# Adjuvants, glyphosate efficacy and post-spraying rainfall

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## Summary

Eleven adjuvants were investigated to assess their ability to reduce glyphosate susceptibility to rainfall occurring in the critical 6 hour post-spraying period. Adjuvants were added to glyphosate CT which was applied at 0.54 kg a.i. $ha^{-1}$ in a spray volume of 60 L $ha^{-1}$. Young plants of Wimmera ryegrass (*Lolium rigidum*), hedge mustard (*Sisymbrium officinale*), wild oats (*Avena fatua*) and radish (*Raphanus sativus* cv. Round Red) were grown in the glasshouse and used for evaluation. Plants were subjected to simulated rainfall at an intensity of 5-6 mm $hr^{-1}$ for a period of 1 hour at one, three and six hours post-spraying. Adjuvant performance was assessed by measuring plant freshweights 25 days after treatment.

The effect rainfall had on glyphosate efficacy was as expected. That is, as the rain-free period increased, plant freshweight decreased and hence the degree of control increased. Glyphosate without adjuvant requires a rain-free period of greater than 6 hours post-spraying, regardless of species, to gain results similar to those when no rain was applied. With the addition of an adjuvant to glyphosate, generally, control was enhanced when plants were subjected to post-spraying rainfall. However, glyphosate/adjuvant combinations varied in effectiveness with adjuvants and plant species. The non-ionic adjuvant Activator 90 gave the most effective and consistent enhancement of activity following post-spraying rainfall. Activator 90 reduced the critical post-spraying period from 6-8 hours down to 1-3 hours. With the exception of Activator 90 and LI700, adjuvants which significantly ($P<0.05$ and $P<0.01$) enhanced glyphosate activity on dicotyledonous plants did not necessarily enhance glyphosate activity on graminaceous plants. These adjuvants were Sprayfast, Meteor and Codacide oil. On the other hand, Pulse significantly ($P<0.01$) enhanced glyphosate activity on graminaceous rather than dicotyledonous plants. Such results may reflect differences in leaf shape, orientation and surface waxes between the two plant Classes. Therefore, Activator 90 in particular and to a lesser extent LI700 may enhance glyphosate activity so as to overcome differences in plant foliar characteristics. Adjuvant performance was ranked as follows: Activator 90 > LI700 (0.50%) > LI700 (0.25%) > Pulse > Sprayfast = Meteor = Codacide oil > Adjuvant E > Bond > Sodium bisulphate = Glyphosate alone > Enersol. Enersol caused a slight reduction in glyphosate phytotoxicity across all plant species.

## Introduction

Glyphosate is a highly effective broad-spectrum herbicide. Adjuvants, more specifically surfactants, are important spray additives which enhance glyphosate efficacy particularly when target plants are grown under adverse environmental conditions (Kudsk and Kristensen 1989). Many different glyphosate/adjuvant combinations have been studied on numerous weed species (Wyrill and Burnside 1977, Turner 1985, Field and Bishop 1988, Anderson and van Haaren 1989, Swietlik 1989, Yonce and Skroch 1989), but few have considered rainfall in the critical 6-8 hour period post-spraying (Olesen and Kudsk 1987, Field and Bishop 1988). Glyphosate is water-soluble, and is very prone to dilution and/or removal from plant leaves by rainfall (Coupland and Caseley 1981, Olesen and Kudsk 1987, Bryson 1988). It is therefore recommended that a rain-free period of 6-8 hours is required for maximum herbicidal effectiveness (Baird and Upchurch 1972, Coupland and Caseley 1981). Levels of rainfall from as low as 0.9 mm one hour post-spraying may reduce glyphosate efficacy (Wells unpub.). Olesen and Kudsk (1987) found that rainfall intensities of 2.8 and 32 mm $h^{-1}$, six hours post-spraying, removed 20% of the glyphosate from barley leaves.

The addition of an adjuvant to glyphosate may reduce its susceptibility to post-spraying rainfall. This may be achieved by increasing spreading and/or penetration and subsequent translocation or increasing retention on the leaf surface by preventing dilution and the physical forces of rainfall removing the herbicide (van Valkenburg 1982). To reduce the critical 6-8 hour period post-spraying for glyphosate and/or increase its retention would be of considerable advantage in situations where rainfall is difficult to predict. Presently, glyphosate is rarely used in such situations since the loss of efficacy due to rainfall is expensive in terms of herbicide cost, poor weed control, labour and time.

The aim of this study was to determine if the adjuvants chosen significantly affect glyphosate activity against four plant species following short-term post-spraying rainfall.

## Materials and methods

### *Growth of Plants*

Four test species were used; Wimmera ryegrass (*Lolium rigidum*), wild oats (*Avena fatua*), hedge mustard (*Sisymbrium officinale*) and cultivated radish (*Raphanus sativus* cv. Round Red). Seeds of each were pre-germinated in a growth chamber for approximately 4-6 days at 15/25°C 12 hours dark/light respectively. Germinated seeds were planted into 10 cm diameter plastic pots. One plant per pot represented one replicate plant. There were four replicates per treatment per species.

A commercial potting mix (Debco) was used to which the following fertilizers were added per 45 L of soil mix: dolomite (lime) (14 g), superphosphate (30 g), iron chelate (5.6 g), Osmocote 'slow' (35 g) and mixed trace elements (70 g). The plants were grown and maintained in glasshouse conditions (15/20°C, night/day, 70% r.h.).

### *Spraying of Plants*

Adjuvants were added to glyphosate (Nufarm Glyphosate CT, 0.45 kg a.i. $L^{-1}$) which was used at 0.54 kg a.i. $ha^{-1}$ (Table 1). Adjuvant mixtures of glycerine (2% v/v) and Meteor (1% v/v) with both Adjuvant E (0.20% v/v) and Activator 90 (0.125% v/v) were also tested. A higher rate of Activator 90 (0.22% compared with 0.125%) was inadvertently used when hedge mustard and wild oats were sprayed.

Glyphosate/adjuvant combinations were applied with a laboratory sprayer fitted with two Spraying Systems 11001 'Tee-jet' nozzles operating at 300 kPa. The speed of the nozzle carriage was adjusted to deliver 60 L $ha^{-1}$ at the following growth stage: ryegrass was sprayed at the 15 leaf stage, hedge mustard 6 to 7 leaf stage, wild oats and radish 6 leaf stage. Simulated rainfall was applied after spraying.

### *Rainfall simulation*

A rainfall simulator was constructed using the design of Taylor and Matthews (1986). This produced a droplet spectrum and terminal velocities resembling natural rainfall and provided a target area of 1.5 $m^2$. Local town water supply (pH 6.8) was used at a working pressure of 150 kPa. It was decided from preliminary work that rainfall at an intensity of 5-6 mm $h^{-1}$ for a duration of 1 hour at one, three and six hours post-spraying would be used.

### *Adjuvant Properties*

Surface tension of the spray mixtures were measured using a torsion balance (White Electrical Instruments, England). Contact angles were measured using the projection method (Ebeling, 1939), by placing approximately 2 $\mu$L drops of spray solution onto a slide evenly coated in beeswax and calculating the angle from the projected image. Beeswax was used as an appropriate standard measurement surface for reasons of uniformity and representation of surface waxes found in leaves. Ideally, leaves from the test species should have been used, but this was not practical at the time. Measurements of pH were made using an Activon

**Table 1. Adjuvants investigated.**

| Trade name | Chemical description | Source[a] | Ionic form[b] | Percentage spray volume (v/v) |
|---|---|---|---|---|
| Pulse | organosilicone | Monsanto | N | 0.20 |
| Bond | 450 g/L synthetic latex + 100 g/L surfactant | Nufarm | N | 0.14 |
| LI700 | 750 g/L soyal phospholipids | Nufarm | amphoteric | 0.25, 0.50 |
| Sprayfast | d-1-p-menthene and nonyl phenol ethylene oxide condensate | Key Chemicals | N | 0.25 |
| Meteor | 800 g/L ethoxylated tallow amine | Nufarm | C | 1.00 |
| Sodium bisulphate | $NaHSO_4$ | Nufarm | - | 0.80 (w/v) |
| Adjuvant E | organosilicone | Nufarm | N | 0.20 |
| Activator 90 | 850 g/L alkyl polyoxyethylene ether and free fatty acids + 50 g/L Isopropanol | Nufarm | N | 0.125 |
| Liase | 40% ammonium sulphate | Nufarm | - | 2.00 |
| Enersol | leonardite suspension as 12% humic acid | American/ Colloid | - | 3.30 |
| Codacide oil | 95% rape oil + 5% emulsifiers | Spray Tech | N | 2.0 |

[a] Monsanto Australia Ltd., Somerville Rd., Footscray West 3012, Vic.
Nufarm Ltd., 103 Pipe Rd., Laverton North 3026, Vic.
Key Chemicals Ltd., Box 36, 196 Auckland, NZ.
Spray Tech Australasia Pty. Ltd., 61 Crane Cres., Nerang 4211, Qld.
American Colloid Co., Agricultural Group, 5100 Suffield Crt., Skokie, Illinois.
[b] C = cationic; N = non-ionic.

**Table 2. Chemical and physical characteristics of the glyphosate/adjuvant combinations investigated.**

| Trade name | spray pH solution | Surface tension ($Nm^{-1}$) | contact angle (degrees) |
|---|---|---|---|
| Tap water | 6.80 | 0.070 | 97° (±2°) |
| Glyphosate CT | 4.62 | 0.048 | 66° (±4°) |
| Pulse | 4.56 | 0.025 | 24° (±3°) |
| Bond | 4.58 | 0.045 | 65° (±3°) |
| LI700(0.25%) | 4.26 | 0.034 | 53° (±2°) |
| LI700(0.50%) | 4.10 | 0.032 | 49° (±1°) |
| Sprayfast | 4.60 | 0.039 | 62° (±3°) |
| Meteor | 4.67 | 0.043 | 68° (±3°) |
| Sodium bisulphate | 2.22 | 0.042 | 72° (±3°) |
| Adjuvant E | 4.59 | 0.026 | 25° (±1°) |
| Activator 90 | 4.56 | 0.029 | 35° (±1°) |
| Liase | 4.55 | 0.046 | 72° (±2°) |
| Enersol | 4.90 | 0.044 | 73° (±3°) |
| Codacide oil | 4.58 | 0.037 | 53° (±2°) |

pH, ion, mV, temperature meter (Activon Scientific Products, Sydney).

*Assessment*

Observations were made at weekly intervals, and plant freshweights recorded approximately 25 days after treatment. Transformations were necessary on all data sets as indicated by a Box/Cox procedure (Box and Cox 1964). Analyses of variance on transformed data was performed using SAS (SAS Institute Inc., Box 8000, Cary, North Carolina 27511-8000).

## Results

*pH, Surface Tension and Contact Angle Measurements.*

The chemical and physical properties measured are shown in Table 2. Generally, the addition of adjuvants only changed pH marginally compared to glyphosate alone, which reduced tap water pH from 6.80 to 4.62. The addition of sodium bisulphate caused the spray solution to become highly acidic (2.22).

The organosilicones, Pulse and Adjuvant E, had the lowest surface tensions, 0.024 $Nm^{-1}$ and 0.026 $Nm^{-1}$ respectively. Activator 90 (0.029 $Nm^{-1}$) and LI700 (0.25 and 0.50%) at 0.034 $Nm^{-1}$ and 0.032 $Nm^{-1}$ respectively were the next lowest, followed by Codacide oil (0.037 $Nm^{-1}$) and Sprayfast (0.039 $Nm^{-1}$). Figure 1 shows the relationship between surface tension and contact angle. As surface tension decreased so did the contact angle. These two parameters are important as surface tension influences droplet spectrum and retention, while contact angle indicates the degree of spread of droplets. The product-moment coefficient of linear correlation (r) for glyphosate/adjuvant solutions is 0.95. Pulse (24°) had the lowest contact angle, then Adjuvant E (25°), Activator 90 (35°) LI700 (0.25 and 0.50%; 53° and 49° respectively) and Codacide oil (54°). However, the addition of Meteor, Sodium bisulphate, Liase and Enersol to glyphosate spray solution caused an increase in contact angle.

*Ryegrass*

As the time interval between spraying and the onset of rainfall increased, ryegrass freshweight decreased and hence control increased (Table 3). Several adjuvants, particularly LI700 (0.50%), Activator 90 (0.125%) and Codacide oil (2.0%) significantly ($P<0.05$) enhanced glyphosate activity on ryegrass even though rain fell 1, 3 and 6 hours post-spraying. These adjuvants more than halved freshweight when rain fell 1 hour post-spraying compared with glyphosate alone. Other adjuvants, Pulse (0.20%), LI700 (0.25%), Sprayfast (0.25%) and Adjuvant E (0.20%) also gave significant ($P<0.05$ and $P<0.01$) enhancement of glyphosate activity on ryegrass but only from when a minimum 3 hour interval occurred between spraying and rainfall. Adjuvant E and Activator 90 gave virtually complete control when rain fell 3 and 6 hours post-spraying. The addition of Enersol (3.30%) to the glyphosate spray solution retarded herbicide activity on ryegrass.

*Hedge mustard*

The general trend is similar to the results of ryegrass (Table 4). Adjuvants that significantly ($P<0.05$) enhanced glyphosate activity on hedge mustard, even though rain occurred at 1,3 and 6 hours post-spraying, were LI700 (0.25% and 0.50%), Sprayfast (0.25%), Activator 90 (0.22%) and Codacide oil (2.0%; except at 6 hours post-spraying). Activator 90 gave complete control at all times. LI700 (0.25% and 0.50%), Sprayfast and Codacide oil significantly ($P<0.05$) reduced freshweight compared with glyphosate alone, when rain fell 1 hour post-spraying, 3 hours post-spraying (LI700 0.25%; $P = 0.0566$) and 6 hours post-spraying (except Codacide oil; $P = 0.0672$). The inconsistent result with Codacide oil when rainfall occurred 6 hours post-spraying is difficult to explain, as are the results for glyphosate alone when rainfall occurred 6 hours post-

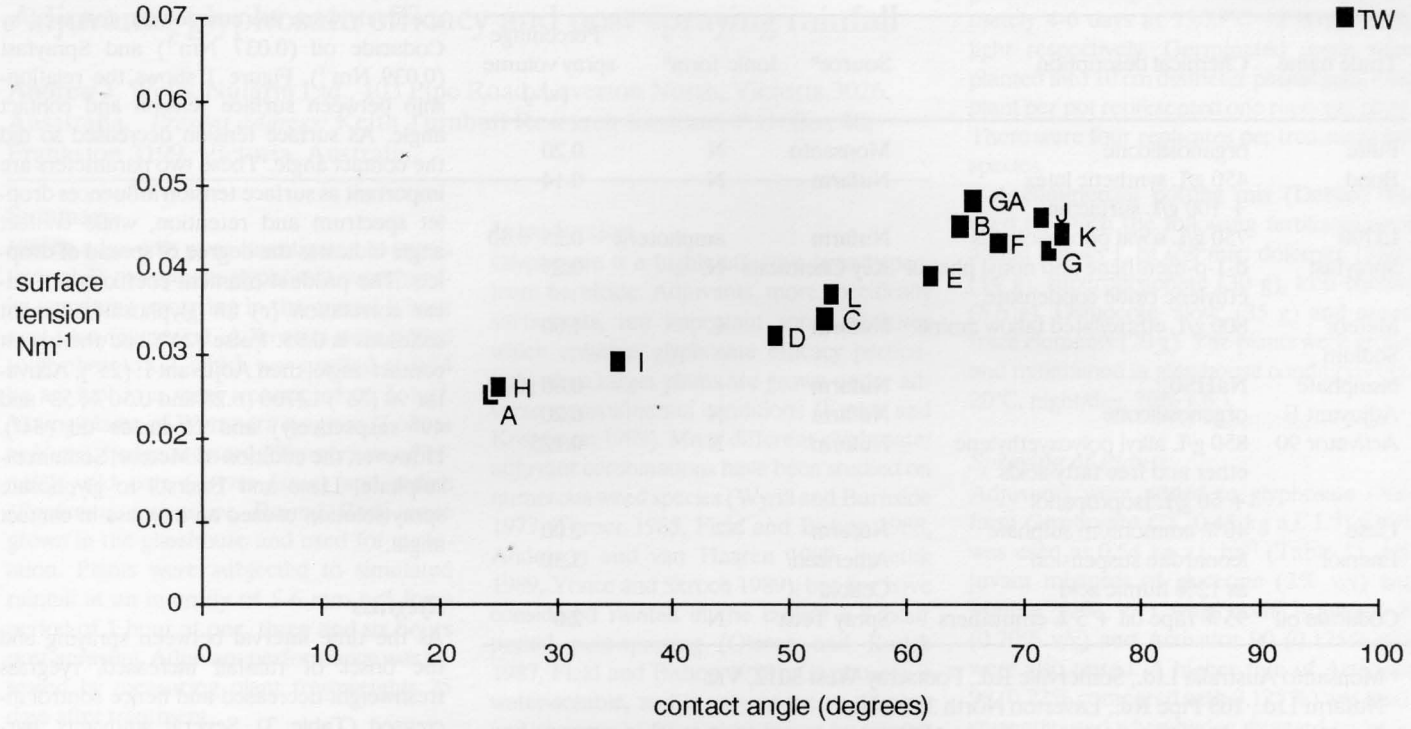


**Figure 1. The relationship between surface tension and contact angle.**
**TW = Tap water, GA = Glyphosate alone, A = Pulse, B = Bond, C = LI700 (0.25%), D = LI700 (0.5%), E = Sprayfast, F = Meteor, G = Sodium bisulphate, H = Adjuvant E, I = Activator 90, J = Liase, K = Enersol, L = Codacide oil.**

**Table 3. The effect of adjuvants on glyphosate activity against ryegrass (*Lolium rigidum*) subjected to post-spraying rainfall.**

| Adjuvant trade name | Mean freshweight (g) 25 days after treatment | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | rain 1 hour post-spraying | | rain 3 hours post-spraying | | rain 6 hours post-spraying | | control (no rain) | |
| Glyphosate alone | 2.01 | (1.67)[a] | 2.21 | (1.63) | 1.36 | (2.08) | 0 | (3.32) |
| Pulse | 1.25 | (2.05) | 0.71 | (2.45)$^{xy}$ | 0.36 | (2.84)$^{x}$ | 0.38 | (2.75) |
| Bond | 1.21 | (2.07) | 1.61 | (1.93) | 1.46 | (1.96) | 0.40 | (2.63) |
| LI700(0.25%) | 1.87 | (1.89) | 0.43 | (2.61)$^{xy}$ | 0.22 | (2.96)$^{xy}$ | 0 | (3.32) |
| LI700(0.50%) | 0.75 | (2.29)$^{x}$ | 0.40 | (2.94)$^{xy}$ | 0 | (3.32)$^{xy}$ | 0 | (3.32) |
| Sprayfast | 1.69 | (1.81) | 0.40 | (2.74)$^{xy}$ | 0 | (3.32)$^{xy}$ | 0.25 | (3.01) |
| Meteor | 1.78 | (1.79) | 0.85 | (2.26)$^{x}$ | 1.13 | (2.08) | 0 | (3.32) |
| Sodium bisulphate | 2.61 | (1.57) | 0.54 | (2.68)$^{xy}$ | 1.26 | (2.25) | 0.32 | (2.98) |
| Adjuvant E | 1.50 | (2.10) | 0 | (3.32)$^{xy}$ | 0 | (3.32)$^{xy}$ | 0 | (3.32) |
| Activator 90 | 0.83 | (2.61)$^{xy}$ | 0.05 | (3.22)$^{xy}$ | 0 | (3.32)$^{xy}$ | 0 | (3.32) |
| Liase | 2.48 | (1.64) | 0.75 | (2.39)$^{x}$ | 3.09 | (2.23) | 0 | (3.32) |
| Enersol | 3.73 | (1.35) | 2.50 | (1.61) | 1.75 | (1.75) | 1.82 | (1.82) |
| Codacide oil | 0.74 | (2.32)$^{x}$ | 0.75 | (2.41)$^{x}$ | 0 | (3.32)$^{xy}$ | 0 | (3.32) |

LSD values refer to transformed data and are compared with glyphosate alone
LSD (P=0.05):0.60 (denoted by $^{x}$)
LSD (P=0.01):0.79 (denoted by $^{y}$)
[a]Freshweight data transformed by 1/LOG(FWT + 2)

spraying and the Sprayfast control (P = 0.5827) which survived. Such anomalies may reflect inadequate replication.

*Wild oats*

A number of adjuvants when added to the glyphosate spray solution gave improved tolerance to rainfall compared to glyphosate alone (Table 5). However, only a few adjuvants significantly (P<0.01) improved glyphosate activity and hence freshweight reduction of wild oats when rainfall occurred 1, 3 and 6 hours post-spraying. These were Pulse (0.20%), Bond (0.14%; except at 6 hours post-spraying) and Activator 90 (0.22%). Activator 90 gave complete control when rain fell 3 and 6 hours post-spraying. Enersol (3.30%) significantly (P<0.05) retarded glyphosate activity on wild oats irrespective of rainfall occurring or not.

*Radish*

Several adjuvants, compared to glyphosate alone, improved glyphosate phytotoxicity to radish, even though rainfall occurred during the critical 6 hour period post-spraying (Table 6). Glyphosate alone was not suffi-

cient to completely control radish even though rain did not occur within 6 hours post-spraying. Nevertheless, the addition of Pulse (0.20%), Bond (0.14%), LI700 (0.25% and 0.50%), Sprayfast (0.25%), Meteor (1.0%) and Activator 90 (0.125%) enhanced glyphosate activity to give complete control of radish in the 'no rain' treatment. Several adjuvants, particularly LI700 (0.25% and 0.50%), Sprayfast, Meteor, Adjuvant E (0.20%), Activator 90 and Codacide oil (2.0%) significantly ($P<0.05$ and $P<0.01$) enhanced glyphosate activity, compared to glyphosate alone, even though rain fell 1, 3 and 6 hours post-spraying. Of these, LI700 (0.25% and 0.50%), Sprayfast and Meteor when added to glyphosate gave greatest control at virtually all treatments.

*Graminaceous and Dicotyledonous Data*

Data from ryegrass and wild oats were combined and re-analysed as were data from hedge mustard and radish (Tables 7 and 8). Both sets of data show that as the time interval between spraying and the onset of rainfall increases, plant freshweight decreases and

**Table 4 The effect of adjuvants on glyphosate activity against hedge mustard (*Sisymbrium officinale*) subjected to post-spraying rainfall.**

| Adjuvant trade name | Mean freshweight (g) 25 days after treatment | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | rain 1 hour post-spraying | | rain 3 hours post-spraying | | rain 6 hours post-spraying | | control (no rain) | |
| Glyphosate alone | 2.31 | (0.63)[a] | 1.01 | (0.77) | 1.44 | (0.72) | 0 | (1.00) |
| Pulse | 1.49 | (0.71) | 0.95 | (0.79) | 0.22 | (0.91)[x] | 0 | (1.00) |
| Bond | 1.98 | (0.61) | 2.18 | (0.66) | 2.12 | (0.58) | 0 | (1.00) |
| LI700(0.25%) | 0.71 | (0.82)[x] | 0.13 | (0.94) | 0.08 | (0.97)[xy] | 0 | (1.00) |
| LI700(0.50%) | 0.48 | (0.86)[x] | 0.01 | (0.99)[x] | 0.12 | (0.95)[x] | 0.01 | (0.99) |
| Sprayfast | 0.25 | (0.85)[x] | 0.08 | (0.97)[x] | 0.05 | (0.98)[xy] | 0.14 | (0.95) |
| Meteor | 1.14 | (0.74) | 0.73 | (0.82) | 0.70 | (0.78) | 0.04 | (0.98) |
| Sodium bisulphate | 1.85 | (0.59) | 1.23 | (0.75) | 0.65 | (0.80) | 0.33 | (0.89) |
| Adjuvant E | 2.37 | (0.64) | 0.55 | (0.82) | 0.29 | (0.90)[x] | 0.18 | (0.93) |
| Activator 90 | 0.02 | (0.99)[xy] | 0 | (1.00)[xy] | 0 | (1.00)[xy] | 0 | (1.00) |
| Liase | 6.34 | (0.42) | 0.27 | (0.90) | 0 | (1.00)[xy] | 0 | (1.00) |
| Enersol | 6.16 | (0.37) | 2.33 | (0.62) | 0.49 | (0.83) | 0 | (1.00) |
| Codacide oil | 0.08 | (0.97)[xy] | 0.03 | (0.99)[x] | 0.67 | (0.83) | 0.06 | (0.97) |
| Meteor (1%)and Activator 90 (0.125%) | 0.27 | (0.92)[xy] | 0.14 | (0.95)[x] | - | | 0 | (1.00) |
| Meteor (1%)and Adjuvant E (0.2%) | 0.15 | (0.94)[xy] | 0.06 | (0.97)[x] | - | | 0 | (1.00) |

LSD values refer to transformed data and are compared with glyphosate alone
LSD (P = 0.05):0.17(denoted by [x])
LSD (P = 0.01):0.23(denoted by [y])
[a]Freshweight data transformed by 1/SQRT(FWT+1)

**Table 5. The effect of adjuvants on glyphosate activity against wild oats (*Avena fatua*) subjected to post-spraying rainfall.**

| Adjuvant trade name | Mean freshweight (g) 25 days after treatment | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | rain 1 hour post spraying | | rain 3 hours post-spraying | | rain 6 hours post-spraying | | control (no rain) | |
| Glyphosate alone | 3.21 | (0.71)[a] | 2.07 | (0.60) | 1.11 | (0.49) | 0 | (0.30) |
| Pulse | 0.31 | (0.36)[xy] | 0.20 | (0.34)[xy] | 0.09 | (0.32)[xy] | 0.10 | (0.32) |
| Bond | 1.33 | (0.51)[xy] | 0.64 | (0.40)[xy] | 0.43 | (0.46) | 0 | (0.30) |
| LI700(0.25%) | 2.55 | (0.63) | 0.93 | (0.45)[x] | 0.73 | (0.43) | 0 | (0.30) |
| LI700(0.50%) | 2.57 | (0.64) | 0.72 | (0.41)[xy] | 0.63 | (0.41) | 0 | (0.30) |
| Sprayfast | 2.39 | (0.64) | 1.20 | (0.50) | 1.46 | (0.53) | 0.17 | (0.33) |
| Meteor | 2.55 | (0.65) | 1.64 | (0.56) | 1.03 | (0.47) | 0 | (0.30) |
| Sodium bisulphate | 1.43 | (0.53)[xy] | 1.74 | (0.56) | 1.27 | (0.51) | 0.61 | (0.41) |
| Adjuvant E | 1.96 | (0.59) | 1.27 | (0.51) | 1.27 | (0.51) | 0.83 | (0.44) |
| Activator 90 | 0.86 | (0.45)[xy] | 0 | (0.30)[xy] | 0 | (0.30)[xy] | 0 | (0.30) |
| Liase | 2.48 | (0.64) | 1.43 | (0.52) | 0.85 | (0.45) | 0.09 | (0.32) |
| Enersol | 3.53 | (0.74) | 3.72 | (0.75) | 3.88 | (0.76) | 2.42 | (0.64) |
| Codacide oil | 4.80 | (0.83) | 1.96 | (0.57) | 0.32 | (0.36)[x] | 0 | (0.30) |

LSD values refer to transformed data and are compared with glyphosate alone
LSD (P = 0.05):0.12(denoted by [x])
LSD (P = 0.01):0.16(denoted by [y])
[a]Freshweight data transformed by LOG(FWT+2)

**Table 6. The effect of adjuvants on glyphosate activity against radish (*Raphanus sativus* cv. Round Red) subjected to post-spraying rainfall.**

| Adjuvant trade name | Mean freshweight (g) 25 days after treatment: rain 1 hour post-spraying | | rain 3 hours post-spraying | | rain 6 hours post-spraying | | control (no rain) | |
|---|---|---|---|---|---|---|---|---|
| Glyphosate alone | 4.00 | (1.31)[a] | 2.62 | (1.66) | 1.47 | (1.89) | 0.46 | (2.74) |
| Pulse | 1.93 | (1.69) | 0.88 | (2.37)[x] | 0.69 | (2.38) | 0 | (3.32) |
| Bond | 1.91 | (1.76) | 0.28 | (2.89)[xy] | 0.29 | (2.89)[xy] | 0 | (3.32) |
| LI700(0.25%) | 0.40 | (2.65)[xy] | 0.20 | (2.99)[xy] | 0 | (3.32)[xy] | 0 | (3.32) |
| LI700(0.50%) | 0.22 | (2.95)[xy] | 0.32 | (2.83)[xy] | 0.04 | (3.23)[xy] | 0 | (3.32) |
| Sprayfast | 1.38 | (1.91)[x] | 0.31 | (2.85)[xy] | 0 | (3.32)[xy] | 0 | (3.32) |
| Meteor | 0.34 | (2.78)[xy] | 0.35 | (2.74)[xy] | 0.11 | (3.14)[xy] | 0 | (3.32) |
| Sodium bisulphate | 2.20 | (1.62) | 1.87 | (1.79) | 1.07 | (2.18) | 0.79 | (2.51) |
| Adjuvant E | 1.40 | (1.92)[x] | 0.69 | (2.45)[xy] | 0.51 | (2.74)[xy] | 1.31 | (1.97) |
| Activator 90 | 1.47 | (1.92)[x] | 0.50 | (2.71)[xy] | 0.33 | (2.85)[xy] | 0.03 | (3.25) |
| Liase | 1.76 | (2.09)[xy] | 1.05 | (2.31)[x] | 1.01 | (2.11) | 0.16 | (3.06) |
| Enersol | 2.62 | (1.65) | 0.95 | (2.18) | 1.68 | (1.99) | 0.80 | (2.42) |
| Codacide oil | 1.66 | (1.92)[x] | 0.38 | (2.73)[xy] | 0.31 | (2.92)[xy] | 0.25 | (3.01) |

LSD values refer to transformed data and are compared with glyphosate alone
LSD (P = 0.05):0.58 (denoted by [x])
LSD (P = 0.01):0.77 (denoted by [y])
[a]Freshweight data transformed by 1/LOG(FWT+2)

**Table 7. The effect of adjuvants on glyphosate activity against ryegrass (*Lolium rigidum*) and wild oats (*Avena fatua*), combined data, subjected to post-spraying rainfall.**

| Adjuvant trade name | Mean freshweight (g) 25 days after treatment: rain 1 hour post-spraying | | rain 3 hours post-spraying | | rain 6 hours post-spraying | | control (no rain) | |
|---|---|---|---|---|---|---|---|---|
| Glyphosate alone | 2.61 | (0.54)[a] | 2.14 | (0.58) | 1.23 | (0.70) | 0 | (1.00) |
| Pulse | 0.77 | (0.80)[xy] | 0.45 | (0.86)[xy] | 0.22 | (0.92)[xy] | 0.24 | (0.92) |
| Bond | 1.27 | (0.70)[xy] | 1.12 | (0.75)[xy] | 1.19 | (0.70) | 0.20 | (0.92) |
| LI700(0.25%) | 2.20 | (0.61) | 0.67 | (0.80)[xy] | 0.47 | (0.85)[x] | 0 | (1.00) |
| LI700(0.50%) | 1.50 | (0.66)[x] | 0.55 | (0.87)[xy] | 0.31 | (0.92)[xy] | 0 | (1.00) |
| Sprayfast | 2.04 | (0.59) | 0.80 | (0.78)[xy] | 0.72 | (0.82)[x] | 0.21 | (0.94) |
| Meteor | 2.15 | (0.58) | 1.24 | (0.69) | 1.08 | (0.71) | 0 | (1.00) |
| Sodium bisulphate | 2.02 | (0.59) | 1.13 | (0.73)[xy] | 1.26 | (0.70) | 0.46 | (0.87) |
| Adjuvant E | 1.72 | (0.64) | 0.63 | (0.83)[xy] | 0.63 | (0.80) | 0.41 | (0.89) |
| Activator 90 | 0.84 | (0.79)[x] | 0.02 | (0.99)[xy] | 0 | (1.00)[xy] | 0 | (1.00) |
| Liase | 2.48 | (0.56) | 1.08 | (0.72)[x] | 1.96 | (0.74) | 0.04 | (0.98) |
| Enersol | 3.62 | (0.47) | 3.10 | (0.51) | 2.81 | (0.53) | 2.12 | (0.58) |
| Codacide oil | 2.76 | (0.59) | 1.35 | (0.72)[x] | 0.16 | (0.96)[xy] | 0 | (1.00) |

LSD values refer to transformed data and are compared with glyphosate alone
LSD (P = 0.05):0.12 (denoted by [x])
LSD (P = 0.01):0.16 (denoted by [y])
[a]Freshweight data transformed by 1/SQRT(FWT+1)

hence the degree of control increases. The graminaceous data (Table 7) show Pulse, LI700 and Activator 90 to significantly ($P<0.05$ and $P<0.01$) enhance glyphosate activity when rain fell 1,3 and 6 hours post-spraying. The dicotyledonous plant data (Table 8) show LI700 (0.25 and 0.50%), Sprayfast, Meteor, Activator 90 and Codacide oil to significantly ($P<0.01$; except Meteor when rain fell 3 hours post-spraying $P = 0.0138$) enhance glyphosate activity when rain fell 1, 3 and 6 hours post-spraying.

*Adjuvant Mixtures and Glyphosate*

Glycerine (2%) was tried with Adjuvant E (0.20%) and Activator 90 (0.125%) on ryegrass plants without success (results not shown). However, the combination of Meteor (1%) with Adjuvant E (0.20%) and Activator 90 (0.125%) gave excellent control ($P<0.05$) of hedge mustard plants when rain fell 1 and 3 hours post-spraying (Table 3). A 6 hour post-spraying rainfall treatment was not included.

## Discussion

Post-spraying rainfall reduced the control of all plant species by glyphosate, but as the time between spraying and the onset of rainfall increased so too did the degree of control. It is apparent that rainfall occurring 6 hours post-spraying reduces glyphosate activity confirming the author's preliminary findings and those of Olesen and Kudsk (1987).

Activator 90 (0.125% and 0.22%) and LI700 (0.50%) most consistently enhanced

**Table 8 The effect of adjuvants on glyphosate activity against hedge mustard (*Sisymbrium officinale*) and radish (*Raphanus sativus* cv. Round Red), combined data, subjected to post-spraying rainfall.**

| Adjuvant trade name | Mean freshweight (g) 25 days after treatment | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | rain 1 hour post-spraying | | rain 3 hours post-spraying | | rain 6 hours post-spraying | | control (no rain) | |
| Glyphosate alone | 3.15 | (1.60) | 1.81 | (2.03) | 1.44 | (2.05) | 0.23 | (3.03) |
| Pulse | 1.70 | (1,93) | 0.90 | (2.43) | 0.44 | $(2.66)^{x}$ | 0 | (3.32) |
| Bond | 1.94 | (1.77) | 1.22 | (2.46) | 1.20 | (2.28) | 0 | (3.32) |
| LI700(0.25%) | 0.55 | $(2.61)^{xy}$ | 0.16 | $(3.02)^{xy}$ | 0.03 | $(3.25)^{xy}$ | 0 | (3.32) |
| LI700(0.50%) | 0.35 | $(2.84)^{xy}$ | 0.16 | $(3.07)^{xy}$ | 0.08 | $(3.18)^{xy}$ | 0 | (3.32) |
| Sprayfast | 0.99 | $(2.33)^{xy}$ | 0.19 | $(3.01)^{xy}$ | 0.02 | $(3.27)^{xy}$ | 0.07 | (3.21) |
| Meteor | 0.73 | $(2.52)^{xy}$ | 0.53 | $(2.65)^{x}$ | 0.40 | $(2.77)^{xy}$ | 0.02 | (3.28) |
| Sodium bisulphate | 2.02 | (1.67) | 1.54 | (2.06) | 0.85 | (2.33) | 0.55 | (2.68) |
| Adjuvant E | 1.88 | (1.93) | 0.61 | (2.51) | 0.39 | $(2.81)^{xy}$ | 0.74 | (2.50) |
| Activator 90 | 0.74 | $(2.60)^{xy}$ | 0.25 | $(3.02)^{xy}$ | 0.16 | $(3.08)^{xy}$ | 0.01 | (3.29) |
| Liase | 4.04 | (1.68) | 0.66 | $(2.61)^{x}$ | 0.50 | $(2.72)^{x}$ | 0.07 | (3.19) |
| Enersol | 4.38 | (1.37) | 1.64 | (2.00) | 1.07 | (2.28) | 0.40 | (2.87) |
| Codacide oil | 0.86 | $(2.54)^{xy}$ | 0.21 | $(3.00)^{xy}$ | 0.48 | $(2.78)^{xy}$ | 0.15 | (3.11) |

LSD values refer to transformed data and are compared with glyphosate alone
LSD (P = 0.05): 0.50 (denoted by $^{x}$)
LSD (P = 0.01): 0.65 (denoted by $^{y}$)
[a]Freshweight data transformed by 1/LOG (FWT+2)

glyphosate activity. The non-ionic adjuvant Activator 90 gave a low surface tension (0.029 $Nm^{-1}$) and contact angle (35°) to the spray solution (Table 2). Activator 90 significantly ($P<0.01$) enhanced glyphosate activity on ryegrass, hedge mustard, wild oats and radish ($P = 0.0408$ when rain fell 1 hour post-spraying) despite rain occurring 1 hour or later post-spraying. Radish was less susceptible to the rate of glyphosate (0.54 kg a.i. $ha^{-1}$) used compared to the other plant species (ryegrass, hedge mustard and wild oats), although this was not statistically substantiated. However, when Pulse, Bond, LI700, Sprayfast and Meteor were individually added to the spray solution, glyphosate activity was sufficiently enhanced to overcome the exhibited tolerance. When test species were grouped into their respective Classes, some adjuvants exhibited a selectivity to a particular species and Class (Sands and Bachelard 1973). With the exception of Activator 90 and LI700, adjuvants which significantly ($P<0.05$ and $P<0.01$) enhanced glyphosate activity on dicotyledonous plants did not necessarily enhance glyphosate activity on graminaceous plants. These adjuvants were Sprayfast (non-ionic), Meteor (cationic) and Codacide oil(non-ionic) (Table 8). On the other hand, Pulse (non-ionic) significantly ($P<0.01$) enhanced glyphosate activity on graminaceous rather than dicotyledonous plants (Table 7). Such results may reflect differences in leaf shape, leaf orientation and epicuticular crystalline waxes (de Ruiter and Uffing 1988) and consequently spray deposition, retention, wetting and/or penetration. Similarly, Combellack *et al.* (1989) found that several cationic adjuvants added to "Tillmaster", a 2,4-D/glyphosate formulation (Nufarm LTD), gave improved control of subterranean clover (*Trifolium subterranean*), but had a negative affect on Wimmera ryegrass (*Lolium rigidum*). However, their results indicated that when LI700 was used with "Tillmaster", ryegrass control was better than that of subterranean clover. Although differences may be due, in part, to the different herbicides used, the results of Combellack *et al.* (1989) are contrary to the findings in this study.

The organosilicones Pulse and Adjuvant E impart very high wetting characteristics to the spray solution. This is important for plants such as wild oats which are difficult to wet owing to their vertical orientation and the presence of epicuticular crystalline waxes (McShane 1986, Anderson *et al.* 1987, Field and Bishop 1988, de Ruiter and Uffing, 1988). Nevertheless, the improvements in biological performance of glyphosate when these adjuvants were used varied considerably. Excellent control of wild oats with Pulse and hedge mustard with Adjuvant E was achieved, but these results were not repeated for other species. It is suggested (Combellack pers. comm.) that at high temperatures and low humidity the effectiveness of the organosilicones may be reduced at low spray volumes, since spray droplets are spread so thinly and thus evaporate before leaf penetration occurs. Zabkiewicz *et al.* (1988) showed that the organosilicones, particularly Pulse (Silwet L-77), gave the greatest spreading and leaf wetting characteristics, but also dried far more quickly compared to organic surfactants. Therefore, the incorporation of a humectant with the spray solution containing organosilicone surfactant may reduce evaporation (Combellack pers. comm., Field *et al.* 1989). Glycerine (2%) was tried with Activator 90 (0.125%) and Adjuvant E (0.2%) on ryegrass without success. However, Field *et al.* (1989) found that glycerine (3-6% v/v) added to a glyphosate solution (720 g a.i. $ha^{-1}$) containing organosilicone surfactant (Silwet L77, 0.1%) overcame tolerance and enhanced uptake of glyphosate in *Paspalum dilitatum*. The combination of Meteor (1%) with both Activator 90 (0.125%) and Adjuvant E (0.2%) gave excellent control ($P<0.05$) of hedge mustard plants when rain fell 1 and 3 hours post-spraying (Table 4). In this situation, Meteor may be acting as a humectant for the organosilicone as well as promoting glyphosate phytotoxicity. Such combinations warrant further investigation.

To conclude, adjuvants can significantly reduce the effect post-spraying rainfall has on glyphosate activity. However, differences in glyphosate activity due to factors such as leaf morphology and surface waxes were not completely overcome by the addition of any single adjuvant (Zabkiewicz *et al.* 1988).

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## References


Anderson, N.H., D.J. Hall and D. Seaman (1987). Spray retention: effects of surfactants and plant species. *Aspects of Applied Biology* 14, 233-243.

Anderson, T.M. and P.E. van Haaren (1989). Rainproofing glyphosate with 'Bondcrete' cement additive for improved Bitou Bush control. *Plant Protection Quarterly* 4, 45-46.

Baird, D.D. and R.P. Upchurch (1972). Postemergence characteristics of a new herbicide. MON-0468, on johnsongrass. *Proceedings of the Southern Weed Science Society* 25, 113-116.

Box, G.E.P. and D.R. Cox (1964). An analysis of transformations. *Journal of the Royal Statistical Society* 26, 211-243.

Bryson, C.T. (1988). Effects of rainfall on foliar herbicides applied to seedling johnsongrass (*Sorghum halepense*). *Weed Technology* 2, 153-158.

Combellack, J.H., A. McShane and R.G. Richardson (1989). The influence of adjuvants on the performance of a glyphosate/2,4-D mixture. 2nd International Symposium on Adjuvants for Agrichemicals. (in press).

Coupland, D. and J.C. Caseley (1981). Environmental influences on the effects of glyphosate on *Agropyron repens*. Proceedings of the AAB Conference. Grass Weeds in Cereals in the U.K., 109-114.

de Ruiter, H. and A.J.M. Uffing (1988). The influence of surfactants and plant species on the retention of spray solutions. Proceedings of the European Weed Research Society. Factors affecting herbicidal activity and selectivity, 163-168.

Ebeling, W. (1939) The role of surface tension and contact angle in the performance of spray liquids. *Hilgardia* 12, 665-698.

Field, R.J. and N.G. Bishop (1988). Promotion of stomatal infiltration of glyphosate by an organosilicone surfactant reduces the critical rainfall period. *Pesticide Science* 24, 55-62.

Field, R.J., N.N. Dobson, and L.J. Tisdall (1989). Species-specific sensitivity to organosilicone surfactant-enhancement of glyphosate uptake. 2nd International Symposium on Adjuvants for Agrichemicals (in press).

Kudsk, P. and J. Kristensen (1989). Herbicide rainfastness. 7th Danish plant protection conference, 196-203.

McShane, A. (1986). Some effects of adjuvants on the performance of glyphosate and phenoxy-herbicides. MSc. Thesis. Department of Bio-aeronautics. Cranfield Institute of Technology.

Olesen, T. and P. Kudsk (1987). The influence of rain on the effect of chlorosulfuron, fluazifob-butyl and glyphosate 5th Danish plant protection conference, 256-265.

Sands, R. and E.P. Bachelard (1973). Uptake of picloram by Eucalypt leaf discs. I. Effect of surfactants and nature of the leaf surfaces. *New Phytologist* 72, 69-86.

Swietlik, D. (1989). Adjuvants affect the efficacy of glyphosate on selected perennial weeds. *HortScience* 24, 470-472.

Taylor, N. and G.A. Matthews (1986). Effect of different adjuvants on the rainfastness of bendiocarb applied to Brussels sprout plants. *Crop Protection* 5, 250-253.

Turner, D.J. (1985). Effects on glyphosate performance of formulation, additives and mixing with other herbicides. *In* 'The herbicide glyphosate'. Eds. E. Grosbard and D. Atkinson, 221-240.

Wade van Valkenburg, J. (1982). Terminology, classification and chemistry. *In* 'Adjuvants for herbicides'. Ed. R.H. Hodgson. Weed Science Society of America, 1-9.

Wyrill, J.B. and O.C. Burnside (1977). Glyphosate toxicity to common milkweed and hemp dogbane as influenced by surfactants. *Weed Science* 25, 275-287.

Yonce, M.H. and W.A. Skroch (1989). Control of selected perennial weeds with glyphosate. *Weed Science* 37, 360-364.

Zabkeiwicz, J.A., D. Coupland and F. Ede (1988). Effects of surfactants on droplet spreading and drying rates in relation to foliar uptake. *In* 'Pesticide formulations: innovations and developments'. Ed. B. Cross and H.B. Scher, ACS Symposium Series 371, 77-89.