmful effects from fungicides prolonging grain drying on this quality parameter. They also considered that pre-harvest application may even be of potential value in weed-free and evenly-maturing crops, irrespective of fungicide application, where the weather results in slow grain drying. However, whilst the relationship of drying rate and HFN existed in their 11 field experiments, it was not possible to predict the HFN at harvest from an assessment of drying rate. The overall relationship was poor with only one third of the variation accounted for. They concluded that another seasonal factor may have been involved in triggering pre-maturity amylase formation in addition to grain drying rate. The 11 field experiments in this project, carried out in evenly-maturing and weed-free wheat crops, failed to record an advantage to pre-harvest glyphosate on HFN.

The research done by Astbury & Kettlewell was carried out in wheat treated with triazole fungicides and overall there were limited yield responses to their use. Indeed, the only significant effect of triazole fungicides reducing HFN occurred in conjunction with a large yield increase. This supports other research which suggests also that a detrimental effect of fungicides on HFN occurs only when there are considerable benefits on yield (Kettlewell *et al*., 1987; West, 1990). The relatively cool and humid conditions conducive to large responses to fungicides may be comparable to those where an extension of grain drying time could result in lower HFN.

The introduction of strobilurin fungicides resulted in a more prolonged retention of green leaf than from the triazoles. Jorgensen & Olesen (1992) demonstrated in experiments in Denmark that strobilurins increased the grain moisture content of wheat at harvest more than the triazoles. However the differences were relatively small when the doses of the strobilurins were close to levels used commercially in the UK.

There has been no consistent impact on HFN of pre-harvest application of glyphosate in five TAG trials in weed-free and evenly-maturing crops, even where large doses of strobilurins have been employed. The number of cases where there was a trend towards an increase in HFN was matched by the number of cases where there was a trend towards a decrease. The results are in line with current knowledge which clearly suggests that it is difficult to imagine alpha-amylase synthesis at moisture contents below 35% (John Flintham, John Innes Centre, personal communication).

Other quality factors

TAG trials also indicate that there is no impact on the specific or thousand grain weight of grain as a result of the pre-harvest application of glyphosate to weed free and evenly-maturing wheat crops. This has been confirmed by a number of other authors.

The response of malting of barley and bread making qualities of wheat to glyphosate pre-harvest showed no effect on energy potential, protein or tetrazolium-test data in barley or protein in wheat (O’Keeffe, 1981b).

Fernandez *et al*., (2001) and Manthey *et al*., (2004) and others have confirmed no disadvantages to malting or baking characteristics.

There is no published data on the impact of the pre-harvest application on mycotoxins in wheat but there is data on the influence of glyphosate used in stubbles (Fernandez *et al.*, 2005; Henriksen & Elen, 2005).

Conclusions

- Reductions in the incidence of glyphosate residues will only be achieved by reducing proportion of crops treated.

- Pre-harvest application of glyphosate to wheat and barley does not reduce yields provided that the crop is evenly-maturing and that application is made when the crop has a bulk grain moisture content of 30% or less.

- There appears to be no advantage, in terms of moisture content of the grain and straw and Hagberg falling number, of the pre-harvest application of glyphosate to evenly maturing and weed free wheat crops.

- There appears to be a more consistent advantage from pre-harvest glyphosate in reducing the straw and grain and moisture content of barley but most of the trials were carried out in weed infested crops or in the presence of secondary tillers. The greater impact on barley may be explained by the fact that the grain is more exposed than wheat to the direct spray or that treated wheat grain and straw more readily reabsorbs moisture from the atmosphere.

- The pre-harvest application of glyphosate for the control of perennial weeds has been of tremendous value to the agricultural industry. It has enabled high levels of control whilst not causing delays in subsequent field operations.

- An approach suggested by some to reduce the incidence of glyphosate residues is to recommend threshold levels of perennial weeds that have to be exceeded prior to application. However, this is not realistic due to the fact that the opportunity may not exist every year to apply glyphosate pre-harvest, because of cropping or weather restrictions and also because the patchy nature of the field distribution. Applications to very low populations of perennial weeds will, however, still have a profound impact on their long term dynamics.

- Potentially there are advantages to the harvesting operation of applying pre-harvest glyphosate to wheat to control significant levels of annual or perennial weeds or secondary crop tillers. The extent of the advantages is likely to be dependent on subsequent weather conditions and therefore, it is unlikely that thresholds can be clearly identified. Controlling green grains of wheat is also likely to increase HFN. The reduction in the moisture content of the green stems of ears that contain grain that is 'harvest dry' has not been tested in experiments although a survey of combine drivers suggests that it is financially beneficial.

- Hence, the incidence of glyphosate residues may be reduced by targeting the application to situations where clear advantages have been recorded. However, the risk to crop yield from applications to unevenly-maturing crops needs to be highlighted, should a significant proportion of the crop have a moisture content well above 30% at the time of application. Residues in the grain may be higher when glyphosate is applied to grain with moisture contents significantly above 30% (Cessna *et al*., 1994 & 2002).

- There is some evidence from North America to suggest that the benefits to grain and straw moisture content are more likely when the application is made to wheat crops that are slowly maturing in dry and low humidity conditions. It is hypothesised that this may be because the treated straw and grain is more likely to re-absorb moisture. Trials in Scotland suggest the converse may be true in barley, and the benefit may be clearer in wet and humid harvests, particularly when secondary tillers or volunteer wheat are present. However, there is a need for research on this issue.

- The case for pre-harvest glyphosate in both wheat and barley for perennial weed or secondary tiller control is easily made. Caution should be exercised on treating evenly-maturing and weed-free wheat crops, particularly in unsettled weather conditions. However, the approximately one percent reduction in the grain moisture content in spring barley in Scotland provides an economic case for the application of pre-harvest glyphosate unless the harvest weather is very dry. This is because the treatment is cheaper than drying the grain by one percent (currently a reduction of grain MC by 1% is valued at c £6.75/t grain (Contractor & Large Scale Farmer, Jan 2007)), or that it provides one day's extra combining. This suggests that a pre-harvest application could be justified to an area of evenly-maturing and weed-free spring barley equivalent to one day's combining where the rate of grain drying under the prevailing weather conditions is limited. However, the end user should be consulted before taking a decision to apply this treatment. There is more information on the economics of pre-harvest application in the Appendix.

- Controlling green grains in wheat with the pre-harvest application of glupohsate is likely to increase HFN. Experiments have not confirmed whether pre-harvest glyphosate reduces the moisture content of green stems of ears that contain grain that is 'harvest dry' and consequently improve the harvesting operation.

- Of late, it has been recognised that pre-harvest application for annual broad-leaved weed control rather than earlier conventionally timed applications of a selective herbicide may result in benefits in terms of providing weed hosts to insects that make a significant contribution of biodiversity. However, unless this approach is carefully targeted, the crop may suffer from competition that will result in yield losses and it is not always possible to apply the pre-harvest glyphosate at the specified timing because of soil, crop or weather conditions. However, a pre-harvest application may prevent or reduce seed production of some weeds species, thus reducing a feed source for some seed eating farmland bird species.

Further research:

- Investigate the impact of post application humidity and rainfall on the moisture content of grain and straw of wheat and barley in order to help to elucidate the different results in the two species achieved by pre-harvest glyphosate.

- Re-assess, with current agronomy and harvesting machinery, the impact on the harvesting operation of pre-harvest application of glyphosate of evenly-maturing and weed-free spring barley. Experiments on the impact on the wheat harvesting operation of pre-harvest glyphosate should not be carried out unless it is proven that treated grain and straw do not readily reabsorb moisture. However it should be noted that experiments have not confirmed whether pre-harvest glyphosate reduces the moisture content of green stems of ears that contain grain that is 'harvest dry' and consequently improve the harvesting operation.

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Appendix - Review of SIAE(SCAE)/ ESCA(SAC) trials 1979-89

Review of straw throughput/ MOG throughput, separation losses and wheeling losses

Three groups of trials with glyphosate pre-harvest treatments are reviewed. These trials were initiated by SIAE (later SCAE) and ESCA (later SAC) at Bush Estate, Penicuik, Midlothian in 1979 and were completed in 1989. Funding was provided by Monsanto Agricultural Company and local core funding.

The trials were initiated to examine the potential for pre-harvest glyphosate to control couch-grasses, a serious problem at that time for UK farming, with treatment applied once the crop grain moisture content (MC) was less than 30%. Up to that point (since 1974), glyphosate had been used post-harvest in stubbles, but this was an unreliable treatment, particularly in late harvest areas (O'Keeffe, 1980; O'Keeffe *et al*., 1981).

The concept of a pre-harvest treatment was first reported in the UK by O'Keeffe (1980). He showed that crop safety was suitable so long as treatment was undertaken after the crop had a grain moisture content (MC) of less than 30%.

O'Keeffe *et al*. (1981) reported the first trials mentioned above (1979-80): Series 1. A second group of trials from 1983-85 comprising published (Sheppard *et al*., 1987) and unpublished data was then undertaken: Series 2. These were mostly in spring barley, but included winter barley and spring oats. A final Series 3 was undertaken in winter wheat in 1988/9 (Sheppard *et al*., 1989).

The trials examined short and long-term control of couch-grass, short-term control of annual weeds at harvest and then secondary crop growth. This led to the concept of a harvest-aid treatment, allowing more efficient and possibly earlier combining. This was an attractive option for wet years and in areas with traditionally later and more difficult harvests in the North and West.

The following part of the review examines the impact of the pre-harvest glyphosate treatment on:

- Straw throughput/matter other than grain (MOG) throughput
- Separation losses
- Wheeling losses from this late treatment

It should be noted that some of the trials included both weed control and crop assessments. The differences in treatment crop responses appear to be retained whether weeds were present or not, so the dual-targeted trials are retained in the review.

Straw throughput/ MOG throughput

Series 1 (1979-81) Table 1

In this series, glyphosate was applied at 0.72 and 1.44 kg acid equivalent (ae)/ha, equivalent to 2 and 4 l/ha of the Roundup formulation available, and compared with untreated crop. Straw throughput and MOG throughput can be counted as the same material despite a change in name between trials sets.

At all sites, pre-harvest glyphosate reduced straw/ MOG throughput. The meaned data for this trial set is given in Table 1.

Glyphosate dose	All sites	Sites with common couch	Sites without common couch
Untreated	6.28	5.80	6.41
0.72kg ae/ha	4.94	4.60	5.13
1.44kg ae/ha	5.07	4.83	5.21

Table 1. Straw throughput/MOG throughput (t/ha); Series 1 (1979-81)

The differences between untreated and treated plots probably reflects reduced MC of the MOG, but that was not measured. There were no major differences between doses of glyphosate, indicating that 0.72kg ae/ha would be sufficient to help harvesting.

When sites with and without couch-grass are compared, the difference between treatments remained similar, but MOG appeared higher in sites without couch-grass. This may reflect site differences, but may indicate reduced straw yield where couch-grass was competing.

Series 2 (1983-85)

In this series lower doses of glyphosate were examined, specifically to assess harvest-aid crop responses, although weeds were present at some of the sites. Specific MOG data is not given in the report paper, but combine header separation losses were examined, and are reviewed below. However, there is evidence from this series of a significant reduction of MC of straw in 1985, a wet harvest, at 4 sites where this was measured. Three sites were measured in 1984, a dry harvest, and at one there was a significant reduction. This reduction in straw MC confirms the likely reason for the impact of the treatments on MOG weights indicated in Series1.

Series 3 (1988-89) Table 2

This series comprises two trials in winter wheat. In this series, two formulations of glyphosate were provided by Monsanto and compared with untreated crop: MON14478 + X-78 adjuvant and Roundup Four80 + Team Four80 surfactant. It is believed that the doses of 0.75 and 1.0 l/ha are equivalent to 0.36 and 0.48 kg ae/ha glyphosate.

The two trials clearly show that both formulations gave a significant reduction in MOG throughput of about 0.5 t/ha. Percent MC of MOG at wheat harvest was measured at these sites and is given in Table 2, modified from Sheppard *et al*. (1989):

At Site 1, MOG MC was reduced by the treatments, but at site 2 rain fell just before sampling. In this situation there appeared to be a formulation advantage to Roundup Four80. There was no difference between the treatment doses tested.

Separation Losses

Series 1 (1979-81) Table 3

With a few exceptions, pre-harvest glyphosate reduced separation losses at combining. Table 3 gives the mean separation loss (% yield) response to glyphosate treatments in this Series, combined sites and those with and without couch-grass.

The improvement in separation losses were maintained whether couch-grass was present or not, with perhaps a greater reduction where couch-grass was present.

Treatment (l/ha)	Site 1	Site 2
Untreated	31.2	44.3
MON14478 0.75	26.1	47.2
MON14478 1.00	22.9	47.1
Roundup Four80 0.75	28.9	39.1
Roundup Four80 1.00	26.2	39.3
SED	3.37	4.91

Table 2. Percent moisture content of MOG; Series 3 (1988-89)

Treatment (kg ae/ha)	All sites	Sites with common couch	Sites without common couch
Untreated	3.06	3.93	2.40
0.72	2.04	2.98	1.75
1.44	1.88	2.35	1.88

Table 3. Separation losses (% of yield); Series 1 (1979-81)

Series 2 (1983-85) Tables 4, 5, 6

In this series, lower doses of glyphosate were tested and separation losses were split into whole head and grain losses (by no./m^2) as well as overall separation losses at combining (% yield). Table 4 gives the meaned data for separation losses x glyphosate doses. The sites varied as to doses tested as well as weed populations and crop secondary growth. This variation in dose prevents a full comparison, but the sites can be grouped by doses used. As some sites had spring barley and some winter barley, a further comparison is made between sites with similar treatments in winter and spring barley.

The combined data tends to suggest that glyphosate treatments at these low doses continue to reduce separation losses, but splitting the data to compare spring and winter barley shows a greater impact on winter than spring barley. Differences between doses, where available, are small.

There was a tendency for the 0.54 kg ae/ha glyphosate to reduce head losses, but not lower doses (Table 5). However, there was no such response pattern to glyphosate treatment for number of grains shed (Table 6).

	All sites			WB v SB		WB v SB	
Sites	1/2/3	4/5/6	7/8/10	5/7/8	v 4/6/10	7/8	v 1/2/3/10
Glyphosate dose (kg ae/ha)							
Untreated	2.47	7.77	3.73	8.30	3.20	4.95	3.23
0.27	2.60	-	-	-	-	-	-
0.35	-	6.50	2.97	7.07	2.40	-	-
0.54	2.47	-	3.40	-	-	4.40	2.93

Table 4. Separation losses (% of yield) in winter barley (WB) and spring barley (SB); Series 2 (1983-85)

	All sites			WB v SB		WB v SB	
Site	1/2/3	4/5/6	8/9/10	5/8/9 v	4/6/10	8/9 v	1/2/3/10
Glyphosate dose (kg ae/ha)							
Untreated	11.40	2.30	8.67	6.90	4.07	10.00	10.05
0.27	11.90	-	-	-	-	-	-
0.35	-	2.97	10.67	9.53	4.10	-	-
0.54	9.30	-	7.33	-	-	9.00	7.98

Table 5. Heads shed (/m^2) at combining in winter barley (WB) and spring barley (SB); Series 2 (1983-85)

	All sites			WB v SB		WB v SB	
Site	1/2/3	4/5/6	8/9/10	5/8/9 v	4/6/10	8/9 v	1/2/3/10
Glyphosate dose (kg ae/ha)							
Untreated	13.23	4.37	12.67	8.27	8.87	12.00	13.43
0.27	1.27	-	-	-	-	-	-
0.35	-	3.70	10.67	8.40	6.97	-	-
0.54	12.67	-	17.33	-	-	20.05	12.25

Table 6. Grains shed (/m^2) at combining in winter barley (WB) and spring barley (SB); Series 2 (1983-85)

Series 3 (1988/89)

This series examined the effect of two formulations of glyphosate pre-harvest in winter wheat (as described above) on two sites. There was a small but significant effect from the higher (1.0l/ha) dose of both formulations on separation losses, but as in Series 2, little or no effect on head or grain losses (shedding losses) or header losses.

Wheeling Losses

Series 1 (1979-81) Table 7

Wheeling losses from pre-harvest treatments were assessed in Series 1 trials. These sites were not all tramlined but either wheeled or tramlined. The combined mean effects are given in Table 7.

Glyphosate dose kg ae/ha	Wheeling losses (% yield)
Untreated	0
0.72	3.91
1.44	2.92
SED	

Table 7. Wheeling losses (% yield), Series 1 (1979-81)

Overall there was an impact of 3-4% yield loss due to the late sprayer pass through the crop. There was no difference in response to a late pass of the sprayer through the crop whether the crop had been tramlined from early in the season at one site to where wheelings had been created by previous passes of the sprayer and other equipment at other the sites.

Costs and benefits assessments

For the factors covered in this section, and for these Scottish trial series, the following costs and benefits may be assignable to pre-harvest glyphosate treatments:

Straw/ MOG throughput and separation losses

Losses due to these factors are approximately as follows:

Series 1: 1.0 t/ha (overall spring and winter barley)
0.9 t/ha (where couch-grass present)
1.2-1.5 t/ha (where no couch-grass present)

Series 3: 0.5 t/ha (in winter wheat)

Reductions in MOG throughput would increase combine speed and reduce grain losses. Sheppard *et al*. (1984) shows a close relationship between grain loss and MOG throughput. In their paper, which includes results described as Series 1 above, they indicate that reductions of 11-31% in feed rate from the desiccation of crop and weeds could lead to a 10-50% reduction in grain loss or an increase of 11-31% in forward speed at a given grain loss level.

Grain losses are variable, and in these trials ranged between 1 and 6% of yield. As an example, a 25% reduction in grain losses would reduce the loss range to 0.75 to 4.5% of yield. For a 7 t/ha spring barley crop, this would equate to 17.5-315 kg/ha; at a value of £100/t, this equates to £1.75 to £31.50/ha saving. For a 10 t/ha wheat crop, this would equate to as to 25-450 kg/ha loss reduction, or at £100/t crop value, £2.50 to £45.0/ha loss reduction.

However, in series 2 there was not a strong effect on grain shed onto the ground at combining, so the lower end of the benefits above may be the best representation of the mean effects of the treatment.

Assessing the benefits on combine efficiency and speed is more difficult to assess. An 11-31% efficiency improvement (Sheppard *et al*., 1984) will give some time benefits. Currently contractors charge around £66.20/ha for combining (SAC, 2007), so time is not included directly in this value. Nevertheless, if 10% more area can be combined over a given period, then this will prove beneficial to the grower if they are also combining the crop.

However, these trials were undertaken more than 20 years ago, and improvements in combine technology may have improved their ability to cope with high MOG crops, although fuel and time costs inherent in going through weedy or greener crops will still be significant.

Wheeling losses

Wheeling losses in Series 1 averaged about 3.5% of grain yield. In spring barley at 7.0 t/ha, this would equate to a cost of 245 kg/ha grain, and at £100/t, this equates to £24.50/ha. In wheat at 10.0 t/ha, the loss would be £350 kg/ha; at £100/t this equates to £35/ha.

These costs are not generally taken into consideration by growers when taking a decision as to whether or not to use a pre-harvest treatment as a harvest-aid. The benefits outlined above in reducing MOG throughput and separation losses and improving combine efficiency balance this out to some extent, apart from any benefits in grain qualities outlined elsewhere in this review. The more difficult the harvesting conditions, such as in a wet harvest or in late harvesting areas, the more attractive the improvements in combining efficiency become; particularly in barley. The costs of delaying harvest in terms of grain moisture and drying are evaluated elsewhere.