

SOME FACTORS INFLUENCING GLYPHOSATE CONTROL OF *PANICUM REPENS* (TORPEDOGRASS) IN UP-COUNTRY TEA FIELDS IN SRI LANKA

M.H.G. WEERASINGHE and J.P.N.R. CHANDRASENA¹

Department of Botany, University of Colombo, P.O. Box 1490, Colombo 3.

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Abstract : Glasshouse and field studies were conducted to investigate the effects of formulation and application methods on the activity of glyphosate [N-(phosphonomethyl) glycine], against the perennial, rhizomatous grass-weed *Panicum repens* L. (torpedograss). Glasshouse studies were carried out with an application of 0.125 kg a.i./ha, a sub-lethal rate of glyphosate on 11-12 week old, well-established *P. repens* plants. Phytotoxicity evaluations were based on visual symptoms and an evaluation of inhibition of regrowth potential of the weed. Among the ammonium salts added to spray solutions, $(\text{NH}_4)_2\text{SO}_4$ and urea, each at 0.5 or 2.0 kg/ha, enhanced the visual phytotoxicity caused by glyphosate, while NH_4SCN did not. However, synergism between ammonium salts and glyphosate inhibition of regrowth was not clearly seen. Glyphosate was less phytotoxic when applied in the presence of 100 mM solution of CaCl_2 or ZnSO_4 , while the addition of MgSO_4 or NaHCO_3 did not alter activity. The addition of non-ionic surfactants Agral-90 or Surfactant-N, at 0.1 % or 1.0 % (v/v), significantly increased the efficacy of glyphosate. However, petroleum oils (car engine oil or petrol) or vegetable oils (coconut or soybean oil) in the spray solutions at 1.0 % (v/v), did not significantly alter glyphosate activity. Glyphosate applications exhibited the highest phytotoxicity against *P. repens* at pH 6.0. The field performance of glyphosate at 1.0 or 2.0 kg/ha was significantly enhanced when de-ionized water was used instead of ground water, as a carrier. Reduction of the carrier-volume from 600 l/ha to 300 l/ha did not significantly alter activity. The performance of a high rate of glyphosate (4.0 kg/ha) was not affected by water quality or carrier-volume.

Key words: Glyphosate, *Panicum repens*, Tea fields.

INTRODUCTION

Panicum repens L. (torpedograss), a perennial, rhizomatous grass, has been long regarded as one of the most troublesome weeds in Sri Lanka,^{1,2} and other tropical areas.³⁻⁷ It is known that *P. repens* has wide ecological amplitudes, and an ability to thrive in a variety of soil conditions and geographical locations, displacing many native grass species in both terrestrial and aquatic environments.^{3, 6, 7} Major problems with cropping systems, irrigation, flood control, navigation and recreation are encountered when this grass becomes dominant in diverse ecosystems.^{3, 6, 7} In Sri Lanka too, *P. repens* is reported to have a wide ecological range.^{2, 8, 9}

¹Present Address: Australian Water Technologies (AWT) EnSight, 51, Hermitage Road, West Ryde, NSW 2114, Australia

Being a perennial weed, the control of *P. repens* requires the depletion of rhizome energy reserves, prevention of development of leafy shoots, destruction of the underground rhizome system or a reduction in the supply of viable rhizome buds. Glyphosate, a non-selective, systemic herbicide has been one of the most effective chemicals to achieve all these, and control *P. repens* in a variety of situations in different countries, including aquatic environments.⁴⁻⁷ However, many researchers, particularly from U.S.A, have reported that in aquatic situations *P. repens* was more difficult to control in aqueous than in terrestrial environments; higher rates of glyphosate, in excess of 4 kg/ha, and repeat applications have been necessary to achieve acceptable levels of control in aquatic environments.^{6,7} Sharma *et al.*¹⁰ reported from India that *P. repens* in tea fields could be effectively controlled at 1.68 kg/ha. Other reports from U.S.A. indicated that glyphosate was required at 2.51 kg/ha to control heavy terrestrial infestations of the weed, and that rates of 2.24 kg/ha or higher were required for control in lawns.^{3,6,7} In Sri Lanka, the current recommendation of glyphosate for *P. repens* control in tea estates is as high as 4.4 kg a.i/ha in 600 l/ha of water,¹¹ to be used either in areas not planted with tea, or as carefully directed sprays and spot-applications on yielding tea fields, under severe weed infestations.

The available data therefore indicate that although glyphosate is a very efficacious herbicide, complete control of *P. repens* with this herbicide has been generally difficult, if not impossible. At best the results have been variable and many researchers agree that relatively high rates appear essential for effective control of heavy infestations.^{2,4,12,13} The high cost of glyphosate poses a problem for its use at the recommended rate of 4.4 kg/ha in tea and coconut estates. Chandrasena² reported that superior inhibition of regrowth and rhizome bud-kill of *P. repens* can be achieved with split, sequential applications of glyphosate within the range of 0.5 to 2.0 kg/ha, compared to a one full-rate application, particularly with the use of a non-ionic surfactant as a spray additive.

One possible explanation for variable results and/or lack of adequate control of *P. repens* with glyphosate is the quality of the spray solution. Hardness of water (i.e. calcium, magnesium) and pH of spray solution have both been reported to affect the efficacy of glyphosate.¹²⁻¹⁶ The use of a surfactant, an oil or an inorganic salt in the spray solution, has been long known to enhance the activity of most foliar-applied herbicides, including glyphosate.^{17,18} The enhancement of activity of most foliar-applied herbicides by surfactants and oil-additives in the sprays have been commonly explained by: (a) the reduction of surface tension in spray solutions which usually leads to improved wetting and spreading properties and a resultant increase in area of contact between the herbicide and the leaf surface; (b) 'solubilization' or alteration of the chemistry of the cuticular waxes, leading to greater uptake via the non-polar routes of entry.¹⁸ Inorganic salts used as adjuvants appear to increase the phytotoxicity of certain herbicides only, and glyphosate is well-known to be one of them. Ammonium

salts in particular, have increased the phytotoxicity of glyphosate to many plants, including *Elymus repens* (L.) Gould, a major rhizomatous, perennial grassweed of the Northern hemisphere.^{17,19,20} Although there has been no universally accepted explanation for the effect of salts, enhancement of glyphosate activity has been explained in terms of greater uptake and increased translocation from treated foliage, as indicated by greater reductions in regrowth of plants¹⁹ or greater rhizome bud-kill.²⁰

The present study investigates the enhancement of glyphosate efficacy against *P. repens* achieved by different spray formulations and attempts to understand some of the causes for the varying efficiency of glyphosate control of *P. repens*.

MATERIALS AND METHODS

General: This research was carried out between February and September, 1991, at St. Coombs Estate, Tea Research Institute (TRI) of Sri Lanka, Talawakele, located in the central hill country of the island (1200 m above mean sea level). During this period, the temperature varied between 24-26°C (day) and 7-18°C (night); relative humidity was 65-80% and sunlight was received between 0700 and 1700 h.

Rhizomes of *P. repens* were freshly dug from a heavily infested tea field and cut into 2-3 cm long fragments containing a single node, avoiding the immature rhizome apex and the basal end where the nodes were too close to each other. These fragments were planted 1 cm deep in plastic trays (35 x 22 x 4 cm) containing a clay-loam soil, fortified with compost. Two weeks after emergence, uniformly grown plants were transplanted one plant per pot, into 15 cm diam. pots filled with the same soil. Plants were maintained in a glasshouse until the appropriate age/growth stage with frequent watering. On a weekly basis 40 ml of a soluble fertilizer (2 g/l of a mixture containing urea, superphosphate and muriate of potash; 22.5%N, 22.5% P₂O₅ and 22.5% K₂O) were added to each pot. All glasshouse experiments were carried out with 11- or 12-week old (after transplanting) *P. repens* plants which generally had ca. 80-100 g of fresh rhizomes and 7-8 tillers.

Spray applications and herbicide formulations: Glyphosate, formulated as the commercial product, COUNTER (35.5% e.c. of acid, Monsanto) was used. For all spray applications, a Baur's IRIS V-L-V knapsack sprayer fitted with a flat-fan V-L-V nozzle, operating at a pressure of 2.5-3.0 kg/cm², with a flow rate of 300 ml/min over an even swathe width of 1 m was used. The carrier volume used in general spraying was 600 l/ha as recommended by the TRI,¹¹ unless stated otherwise. In the glasshouse experiments, the soil of each pot was covered with vermiculite before spraying to ensure that herbicide action was through uptake via foliage. Vermiculite was tipped-off later.

Spray operations were replicated three times for each of the glasshouse experiments; each replicate comprised of a group of 6 or 7 plants. During spraying, each group of plants for a specific treatment, was arranged in a marked areas of 1 m² and then separately sprayed. After spraying, the plants were kept undisturbed for 20 min and then arranged in a randomized complete block design (RCBD) in the glasshouse. Water was applied directly to the soil to avoid washing herbicide from the foliage.

Experimental studies: After a series of preliminary trials, a sub-lethal dose of glyphosate (0.125 kg a.i./ha) which caused only a marginal killing of *P. repens*, was selected for the present studies. This low rate allowed a determination of other factors (especially various additives) influencing herbicide activity. A lethal dose, in excess of 2.0 kg/ha, would have masked the influence of any other factors affecting activity, because of intense phytotoxicity.² Each experiment, reported below, was conducted twice and the data combined for analysis. Each experiment had appropriate controls represented by untreated plants and plants receiving the herbicide treatment without the varied factor.

The effect of incorporating inorganic compound: Batches of *P. repens* plants were treated with foliar sprays of glyphosate, incorporated with either (NH₄)₂SO₄, NH₄SCN or urea, each at rates of 0, 0.5, or 2.0 kg/ha. In separate experiments, batches of *P. repens* plants were treated with glyphosate incorporated with either CaCl₂, MgSO₄, ZnSO₄ or NaHCO₃, all of analytical grade and each at concentrations of 0 or 10 mM. All herbicide solutions were prepared using deionized water.

The effect of incorporation of non-ionic surfactants: *P. repens* plants were treated with glyphosate made up using normal tap water. Spray solutions had either the surfactant Agral 90 (Nonyl phenol ethoxylate, ICI, U.K.) or Surfactant N (Nonidet P40, an ethylene oxide condensate based on octyl phenol, Lankem Ceylon) incorporated at 0, 0.1, or 1.0% v/v.

The effect of vegetable and petroleum oil-additives: Batches of *P. repens* plants were treated with glyphosate, incorporated with either coconut oil, soybean oil, petrol, or car engine oil (SAE 30), each at 0 or 1.0% v/v.

The effect of pH of spray solutions: Glyphosate was applied to batches of *P. repens* plants after adjusting (but not buffering) the pH of the treatment solutions to either 4, 6 or 8, using 0.1N HCl or 0.1N NaOH.

The interaction of carrier volume, dose and water quality on glyphosate efficacy in the field: In a field bare of tea, but heavily infested with *P. repens*, 1 m² plots were laid out with 1.5 m pathways on all sides of each plot. The soil was a clay-loam (Organic matter content: 4.5-5%; pH of soil: 5.5). Plots were treated with

glyphosate at 0, 0.5, 1.0, 2.0 or 4.0 kg a.i./ha, using a diluent volume of 300 or 600 l/ha. Either normal ground water (drawn from "wells") or de-ionized water was used to make the spray solutions. This field study was also conducted twice.

Assesment of phytotoxic effects: Phytotoxicity was estimated visually by effects on the treated foliage at 10-12 DAT, using the following standard scale: 0 = no injury; 1 = slight injury; 2 = 25% of tissues necrosed; 3 = 25-50% of tissues necrosed; 4 = 50-75% of tissues necrosed; 5 = all shoots completely dead. To evaluate regrowth potential, the originally treated shoot system of selected groups of replicate plants was cut at soil level 4 d after treatment. The above ground vegetative mass ('regrowth') produced by the same plants was then harvested after 30 d, their dry weights determined, and compared with regrowth in untreated plants.

In the field experiment, at 7 DAT, two soil cores (each of 15 x 15 cm) were obtained at random from each plot, and the rhizome material in the soil cores washed free of soil. The rhizomes were then divided into 1 or 2-node bearing 3 cm pieces, and planted 1 cm deep in plastic trays filled with loamy soil. Only rhizome buds which produced new shoots over 14-21 d were considered viable. For regrowth potential evaluation, two quadrats (15 x 15 cm) were selected randomly from the 1 m² plots, and the treated plant foliage was clipped-off at ground level at 7 DAT. The dry weight of the regrowth, which occurred in these quadrats after 30 d, was compared with regrowth of plants in untreated control plots.

Statistical analysis: The phytotoxicity response measured as regrowth-dry weights, was analysed by ANOVA and the means compared by the Duncan's New Multiple Range Test or the LSD procedure. Foliage injury scores were analysed using non-parametric statistics and the mean comparisons done according to the Wilcoxon rank sum test. Rhizome bud viability (binomial data), were converted to their logarithms (the log values treated as a normal distribution), and analysed by ANOVA followed by separation of significant means using the LSD procedure.

RESULTS

The effect of incorporating inorganic compounds: (NH₄)₂SO₄ and urea significantly increased the initial phytotoxicity of glyphosate at 0.125 kg/ha (Table 1) as indicated by the foliage injury caused. Such an effect was not seen with NH₄SCN. However, this initial phytotoxicity visible on foliage did not translate well enough to a general enhancement of the activity of the systemic herbicide. By 30 DAT, the suppression of regrowth failed to show enhanced glyphosate activity caused by the incorporation of ammonium salts, compared with the treatment without salts.

All other inorganic salts added to glyphosate decreased the phytotoxicity of the herbicide as indicated by the reduced foliage injury (Table 2). However, based on inhibition of regrowth, the reduction of herbicidal activity was significant only with CaCl_2 and ZnSO_4 .

Table 1: The effect of ammonium salts and area on the performance of glyphosate (0.125 kg/ha) against *Panicum repens*.

Ammonium Salt	Rate (kg/ha)	Regrowth at 30 days (g) ¹	% Regrowth Reduction	Foliage injury Score ²
$(\text{NH}_4)_2\text{SO}_4$	0.5	0.13 ^{bc}	70	4.3*
$(\text{NH}_4)_2\text{SO}_4$	2.0	0.15 ^{bc}	65	4.2*
NH_4SCN	0.5	0.17 ^b	61	3.1
NH_4SCN	2.0	0.12 ^{bc}	72	2.0
Urea	0.5	0.11 ^c	76	4.2*
Urea	2.0	0.16 ^b	63	4.5*
No Salt	-	0.13 ^{bc}	69	2.8
Untreated Control	-	0.44 ^a	0	0

¹Values followed by the same superscript letter are not significantly different ($p < 0.05$) according to the Duncan's multiple range test. ²Foliage injury score; 0 = no injury; 5 = plants dead. (*) indicates values which are significantly different ($p < 0.05$) according to the Wilcoxon rank sum test.

Table 2: The effect of other inorganic salts on the performance of glyphosate (0.125 kg/ha) against *Panicum repens*.

Inorganic Salt	Concentration (M)	Regrowth at 30 days (g) ¹	% Regrowth Reduction	Foliage injury Score ²
MgSO_4	0.01	0.07 ^c	63	3.0*
NaHCO_3	0.01	0.06 ^c	64	3.0*
CaCl_2	0.01	0.09 ^b	52	2.0
ZnSO_4	0.01	0.08 ^b	53	1.0
No Salt	0	0.06 ^c	68	4.0*
Untreated Control	-	0.177 ^a	0	0

¹Values followed by the same superscript letter are not significantly different ($p < 0.05$) according to the Duncan's multiple range test. ²Foliage injury score; 0 = no injury; 5 = plants dead. (*) indicates values which are significantly different ($p < 0.05$) according to the Wilcoxon rank sum test.

The effect of incorporating non-ionic surfactants: Foliage injury, as well as the poor regrowth of *P. repens* showed that, in general, phytotoxicity was significantly greater when a non-ionic surfactant was incorporated with glyphosate, than when the herbicide was applied alone (Table 3). During spray applications, there was a considerable delay in the drying of the herbicide droplets with the surfactant (5-8 min), than without it (30 s-1 min). Although both surfactants produced greater suppression of regrowth in *P. repens*, the relative enhancement of glyphosate activity due to them was not the same. Greater improvement of activity was achieved with Agral 90 at 0.1% or 1.0% (i.e. 83% and 81% of regrowth reduction, respectively). Surfactant-N incorporated at 0.1% or 1.0%, also caused enhanced visual phytotoxicity and regrowth reduction (74% and 82%, respectively).

The effect of incorporation of vegetable or petroleum oil-additives: Foliage injury scores, as well as the regrowth dry weight data (Table 4) showed that incorporation of vegetable or petroleum oils to the glyphosate solutions did not significantly enhance phytotoxicity.

Table 3: The effect of non-ionic surfactants on the performance of glyphosate (0.125 kg/ha) against *Panicum repens*.

Surfactant	Rate (kg/ha)	Regrowth at 30 days (g) ¹	% Regrowth Reduction	Foliage Injury Score ²
Agral 90	0.1	0.16 ^d	83	4.0*
Agral 90	1.0	0.18 ^d	81	3.0*
Surfactant-N	0.1	0.24 ^c	74	3.0*
Surfactant -N	1.0	0.16 ^d	82	3.0*
No Surfactant	-	0.31 ^b	67	2.0
Untreated Control	-	0.92 ^a	0	0

¹Values followed by the same superscript letter are not significantly different ($p < 0.05$) according to the Duncan's multiple range test. ²Foliage injury score; 0 = no injury; 5 = plants dead. (*) indicates values which are significantly different ($p < 0.05$) according to the Wilcoxon rank sum test.

The effect of pH of the spray solutions: The results showed that the highest reduction of *P. repens* regrowth was achieved at pH 6 (Table 5). Foliar injury scores were significantly higher only at pH 6, confirming increased activity at this pH.

Table 4: The effect of vegetable or petroleum oil-additives on the performance of glyphosate (0.125 kg/ha) against *Panicum repens*.

Oil-Additive	Rate (% v/v)	Regrowth at 30 days (g) ¹	% Regrowth Reduction	Foliage injury Score ²
Coconut Oil	1.0	0.20 ^b	71	3.0
Soya Oil	1.0	0.20 ^b	71	2.0
Motor Oil	1.0	0.20 ^b	71	3.0
Petrol	1.0	0.19 ^b	72	3.0
Without Oil	-	0.19 ^b	72	3.0
Untreated Control	-	0.69 ^a	0	0

¹Values followed by the same superscript letter are not significantly different ($p < 0.05$) according to the Duncan's multiple range test. ²Foliage injury score; 0 = no injury; 5 = plants dead. (*) indicates values which are significantly different ($p < 0.05$) according to the Wilcoxon rank sum test.

Table 5: The effect of pH of spray solutions on the performance of glyphosate (0.125 kg/ha) against *Panicum repens*.

pH of Spray solution	Regrowth at 30 days (g) ¹	% Regrowth Reduction	Foliage Injury Score ²
4.0	0.09 ^b	64	1.0
6.0	0.03 ^c	86	3.0*
8.0	0.06 ^{bc}	72	2.0
Untreated Control	0.21 ^a	0	0

¹Values followed by the same superscript letter are not significantly different ($p < 0.05$) according to the Duncan's multiple range test. ²Foliage injury score; 0 = no injury; 5 = plants dead. (*) indicates values which are significantly different ($p < 0.05$) according to the Wilcoxon rank sum test.

The effect of carrier volume, dose and water quality: In the field experiment, the higher carrier volume (600 l/ha) caused 100% wetting of the foliage, from which much of the spray ran-off. In contrast, at the lower carrier volume (300 l/ha), only about 50% of the target foliage was wetted. Analysis of the regrowth data (Table 6) indicated that there was no statistically significant difference in the performance of glyphosate at 1.0 kg/ha applied by either carrier volume. However, at the higher rate of 2.0 kg/ha, while glyphosate activity in deionized water was similar at both carrier volumes, it was significantly greater at the higher carrier volume, with groundwater as the carrier. No regrowth occurred in plots which received

glyphosate at 4.0 kg/ha, while on average, 78% and 63% reductions of regrowth were achieved respectively, by the rates 2.0 and 1.0 kg/ha (Table 6). In general, with both these rates, mean regrowth inhibition was clearly significantly greater when glyphosate was delivered in deionized water, when compared to the ground water carrier.

Glyphosate applied at 4.0 kg/ha, irrespective of the carrier volume and water source, achieved 100% rhizome bud-kill even at 4 DAT. Although bud viability data failed to show significant differences in the herbicide performance at the different carrier volumes, at the lower rates of glyphosate, it did confirm superior activity in de-ionized water compared to that in groundwater (Table 6).

Table 6: The effect of carrier volume and two sources of water on the performance of glyphosate (0.125 kg/ha) against *Panicum repens*.

Glyphosate Rate (kg/ha)	Water Source	Carrier Volume (l/ha)		
		300	600	Mean
----- % Regrowth Reduction* -----				
1.0	Deionized water	72	68	70
1.0	Well water	56	54	55
2.0	Deionized water	90	90	90
2.0	Well water	60	72	66
4.0	Deionized water	100	100	100
4.0	Well water	100	100	100
	Mean	79	81	
		LSD (0.05) = 4.0		
----- % Viable Buds* -----				
1.0	Deionized water	14.1	15.4	14.7
1.0	Well water	19.5	17.1	18.3
2.0	Deionized water	10.8	9.4	10.1
2.0	Well water	12.9	13.4	13.1
	Mean	14.3	12.8	
		LSD (0.05) = 2.0		

* Results of 4.0 kg/ha application (i.e. 100% regrowth reduction or bud-kill) were not considered for the statistical analysis.

DISCUSSION

In the present studies, the addition of ammonium salts or urea to glyphosate sprays did not produce a significant enhancement of its systemic activity, despite an increased foliar damage caused by $(\text{NH}_4)_2\text{SO}_4$ and urea. This is in contrast to the results reported from India by Sharma and Sundar,²² and Sharma *et al.*²³ who achieved a positive activation of lower rates of glyphosate (viz. 0.42, 0.84 and 1.26 kg/ha in 450 l/ha of water) by $(\text{NH}_4)_2\text{SO}_4$ added at 1.25 kg/ha, and a depression of herbicide effect at higher rates of ammonium salts. However, previous studies in Sri Lanka conducted by the TRI, also failed to establish an increase in glyphosate activity at 1.0 kg/ha, against *P. repens*, by the addition of ammonium sulphate at 8 kg/ha or urea at 3.58 kg/ha.²⁴ It is possible the high ammonium salt concentration in the TRI study prevented detection of synergism between the salts and glyphosate.

The addition of ammonium salts therefore, may not produce a general enhancement of glyphosate activity under a wide range of environmental conditions, despite previous reports of synergism in the control of weed species such as *Cyperus rotundus* L.¹⁹ and *Elymus repens*.^{18, 21} and also *P. repens*.^{22, 23} Our results appear to be comparable with those reported by Blair²⁵ who stated that evidence for major and reliable improvement through the use of additives such as ammonium sulphate and butyl acid phosphate with glyphosate, was inconclusive. The synergistic interaction of ammonium salts with glyphosate is not well understood. Blair²⁵ suggested increased penetration or translocation of the herbicide by the ammonium salts; Suwunnamek and Parker²⁰ felt that there was some activation within the plant and that a greater translocation reduced the ability of regrowth of perennial weeds. We conclude therefore, that there is insufficient evidence available at present to expect a more generalised influence of ammonium ions mixed with a particular herbicide, promoting phytotoxicity in a wide variety of plant species. It is highly probable that the effect of ammonium salts might be specific only to certain weed species. Whilst the present study and those of Sharma and Sundar²², and Sharma *et al.*²³, indicated that *P. repens* is possibly one of them, a broader study is needed, incorporating a range of lower rates of the herbicide with a range of lower rates of ammonium salts, before a final conclusion is reached.

Addition of inorganic salts, particularly CaCl_2 and ZnSO_4 to glyphosate spray solutions appears to generally reduce the activity of the herbicide, a result which agrees with previous studies in which similar antagonism of glyphosate activity by di- or tri-valent inorganic ions has been recorded.^{12, 14, 15} Glyphosate activity is known to decrease significantly when applied in "hard water" due to the presence of polyvalent cations, such as Ca^{2+} , Mg^{2+} , Fe^{3+} , Al^{3+} , an effect attributed to the formation of "chelates" between glyphosate molecules and cations, which reduce the amount of active ingredient of the herbicide available

for biological activity. Shilling and Haller¹⁶, found that *P. repens* growth was actually stimulated, and not inhibited, by glyphosate both at low and high rates when calcium was present in the spray solution, suggesting strong antagonism between glyphosate and Ca^{2+} . These authors argued that both the decrease in *P. repens* control (lower level of inhibition) and the change in activity characteristics (from inhibition to stimulation), were caused by the formation of Ca-glyphosate complexes which resulted in a reduction in biologically active glyphosate. However, in the same study, the presence of Ca^{2+} had hardly any effect when glyphosate was used at a high rate (4.4 kg a.i/ha).

The reduction of activity due to the presence of Ca^{2+} and other inorganic ions, indicates a major limitation for glyphosate applications, if groundwater drawn from "wells", or freshwater from streams and ponds, is used as the carrier. Although the carrier water was not analysed in this work, it is conceivable that ions such as Ca^{2+} , Zn^{2+} or Mg^{2+} are present in sufficiently high concentrations in groundwater, and this may lead to decreased field performance of glyphosate. Shilling and Haller¹⁶ reported that in Florida, Ca^{2+} concentrations in surface water was up to 3 mM (120 ppm). The same report indicated that Ca^{2+} concentration in groundwater in Florida could be as high as 21.25 mM (850 ppm), with levels of 2.5 mM (100 ppm) and 5 mM (200 ppm) being common. Variable results with glyphosate in the control of *P. repens* could be due to this factor in the spray solution. Reduced phytotoxicity would inevitably result in requiring higher rates of glyphosate to control the weed, and a general under-estimation of the herbicide's capacity to achieve control.

The enhancement of glyphosate activity caused by the incorporation of non-ionic surfactants, is in good agreement with previously reported studies.^{2, 14, 17} O'Sullivan *et al.*¹⁷ reported that in the field, surfactants Tween 20, X-77 and Triton X-100 enhanced the effectiveness of low glyphosate rates on rape (*Brassica campestris* L.), wild oats (*Avena fatua* L.) and barley (*Hordeum vulgare* L.). They also showed that Agral 90 alone had no effect on glyphosate phytotoxicity, but when combined with ammonium sulphate, glyphosate activity was dramatically enhanced. Shea and Tupy¹⁴ reported that glyphosate phytotoxicity to wheat (*Triticum aestivum* L.) was significantly increased by the incorporation of non-ionic surfactants X-77 or MON-0011 and EDTA, compared with the performance of cationic surfactants (contained in a commercial formulation). The exact mechanism by which surfactants enhance glyphosate phytotoxicity is unknown, but it is probable that surfactants directly assist uptake or retention of glyphosate by foliage, or both these processes. The well-known influences that surfactants have on spray applications, such as (a) the reduction of contact angles, (b) the reduction of surface tension between the solid (leaf surface) and the spray liquid interface, and (c) the delay caused in the 'drying' of spray droplets, may all assist the movement of biologically active material into leaves through both cuticular and stomatal penetration.^{18, 25} The

significant increase of toxicity produced on *P. repens* by the addition of surfactants to glyphosate, in the present study, is probably due to the combination of such effects. It appears, therefore, essential to further validate these findings by conducting appropriate field trials, particularly in the tea plantation sector, and make necessary changes to the current recommendation.¹¹

Although the addition of oil additives to glyphosate solutions in this study did not result in a significant enhancement of activity, such additives have been well-known to promote herbicidal activity^{18,26,27}, with the degree of enhancement depending on the plant species and also on the herbicide. At times, oil additives have been even more effective than surfactants in enhancing absorption, such as in the case of atrazine²⁸, chloroprotham²⁹ and bentazon.³⁰ However, Nalewaja and Skrzypczak³¹ reported that the absorption and translocation of fluazifop, a systemic grass-killing herbicide, by oats was less when applied with safflower (*Carthamus tinctorius* L.), sunflower (*Helianthus annuus* L.), soybean (*Glycine max* Merr), palm (*Elais guineensis* Jacq.) and linseed oil, than with petroleum oil. They argued that increased fluazifop solubility in vegetable oils may prevent it from effectively diffusing through the polar routes.

Sprays containing oils are generally likely to remain on leaf surfaces longer than aqueous sprays, allowing a longer time for herbicide penetration through the leaf cuticle, causing softening or solubilization of the cuticle, or alter cuticle chemistry to such an extent that foliar uptake might be facilitated mainly through the lipophilic pathway.^{18,29} In our study, it may be that the concentration of the oils added to the spray solution was not sufficient to produce any alteration of glyphosate activity, or the leaf surface characteristics of *P. repens* were such that there was no response to this modified spray solution. However, in view of the well-known fact that glyphosate activity is generally amenable to enhancement through oil additives, and with a need to make glyphosate treatments more cost-effective and consistent, we recommend that further studies are conducted incorporating a broader range of oils and concentrations.

As pointed out by Sprankle *et al.*³², glyphosate, which is an amino acid, has four pKa values of 2.0, 2.6, 5.6 and 10.6. Buhler and Burnside¹² as well as Shea and Tupy¹⁴ reported that glyphosate activity increased sharply at acidic pH, but did not change significantly from neutrality to more alkaline levels. Shilling and Haller¹⁶ reported that when glyphosate was applied at 0.56 kg/ha to control *P. repens*, inhibition of shoot regrowth was greatest when the spray solution was buffered at pH 6, a result which is in agreement with our studies. However, in the present study, the pH of the spray solution was only adjusted with HCl and NaOH solutions, and not buffered, which may have allowed changes in pH as the spray droplets evaporated. In our other studies, the mean pH value of glyphosate solutions made for applications at rates of 1.1 - 4.4 kg/ha (carrier volume of water 600 l/ha), varied between 4.17 to 4.92, in the acidic region. Therefore, it appears

that adjusting of pH of the spray solutions to 6 may allow the treatment to achieve a high degree of control of *P. repens*.

In agreement with many of the published studies from other countries, the quality of water (determined by its source), the carrier volume used, the applied herbicide dose and their interactions affected glyphosate performance in our study as well. The overall results indicate some clear trends. For instance, the result that the 2.0 kg/ha glyphosate dose was more effective when delivered by 600 l/ha of groundwater, than by 300 l/ha carrier volume, indicates that the use of a medium-range volume might be appropriate to optimise glyphosate performance on *P. repens*, whose leaves are likely to be not-too-easy to wet. Also, it was clear that with both the lower rates, mean regrowth inhibition was significantly greater when glyphosate was delivered in deionized water, when compared to the groundwater carrier, indicating that the latter source of water may cause an inferior performance of glyphosate, possibly due to the presence of a variety of antagonistic di- or tri-valent ions. Confirmation of this decreased performance in the presence of the groundwater carrier was obtained by rhizome bud-kill data as well. Differences in glyphosate efficacy between 'hard' water and distilled water have been well documented. O'Sullivan *et al.*¹⁷ reported that glyphosate applications to barley (*Hordeum vulgare* L.) in distilled water were more phytotoxic than applications in tap water, and that the differences were most evident at low glyphosate rates and high spray volume. The toxicity of low rates of glyphosate to hemp dogbean (*Apocynum cannabinum* L.) was greater when applied in distilled or deionized water, compared to the performance in tap water, according to Schultz and Burnside.³³

As pointed out earlier, in our field trials, the regrowth suppression achieved by glyphosate at 2.0 kg/ha, delivered by groundwater at 600 l/ha (72%), was significantly greater than that achieved with 300 l/ha carrier volume (60%). This result is somewhat contradictory to the suggestion that cations in groundwater may cause an inferior herbicide performance. The only plausible explanation appears to be that, under the particular set of conditions operating in the field trials, a low carrier-volume 300 l/ha may not have resulted in sufficient coverage of the mature *P. repens* foliage, whilst 600 l/ha may have enhanced the herbicide's performance simply by achieving improved coverage. Although, being an efficient systemic herbicide, glyphosate does not require a high degree of 'coverage' of target foliage for activity¹⁹, it does require application to younger and actively growing leaves for optimum performance. Therefore, we believe that the non-inclusion of additional surfactant or oil additives in the spray treatments in this study, may have resulted in a sub-optimal performance from the herbicide. The amount of spray retained by a plant is influenced to a large extent by the diluent volume used to make up and deliver the spray solution. With systemic herbicides in general, the degree of coverage is less important, than with foliar applied herbicide having contact action.¹⁸ However, according to

many researchers, glyphosate applications as low volume sprays, have caused remarkably increased phytotoxicity against many weed species.^{12, 17} O'Sullivan *et al.*¹⁷ argued that such a reduction of phytotoxicity of glyphosate at high diluent volumes may be due to the combined influence of the reduced surfactant-to-water and glyphosate-to-water rates, run-off from the leaf surfaces of target plants, as well as inhibitory effect of the cations (as the spray volume increased, the total amount of cations available to react with glyphosate is increased).

It was also evident that increasing the glyphosate rate removed the differences between the water sources in our experiments, in agreement with many published studies.^{17, 33} The interactions between glyphosate low rates, the target weed species, the nature of its foliage, carrier-volume, and the source of water are complex, and can probably account for much of the known inconsistencies in glyphosate performance. Although it is clear that one way of removing the inconsistency is to use a high dose such as 4.0 kg/ha of glyphosate, this option surely is not economical. Nor is it safe to the tea plants which show marked phytotoxicity, if glyphosate spray drifts fall on the tea foliage. Our experiments clearly indicates that for economical and optimal *P. repens* control by glyphosate, lower rates can be used, assisted by non-ionic surfactant additives. The use of a source of water which contains less or negligible amounts of di- or tri-valent cations would also enhance the performance of glyphosate.

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