EFFECTS OF WEATHER ON HERBICIDE ACTIVITY

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Summary. The variability of the weather is a major cause of unreliable herbicide performance resulting in either inadequate control of weeds or crop damage. In order to make the most economic use of herbicides, with minimal adverse effect on the environment, it is important to know how light, temperature, humidity and rain affect herbicide performance.

Most farmers accept that certain weather criteria must be met for successful application of pesticides and wide use is made of weather forecasts in decision making on this topic. It is less widely appreciated that, even when these criteria for spraying are met, environmental conditions before and after application exert a major influence on herbicide activity.

Field studies provide an overall view of herbicide performance under contrasting soil and weather conditions, but usually the role of individual environmental factors cannot be established. However, the importance of individual factors can be ranked in controlled environment experiments. This approach allows the conditions for optimum herbicide performance to be defined in environment/herbicide performance profiles (EHPPs).

The general principle outlined above are illustrated with reference to the control of annual and perennial weeds with foliage and soil acting herbicides including glyphosate, difenzoquat, paraquat, ioxynil, isoproturon chlorsulfuron, and diclofop-methyl.

INTRODUCTION

In many parts of the world, farmers are faced with declining prices for their crops, accompanied by increasing costs of production, including those for weed control. In Australia, Combellack (8) estimates A$137 million was spent on herbicides for use in agricultural crops in 1985. In addition to economic considerations, possible risks of contaminating the environment with herbicides continue to cause concern. Consequently, means of improving the efficiency of herbicides are particularly appropriate at the present time. One important approach to enhancing herbicide performance involves understanding the role of weather in determining the outcome of a herbicide treatment so that optimum performance may be achieved under a wide range of weather conditions.

In this selective review of weather/plant/herbicide interactions, most examples are taken from work done at the defunct Weed Research Organization, Oxford, U.K. and some of the weeds referred to may be unfamiliar to you, but the principles that they illustrate should be relevant to the Australian situation.

WHEN DOES WEATHER AFFECT HERBICIDE PERFORMANCE?

Most farmers and spraying contractors accept that certain weather criteria must be met for successful application results and wide use is made of weather forecasts in decision making for spray application. It is less widely appreciated that, even when the weather criteria for spraying are met, environmental conditions both before and after application exert a major influence on herbicide activity which may result in either inadequate control of weeds or crop damage.

RANKING THE IMPORTANCE OF ENVIRONMENTAL FACTORS

Field experimentaion may provide an overall view of herbicide performance under contrasting soil and weather conditions, but usually it does not establish the role of individual environmental factors since these are constantly changing and the influence of one cannot readily be distinguished from that of another. For example, as weather conditions change from sunny to cloudy, first light intensity falls, then temperature drops and in turn other factors such as humidity and air movement are affected.

Techniques to control or simulate individual components in the field allow trends due to particular factors to be identified, e.g. the use of irrigation and rain covers to investigate the effect of rain on the activity of soil-applied herbicides. In this type of field experiment, it is important to measure not only the factor that is deliberately being manipulated, but also other components that may alter in response to the imposed treatment.

In order to reach a more precise understanding of the relationship between weather and herbicide performance it is necessary to use a facility where one weather factor can be varied while the others are held constant. Experiments in controlled environments have been particularly valuable for studying the effects of individual environmental factors on the component processes involved in herbicide performance shown in Fig. 1. However, results from studies of this type should be considered in conjunction whith closely monitored outside experimentation before field recommendations are formulated.

Steps in herbicide activity

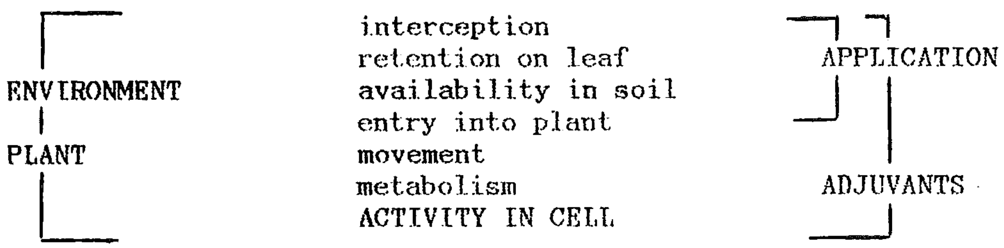

Figure 1. Factors that affect the steps involved in herbicide activity

The major factors which determine the progress of the herbicide from the plant surface to its site of action are the biology of the plant and weather factors. The farmer has little direct control over these, but adjuvants and application techniques, to some extent, may be selected to overcome some of the obstacles they present to optimum herbicide performance.

THE PRE-SPRAYING ENVIRONMENT

During this period the weather affects the size, form, habit and cuticular characteristics of shoots, all factors of particular importance in relation to the efficacy of post-emergence herbicides. Similarly root development and position in the soil profile are affected, which is of importance for herbicides with soil activity. The steps in herbicide activity that are involved include interception, retention, foliar penetration and, to a lesser extent, movement of the herbicide. The pre-spraying environment will also affect the development of storage and regeneration organs in perennials to which herbicide must be transported for effective control.

Light drives photosynthesis and has a major effect on the growth and development of the plant during the pre-spray period. English couch, *Elymus repens*, grown at 50 Wm^{-2}, a low light regime found, for example, within a cereal canopy, had less than half the weight of rhizome of plants grown at 200 Wm^{-2}. Furthermore, the shade grown plants had a high ratio of shoots to nodes which is conductive to control by foliage applied herbicides (5).

Temperature influences plant growth and development by directly affecting the rate of chemical and enzyme-mediated reactions. This is manifested in plant size and habit. Coupland and Caseley (11) grew English couch in day/night regimes of 10/6, 16/10 and 26/16°C and sprayed them at the same growth stage (6 leaves, 3 to 4 tillers); spray retention was found to increase with temperature approximately in the ration 1:2:3. This result was reflected in correspondingly greater herbicide effectiveness on plants grown at the higher temperatures.

The effect on herbicide performance of cold temperatures or frost prior to spraying depends upon several factors including the severity of the cold treatment, when it occurs in relation to spraying, plant species and herbicide. Ivany (19) found in field experiments that glyphosate application after severe frost which caused foliage necrosis, resulted in poor control.

Increasing plant water stress results in gradual stomatal closure and eventually a rapid fall in photosynthesis. Concomitantly there are changes in the level of endogenous plant growth regulators and alterations in membrane and cuticular characteristics resulting in smaller plants with altered morphology and physiology.

Chick weed, *Stellaria media*, plants grown in dry compared with moist soil (50 adn 100% field capacity respectively) developed a more waxy surface, thicker cuticle and had a higher chlorophyll content. The dry grown plants retained less spray, less ^{14}C-labelled ioxynil octanoate entered the leaves and the plants were more resistant to overall treatments of this herbicide (21).

Rain prior to spraying affects plant and soil moisture status, but may also have direct effects on the plant. White mustard, *Sinapis alba*, plants subjected to rainfall of 10.0 mm/h for 1 h on seven consecutive days had less crystalline wax deposits on leaf surfaces and were more susceptible to fluroxypyr than plants receiving no rain on their foliage (16).

There are limited data on the consequences of applying herbicides to wet foliage. Caseley *et al.* (7) showed that applications to foliage wetted with 'light rain' (applied with a laboratory pot sprayer) did not result in reduced glyphosate performance even though visible spray run-off occurred with some treatments.

The examples above illustrate that the long- and short-term pre-spraying environments affect the morphology and physiology of the plant and may subsequently alter the performance of herbicides.

CONSTRAINTS ON SPRAYING

Herbicides should be applied when the tolerance of the crop and susceptibility of the weed are both optimal. The duration of this period depends on the specific herbicide/crop/weed/weather situation. Environmental factors affect the rate of development of the crop and weed, and adverse conditions such as rain and wind limit the opportunities for spraying. Tottman and Phillipson (23) found that spray application of phenoxy herbicides to cereals was limited to around 20 days by the growth stages of the crop and weeds. Levels of rain and wind which prevented spraying reduced this period to between 4 and 8 days.

To some extent the flexibility of spraying programmes has been increased by newer herbicides that can be applied to a wider range of growth stages and during longer periods of the growing season. In addition use of controlled drop application and low ground pressure spray vehicles make it possible to spray herbicides under less favourable environment conditions (2). In spite of these advances, herbicide applications are frequently made under suboptimal conditions due to lack of 'good spray days'.

THE POST-APPLICATION ENVIRONMENT

The hours immediately following application are of paramount importance to post-emergence treatments. Herbicide deposits on the surface of the plant are vulnerable to removal by, for example, heavy rain, and the success of a treatment is not assured until a lethal quantity has penetrated the cuticle. The activity of 1 kg/ha of difenzoquat against wild oats, *Avena fatua*, halved when 2.0 mm/h of rain was applied for one hour immediately after the herbicide treatment. Lesser amounts of rain, up to 0.5 mm immediately after spraying, had no adverse effects on difenzoquat activity although almost one third of the herbicide was removed form the wild oat foliage. Most of this loss occurred from the leaf blade and some herbicide deposit was redistributed to the ligule and inner surface of the leaf sheath, areas known to be more responsive to herbicide treatment (4).

However, even rain at 10.0 mm/h for 100 minutes applied 10 minutes after diclofop-methyl treatment of wild oats had no adverse effect and up to 3.3 mm/h for the same period improved activity compared to herbicide treated plants without rain. The control of the broad-leaved weed creeping speedwell, *Veronica persica*, by phenmedipham is enhanced by rainfall of up to 10.0 mm/h even though 90% of active ingredient is removed from the plant. Redistribution of the remaining 10% active ingredient to the petiole and stem illustrate the importance of preferential sites of entry (15). Herbicides with foliage and soil activity such as chlorsulfuron and fluazifop-butyl tend to be less affected by heavy rain than compounds such as glyphosate which enter the plant exclusively through the shoot.

Thus rainfall soon after application of some foliage-applied herbicides, especially water-soluble ones, reduces their performance. The significance of rainfall within this period, however, depends upon many factors: characteristics of the herbicide, its dose, formulation, period between spraying and the onset of rain, type and intensity of rain, temperature, humidity and other factors.

Increased light intensity has been found to enhance the uptake and translocation of many herbicides and to accelerate the development of herbicide damage. Coupland (9) found that the translocation of ^{14}C-glyphosate from the leaf sheath to the rhizomes of English couch was twice as fast at a light intensity of 117 Wm^{-2} compared to 26 Wm^{-2} over a 24 hour period, but by 40 hours the rhizomes had accumulated similar amounts of herbicide.

In general, glyphosate treatments applied in the middle of the day or night period did not differ significantly from those made at the beginning of the day regime (6). In contrast the performance of the foliage applied herbicide paraquat is markedly reduced when several hours 'light' follow its application as in the mid-morning treatments shown in Table 1.

Table 1. Control of *Paspalum conjugatum* with 0.5 kg/ha paraquat applied in the evening or mid-morning ± bromacil

Time of application	0.2 kg/ha bromacil	% of control after 6 weeks
Evening	-	28
	+	10
Mid morning	-	80
	+	35

(After Headford (18))

In illuminated paraquat treated plants electron flow in photosystem I is diverted and in the presence of oxygen, highly reactive species of oxygen are formed which rapidly damage chloroplast membranes. The paraquat is compartmentalised in damaged tissue preventing systemic action. Following the low light evening application there is little membrane damage and paraquat is mobile in the plant. In the mid-morning treatment including a sub-lethal dose of bromacil, a photosynthesis inhibiting herbicide, electron flow is temporarily blocked and systemic activity of paraquat is achieved.

These results illustrate that individual herbicides may differ in their response to specific environmental factors and that a knowledge of the biochemical and physiological mechanisms involved in the interaction of individual herbicides with environmental factors enables a more logical approach to overcoming adverse environmental effects on herbicide performance.

In general, absorption and translocation of herbicides increase with a rise in temperature. This is due to effects on the rate of diffusion through the plant cuticle, increased rates of transpiration and subsequent apoplastic movement, and an increase in the general metabolic activity of the plant providing suitable energy sources for the active loading of assimilates in the translocation stream. At constant relative humidity, temperature directly influences the rate of spray droplet drying on the plant surface. In this way, herbicide absorption may be restricted under warm, dry conditions since it is thought that water-soluble herbicides need to be in solution to be efficiently absorbed.

In a controlled environment study with a constant absolute humidity Coupland and Caseley (11) grew English couch at 16/10°C, applied glyphosate and then divided the plants into three groups which were placed in cool (10/6°C), warm (16/10°C) and hot (26/16°C) regimes. After 3, 6 and 12 the rhizomes were fragmented into single node pieces and their regrowth determined. Toxic amounts of glyphosate accumulated in more nodes in a shorter time under the warmest conditions.

In experiments of more than one week, research has invariably shown that more effective control is achieved with glyphosate under cooler conditions. Thus despite the fact that more glyphosate is absorbed and transported under warm conditions, in the long term cool conditions result in the best glyphosate performance. One possbile explanation is that plants usually grow faster under warmer conditions and this may lead to an effective dilution of the herbicide within the plant, but probably more importantly enhanced metabolism of the herbicide under warm conditions has been shown by Coupland (10). He treated rhizome fragments with ^{14}C-glyphosate and found a significantly greater depletion of radiolabel at 26/16°C compared with 10/6°C over 21 days. Sustained high temperatures will not have a detrimental effect on the activity of herbicides which are not readily metabolised e.g. difenzoquat.

In relation to crop tolerance Papalia and Blacklow (22) observed that the wheat cultivar Sonora was more susceptible to chlorsulfuron when night soil temperatures were 5°C or 0°C compared to 13°C, and this may well be related to the temperature dependent rate of metabolism of the herbicide to non-phytotoxic metabolites.

A number of processes of importance to herbicide performance are affected by humidity including spray drop drying. A precise correlation between these and RH can only be expected at a given temperature, thus both these factors should be recorded in environmental studies.

Merritt (20) has shown glyphosate and MCPA penetration is enhanced with increasing concentration of the herbicide, but entry is likely to cease if the deposit dries. A fully hydrated cuticle favours the uptake of foliage-applied herbicides, particultural water soluble compounds such as glyphosate, which are believed to enter the plant via a 'hydrophilic pathway'. Transpiration is increased under low humidity regimes, and if adequate water is available from the soil enhanced acropetal movement of foliage and soil applied herbicides will result.

The marked effect that humidity may exert on glyphosate performance during the 24 h following treatment is illustrated by the results in Table 2. Immediately after spraying established English couch with glyphosate, the plants were placed in 50% or 90% RH until the rhizomes were fragmented into single node fragments at three to 24 hours after spraying when node viability was determined.

Table 2. Effect of humidity on node viability of English couch treated with 0.8 kg/ha of glyphosate

	Time between spraying and rhizome fragmentaion (h)			
	3	6	12	24
RH%		Node viability (%)		
90	41	14	0	0
50	89	81	41	6

Light 170 Wm^{-2}, daylength 14 h, temperature 15/10°C. (After Coupland and Caseley (11)).

Soil moisture at the time of spraying and thereafter has a major effect on herbicides with soil activity such as simazine and atrazine. Soil moisture is of the utmost importance as it affects herbicide availability, distribution and degradation in the soil and distribution and development of plant roots through which the herbicide enters the plant.

Application to soil surfaces with a low moisture content tends to reduce herbicide activity. Addala (1) found pre-emergence applications of chlortoluron for wild oat control were less effective when applied to dry (11% FC) compared to moist (100% FC) soil. These results concur with those of Hance and Embling (14) who measured a decreased extraction of three herbicides from a soil solution in a pressure membrane apparatus after herbicide application to dry soil.

At soil moistures below 100% FC surface application of water or rainfall plays a vital role in moving isoproturon down the soil profile and promoting advertitious root development in, *Alopecurus myosuroides*, black-grass (3).

Foliage applied herbicides may also be influenced by soil moisture stress occurring at and after spraying. The wild oat herbicide diclofop-methyl was markedly affected by soil moisture stress imposed from time of spraying for 2-3 weeks. At approximately field capacity 1 kg/ha of dicolfop-methyl applied to the foliage, with the soil protected, reduce wild oat foliage fresh weight to 40% of untreated controls. This level of herbicide activity was approximately halved under the dry regime (50% FC) and doubled on plants in the wet, but not flooded, regime (200% FC). ^{14}C-Diclofop-methyl studies showed that entry and movement were unaffected by the moisture regime (17).

Application of abscisic acid to wild oats kept at field capacity produced the same response to diclofop-methyl as found in water stressed plants indicating the involvement of this endogenous plant growth regulator in depressed herbicide activity (13).

THE ENVIRONMENT/HERBICIDE PERFORMANCE PROFILE (EHPP)

Information collected in controlled environment studies may be considered together with results from outside experiments and synthesised into a herbicide/environment profile, illustrated for glyphosate in Table 3.

Table 3. Individual environmental factors leading to maximum control of English couch with glyphosate[a]

Factor	Pre-application period		Time of application	Post-application period	
	Long	Short		Short	Long
Light	Low**	Low*	-	High**	-
Temperature	Low**	High**	-	Medium**	Low**
Humidity	-	High*	-	High***	-
Rain	-	<0.5mm*	<0.5mm***	<0.5mm***	-
Soil moisture	Medium*	Medium***	Medium***	Medium***	-
Wind	-	-	<12 km/h	-	-

[a] Relative important of factor: * (least) to *** (most). (After Caseley and Coupland (5)).

Low light and temperature for a lengthy pre-application period results in plants with little rhizome and a high ratio of foliage to nodes. High temperature in the week immediately before application favours the development of leaves which are readily wettable and easily penetrated. High humidity, dew, or slight rain immediately before application ensures that the cuticle is fully hydrated, thus aiding penetration. The occurrence of these conditions after application keeps the herbicide in solution, thus facilitating penetration, while warmth and high light during this period favour phloem transport. Finally, low temperature for a lengthy period after penetration of herbicide improves its activity in buds on the rhizomes and reduces recovery.

The information contained in the environment/herbicide performance profile may be used in several ways including:

1. Interpreting results from different sites and seasons

2. Increasing the precision of field recommendations

3. Assisting in the development and evaluation of new formulations and application methods

4. Improving the criteria for choosing periods for spraying

Analysis of meteorological data for the years 1973 to 1980 from four meteorological sites in cereal-growing areas clearly shows that periods of environmental conditions that favour both spraying and glyphosate performance for control of English couch occur more frequently at night. Controlled environment studies show that darkness does not adversely affect uptake of glyphosate, but light is required for the movement of the herbicide to the rhizome (6).

DISCUSSION

Information on the influence of environmental factors on herbicide performance before, during and after application of the spray may assist in the choice of spray periods that not only favour spraying but will also enhance herbicide activity. When the target weed has grown under conditions conductive to herbicide action and the weather forecast is favourable, a reduced dose of active ingredient may be used.

If weather conditions are sub-optimal the EHPP may help in the choice of an adjuvant to overcome adverse environmental conditions. For example, if the target weed has developed under cold or water stress conditions, addition of surfactant or appropriate adjuvant oil may enhance retention and penetration. If rain is forecast a polymer adjuvant may improve adhesion and resistance to wash-off.

When environmental conditions have predisposed the weeds to herbicide tolerance, synergists may be employed. Thus tridiphane reduced the metabolism and increases the phytotoxicity of atrazine in target weeds, but not maize (12).

To conclude, the most effective use of EHPPs requires access to weather records, reliable forecasts and for greatest precision 'on farm' weather monitoring.

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