
Chapter 10

TECHNOLOGY OF PESTICIDE APPLICATION

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The production of crops and pastures has increasingly become dependent on agricultural chemicals for control of weeds, insect pests and diseases. In particular, the trend towards replacement of cultivation by the use of herbicides and the retention of crop residues has required much closer attention to spray-application technology and to understanding plant responses to these chemicals.

As chemicals are expensive and because of greater community concern about environmental issues, the efficiency of pesticide application is of paramount importance. By improving efficiency better control of the target organism can be obtained, rates of chemical may be reduced thereby reducing costs, and the risk of environmental pollution is lowered. The likelihood of development of pesticide resistance is also lowered.

Development of the first hydraulic hollow-cone nozzle, the cyclone nozzle, occurred in the 1860s and revolutionised pesticide application by providing better coverage and reducing the time taken to treat a given area. During the 1880s the boom sprayer was developed in both France and the USA. These early horse-drawn units were designed to spray vines and used a ground-drive positive-displacement pump. Later developments included motorising the pump, pulling the units with tractors, enlarging the tank and increasing boom width. In the 1940s the single-orifice fan nozzle was introduced, particularly for the application of herbicides.

While the use of pesticides has increased dramatically since the 1940s, developments on the boom sprayer have been slow. The changes made could best be described as fine-tuning, including, for example, the introduction of fibreglass tanks, more efficient pumps, more durable and lighter spray lines, better nozzles and nozzle holders, self-levelling booms and even electronic components for measuring speed and fluid volumes. Only in recent years has there been significant change with the development of low-volume, controlled-droplet application (CDA) techniques and the development of electrostatic spraying techniques.

This chapter examines the theory of the spraying operation including droplet production, distribution and collection on the target; and the ways spraying efficiency can be increased. It concludes with some thoughts on the future of spraying.

PRINCIPLES OF SPRAYING

The aim of spraying is to deliver to the target the minimum amount of toxicant that will give a satisfactory level of control with least contamination of the environment. Any excess chemical on the target, and any that misses or is carried away from the target, is wasted.

Combella (1979) noted that the percentage of toxicant reaching the target, i.e. spraying efficiency, is as low as one-millionth of 1% for some insecticide spraying operations. He estimated that spraying of weed seedlings was up to 2% efficient and that spot-spraying mature weeds may be up to 60% efficient. The efficiency of spraying can be improved by understanding and applying the principles of spray application.

A spraying operation has five distinct phases:

- * addition of a herbicide to a diluent to make a spray solution or suspension;
- * droplet production and droplet distribution over the target area;
- * movement of the droplets to the target;
- * impaction and retention of the droplets;
- * effectiveness of deposit in the achievement of a level of control.

Spraying parameters such as droplet size, trajectory, spacing on the plants and placement must be defined in relation to the level and duration of weed control desired, based on criteria such as weed density (Dew, 1972; Gilbey, 1974; Reeves, 1976; Wells, 1979; Zimdahl, 1980) and an estimate of the economic impact of the residual plants (Elliot, 1978; Vere and Campbell, 1979; Zimdahl, 1980). These factors should then be related to the tolerance of the crop to herbicides applied after emergence and to residues of the herbicides applied before sowing.

Defining the optimum spraying parameters will ensure that the amount of spray retained by the target is just sufficient to give the desired level of control, while the amount that misses the target or is lost on the way to the target is minimised. Generally losses within the target area are greater than those outside the target area (Combella, 1981).

DROPLET PRODUCTION

The break-up of a large bulk of liquid into droplets is called atomisation. It is achieved by that most important part of the spray equipment, the nozzle, which performs the three essential functions of metering, disintegrating and dispersing the spray liquid.

Metering of the liquid, the flow rate, depends on the size and shape of the orifice (which is affected by imperfections in its manufacture), the pressure used or the amount of energy input, and the physical characteristics of the liquid particularly its viscosity. In a review of spraying efficiency, Musillami (1979) found that it was not possible to rely on pressure gauges to accurately assess changes in flow rate.

The disintegration of the spray liquid into droplets is complex and is reviewed by Dombrowski and Fraser (1954) and Marshall (1954). The droplet spectra, or range and proportion of droplet sizes produced by a nozzle, dictates its use. Those that produce large volumes of droplets less than 100 μm in diameter may cause an unacceptable droplet drift hazard when herbicides are used although they are preferred for the application of insecticides and fungicides where more complete coverage is usually required. Nozzles that produce large volumes of droplets above 300 μm diameter are inefficient because these droplets are often not collected efficiently by the target and a larger volume of spray is required to give the same coverage as smaller droplets.

Spray nozzles can be classified by energy source and distribution of the output liquid.

Pressure nozzles Hydraulic pressure is used to force liquid through an orifice to produce either flat or conical sheets. Fan-shaped flat sheets of spray can be produced by three types of nozzle - impinging jet, solid-surface impact and single-orifice fan spray nozzles. The third is most commonly used to apply herbicides in Australia. Three mechanisms of sheet break-up can be identified - these are perforated sheet, wavy sheet and rim disintegration (Dombrowski and Fraser, 1954) - all of which produce heterogeneous droplet spectra. The physical characteristics of the spray liquid and the nozzle design, i.e. the size and shape of the orifice, affect the spray angle and the thickness of the spray sheet and thus the droplet spectra (Dombrowski, 1961). With single-orifice flat fan nozzles the wider the spray angle (Figure 10.1) the smaller the orifice (Figure 10.2), and the greater the pressure (Figure 10.3) the larger the proportion of small droplets ($< 100 \mu\text{m}$). Orifice design influences the proportion of the spray broken up by rim disintegration, which produces large droplets. Dombrowski and Fraser (1954) showed that increasing surface tension restricted the development of the sheet size, resulting in larger droplets. An increase in viscosity, at the same pressure, caused the region of sheet break-up to move away from the orifice, resulting in larger droplets. Formulation characteristics did not greatly affect droplet spectra from fan nozzles at pressures of 500-1500 kPa. However, increasing pressure decreased the mean droplet size and increased flow rate (Combella and Matthews, 1981a; 1981b). More recent studies (Dempsey *et al.*, 1985) have shown that formulation and concentration of formulation of 2,4-D change the droplet spectrum at pressures less than 350 kPa.

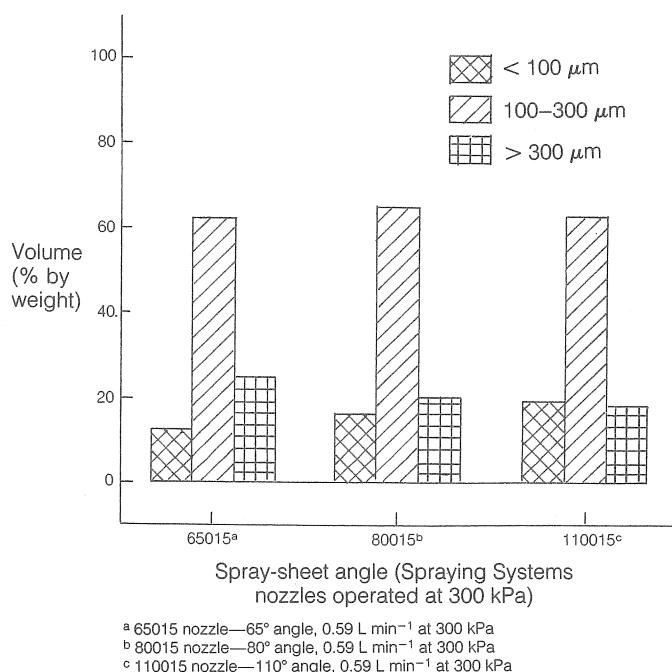


Figure 10.1 Influence of spray-sheet angle on droplet spectra

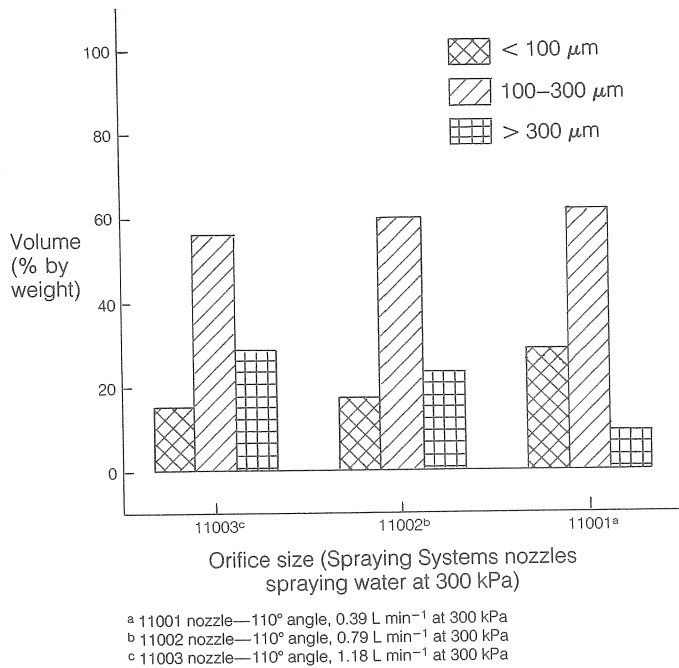


Figure 10.2 Influence of orifice size on droplet spectra

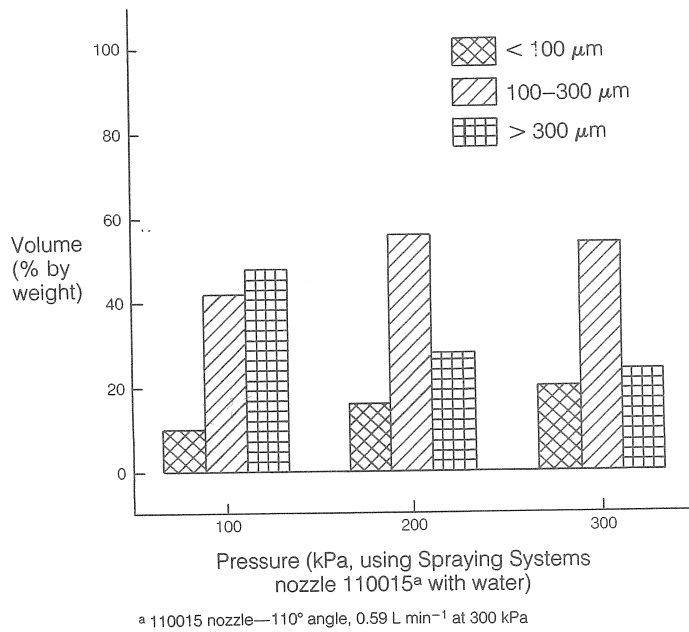


Figure 10.3 Influence of pressure on droplet spectra

Rotary nozzles Rotary nozzles utilise centrifugal energy to disintegrate the spray. Liquid is fed onto or near the centre of a mesh cage, disc or cup, and is then accelerated to the periphery before being discharged. The basic methods of atomisation from rotary nozzles have been summarised by Hinze and Milborn (1950):

- * At low flow rates, droplets are formed directly from a liquid torus around the edge of the nozzle due to the action of centrifugal forces. Generally, a relatively homogeneous droplet spectrum is produced (Figure 10.4). Nozzles used in this way are the basis of many of the controlled-droplet-application (CDA) systems.
- * At higher flow rates, ligaments are produced, which break up into droplets that are relatively homogeneous, but smaller at a given rotational velocity than droplets formed directly (Figure 10.5).
- * At still higher flow rates, the number or thickness of ligaments cannot increase so they join and the torus is flung beyond the edge of the nozzle, forming a sheet, which disintegrates in a similar way to that from flat fan nozzles, and produces a heterogeneous droplet spectrum (Figure 10.6).

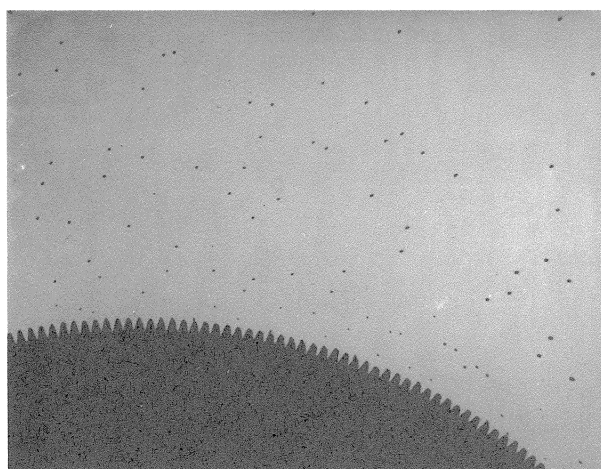


Figure 10.4 Above: Single uniform-size droplets produced from a toothed rotary atomiser disc

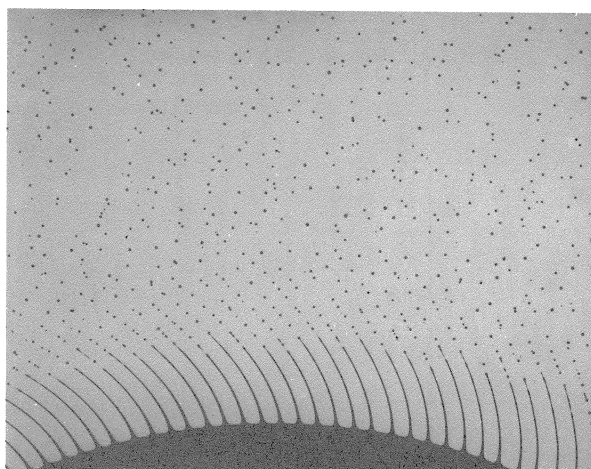


Figure 10.5 Top right: Droplet production from ligaments

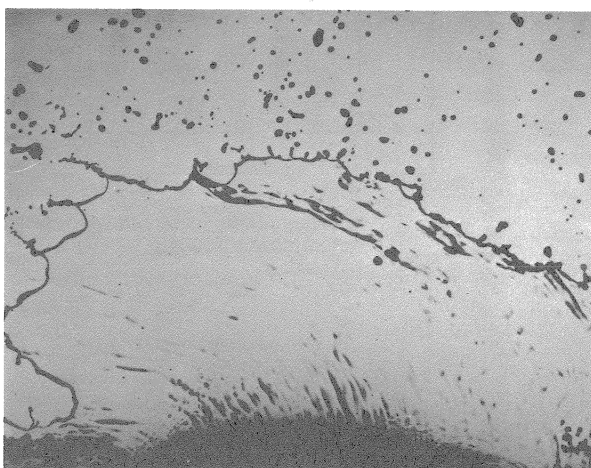


Figure 10.6 Right: Non-uniform droplets and 'sheeting' produced from overloading the rotary atomiser disc

Droplet size is inversely related to disc diameter (Walton and Prewett, 1949) and rotational velocity (Bals, 1969). Boize and Dombrowski (1976) suggested that viscosity does not significantly alter droplet spectra although this is disputed by the evidence of Walton and Prewett (1949) and Frost (1977). Surface tension also affects the break-up of ligaments (Walton and Prewett, 1949; Hinze and Milborn, 1950; Frost, 1977). A formulation containing titanium dioxide produced a significantly greater volume of small droplets ($< 100 \mu\text{m}$) (Combella, 1979) than one without, possibly because the particulate material encouraged the formation of satellite droplets. Although droplet production from rotary nozzles is influenced by a number of variables, relatively homogeneous droplet spectra can be produced under optimum operating conditions.

Other types Other types of nozzles that utilise other forms of energy are occasionally used, for example those using gaseous energy, vibratory energy, both of which have been rarely used, and electrodynamic energy (the Electrodyne nozzle). In the case of the last one, a charge is constantly injected into a basically non-conductive liquid as it leaves the nozzle. The mutual repulsion between different portions of the liquid overcomes surface tension so that it breaks up into ligaments, which then form a homogeneous droplet spectrum usually in the size range $60\text{--}90 \mu\text{m}$ diameter. This system uses high-voltage, $20\text{--}25 \text{ kV}$, but uses little power, approximately 100 mW per nozzle. The system has been extensively tested for insecticides and to a lesser extent on fungicides and herbicides (Pascoe, 1985). Because charged droplets are attracted to target plants they give better coverage than conventional spraying techniques, particularly on the underside of leaves, and use very low volume rates ($1\text{--}10 \text{ L ha}^{-1}$). This has resulted in lower dose rates being effective (Pascoe, 1985). To date the system has only been commercialised as a hand-held unit.

Droplet production from aircraft

Nozzles should be selected to ensure that the aircraft is used efficiently giving accurate delivery within the treated area and minimum loss outside that area. To achieve such an objective the droplet spectra produced under the expected operating parameters must be known. Published data indicate dramatic changes in droplet spectra with changes in nozzle types (Spillman, 1982; Yates, 1981). These will be considered for the two most commonly used nozzle types. The transfer of the droplets to the target is considered elsewhere in this chapter.

Pressure nozzles The droplet spectrum from a nozzle fitted to an aircraft is different from that of a stationary nozzle because of the shearing effect of the airstream, and varies with spray-sheet orientation. Coutts and Yates (1968) showed that volume medium diameter (VMD) of a D6/46 hollow-cone nozzle operated at 275 kPa in an airstream with a velocity of $44.7 \mu\text{m sec}^{-1}$ varied from $450 \mu\text{m}$ when the spray sheet was directed horizontally backward to $235 \mu\text{m}$ when directed horizontally forward. Similar effects have since been reported by Parkin *et al.* (1980) using 8005 flat fan nozzles. These authors also showed that higher air speed decreased mean droplet size, probably as a result of large droplets shattering in the airstream.

A number of other pressure nozzles are also used on aircraft, for example, solid jet, low-pressure flat fan and 'Raindrop' nozzles (Boving and Winterfield, 1980).

Rotary nozzles The most commonly used rotary nozzles on aircraft are the various forms of cages. Droplet spectra from these nozzles depend on the orientation of the blades and hence rotational speed, flow rate and formulation, and may be more heterogeneous than hydraulic-pressure nozzles at chosen flow rates (Spillman, 1982). Another form of rotary nozzle, the 'Rotanet', using a metal foam dispenser, has been described by Parkin (1980). This unit

produced a more homogeneous droplet spectra than a 'Micronaire' rotary cage (Parkin, 1980) but is also reported to be inferior to hydraulic-pressure nozzles (Spillman, 1982). A new disc windmill rotary nozzle has recently been described (Spillman, 1982). This nozzle provides a radially outward airflow at the periphery of the disc thus markedly increasing the flow rate while maintaining ligament-mode droplet production. The droplet spectra from this nozzle are reported to be more homogeneous than for any other rotary or pressure nozzle (Spillman, 1982). Commercialisation of these nozzles will enable efficient, lower application volumes to be used for herbicides, with a concomitant decrease in ecological hazard.

DROPLET DISTRIBUTION

Ground sprayers

Spray patterns from individual nozzles must be such that when nozzles are mounted in a boom, even distribution over the target is obtained. Nystrom (1981) and Combellack, Richardson and Andrew (1982) found large variation in the distribution patterns of new nozzles. However, injection-moulded plastic nozzles, and the use of advanced technology in the manufacture of nozzles have improved their spray-distribution characteristics (Combellack and Andrew, unpublished data). Recent work shows that herbicide formulation (e.g. 2,4-D) affects spray distribution and that the effect varies between sizes of flat fan nozzles (Dempsey *et al.*, 1985).

Sprayer accuracy is greatly influenced by the static and dynamic relationship between the boom and the ground. For instance, at the recommended boom height of 45 cm the pattern produced by cone nozzles was less variable than when positioned 15 cm above or below that height. The fan nozzles tested at the same heights gave a relatively even distribution at the recommended height and 15 cm above it, but when lowered to 31 cm the variability of the distribution increased (Rice, 1970).

On both theoretical and experimental grounds decreasing boom height below the optimum increases variation in deposition more than movement above the optimum (Mahalinga Iyer and Wills, 1978). This has been confirmed by data from a range of flat fan nozzles (Combellack and Richardson, 1985), which demonstrated that the coefficient of variation (CV) increased by 104% when height was reduced by 10 cm, while it only increased by 50% when height was increased by 10 cm above the optimum (50 cm).

Dynamic performance of booms was investigated by Rice (1970) by passing a sprayer's wheels over a wedge 38 cm long and 5 cm high. The resultant application rate varied from 55% to 155% from the mean. In addition, as the amplitude of movement of the horizontal boom increased the variation in distribution also increased. Boom movement was significantly greater for mounted and self-propelled sprayers than for trailed sprayers. Nation (1980) pointed out that vertical velocity of the boom can be particularly important when horizontal rotary-disc nozzles are used, as droplets from these have low emission velocities.

Droplet distribution is affected by nozzle wear. Faber, Goffre and Musillami (1979) compared the effect on spray distribution of worn and new 110° fan nozzles at varying pressures and boom heights. They showed that the CV of worn nozzles was consistently higher than that of new ones. Similarly, Combellack (1984) found that CV increased from 8.2% for new brass nozzles to 31.1% when wear had increased the flow rate by 65.4%.

Variability in droplet distribution does not appear to be sensitive to pressure over the range 100-300 kPa if the nozzle is operated at optimal height (Faber *et al.*, 1979). However, Combellack (1984) and Combellack and Richardson (1985) have found that the CV increases when pressure falls to 100 kPa.

In field studies on ground deposition, Maybank *et al.* (1974) reported that deposits of 2,4-D varied from 10 to 60 mg m⁻² both along and across the boom swath. To obtain an effective deposit of 10 mg m⁻² over 95% of the sprayed area, they had calculated that a dose of 25 mg m⁻² was needed. Grover *et al.* (1978) also reported large variations across (range 40.4-97.6 mg m⁻²) and along (range 35.0-50.0 mg m⁻²) the swath. Sampling with mylar strips gave lower CVs (17.7-24.0%) than sampling with petri dishes (30.1-38.1%), possibly because there were more sampling points for mylar and/or more efficient droplet capture. This illustrates the problem of measuring variation with artificial targets.

Taylor and Merritt (1974) measured the variation in spray distribution from low-volume (4 and 8 L ha⁻¹) rotary-disc and hydraulic nozzles using fluorescent tracers captured in petri dishes. They found that trans-swath variation was more than along the swath. These tests were conducted in a building to reduce the effects of cross-winds, and the overall CV of 16.7% obtained for the pressure nozzle was thought to be the optimum for this type of nozzle. The CV for the rotary-disc was 23.7% for the 8 L ha⁻¹ volume rate. Similar data were obtained by Maybank *et al.* (1980) for rotary-disc nozzles (CV range 12-35%), but uniformity of swath deposit varied from one trial to another in an apparently unpredictable pattern. In field trials in Australia, the CV in the swath has varied from 22% to 27% (R.G. Richardson, unpublished data) when a fluorometric technique was used to measure the amount of spray solution collected per unit leaf area of the crop. These results demonstrate the variation in capture by real targets rather than an artificial collecting system.

Aircraft

Distribution of spray on the target when applied by aircraft is influenced by a range of parameters similar to those pertaining to spray applied by a ground boom. However, the dimensions of the former parameters vary greatly from those for ground application. Trayford and Welch (1977) have simulated many factors affecting distribution and have shown that airflow around the aircraft (in particular wing-tip vortexes and propellor wash) has a major effect on deposition and influences the optimum location of spray nozzles. Flying height, cross-wind and wing configuration have also been discussed.

Effective width of the aircraft is considerably larger than the boom dimension because of dispersion of the spray cloud before it reaches the ground. Procedures for measuring deposit from aircraft and determining the optimum and the most economic flight-lane separation, or swath width, has been described by Parkin and Wyatt (1982). Obviously, lane separation will have to be determined for each type of aircraft, boom and nozzle configuration, flying height and cross-wind. It will also depend on the acceptable level of variability in deposit, which, in turn, will depend on the crop, weed and herbicide combination being considered.

Parkin *et al.* (1985) examined the effect of volume of application on deposition and distribution of chemical within the plant canopy. They concluded that, when spraying cereal crops at 20 L ha⁻¹ (low volume - LV), or 1 L ha⁻¹ (ultra-low volume - ULV), large volumes of spray are deposited below the crop with LV applications, and the proportion of spray airborne at the

field's edge is greater with ULV spraying. They did not consider the biological efficiency of the deposits on the target at the different droplet sizes used.

Movement of droplets to the target

Each droplet within the spray cloud is subjected to external and internal forces that govern its trajectory, velocity and size when it reaches the target. The complexity of the dynamics of spray droplets has led to the development of mathematical models (Seymour and Byrd, 1964; Goering *et al.*, 1972; Williamson and Threadgill, 1974). The lifetime of droplets is used to predict movement and is essentially governed by the rate of evaporation and vaporisation. There is no satisfactory model to cover all the parameters affecting droplet movement although Williamson and Threadgill (1974) give a good approximation for ground sprayers.

Similar situations exist for aerial spraying. Trayford and Welch (1977) and Taylor and Trayford (1975) developed modelling procedures that consider the effect of aircraft parameters (nozzle placement, flying height, etc.) and environmental conditions (cross-winds) on droplet movement. Parkin *et al.* (1985) evaluated the effect of using ULV and LV sprays on deposition and found that the total volume captured was higher with LV spraying than ULV spraying. This echoes work conducted 25 years earlier by Britten and Rose (1959) who found, at constant-volume rates, that as the drop size of the spray recovered was reduced, then the volume of spray recovered was also reduced.

Impact and retention

Dynamic catch (the number of droplets collected by the target expressed as a fraction of the amount that would have passed the same area had the target not been present) is influenced by the velocity and mass of the droplet and the size and shape of the target.

Studies to elucidate the processes involved at the moment of impaction show that the amount of spray retained depends on the physical properties of the droplet and the target. The most important parameters are:

- * droplet size (Hartley and Brunskill, 1958; Johnstone, 1973; Lake, 1977; Hartley and Graham-Bryce, 1980);
- * the physico-chemical nature of the droplet surface, which is particularly affected by surface tension (Hartley and Brunskill, 1958; Ford *et al.*, 1965; Tadros, 1978; Seaman, 1979; Hartley and Graham-Bryce, 1980), and viscosity (Furmidge, 1968);
- * the kinetic energy and trajectory of the droplet at the moment of impaction (Ford *et al.*, 1965; Ford and Furmidge, 1967; Lake, 1977; Hartley and Graham-Bryce, 1980); and
- * the structure of the target's surface (Blackman *et al.*, 1958; Ford *et al.*, 1965; Seaman, 1979).

The reader is referred to the authors indicated for details of processes involved in droplet capture.

Effect of volume of application

When herbicides are applied in high volume ($> 500 \text{ L ha}^{-1}$), droplets coalesce and the consequent runoff causes loss of herbicide (Johnstone, 1973). Many authors have examined the effect of volume of application on efficacy of herbicides and their results are summarised in Table 10.1.

Table 10.1 Effect of volume of application on efficacy of herbicide

Herbicide	Volume range L ha^{-1}	Weed response	Source
MCPA	90–95 to 425–760	No effect	Hellquist (1958)
2, 4-D	119 to 660	Lower rate is more effective	Vega and Obien (1963)
2, 4-D	5–20 (CDA equipment) to	No effect	Lake and Taylor (1974)
Barban	165–200 (hydraulic		Taylor and Merritt (1974)
Difenzoquat	sprayer)		Merritt and Taylor (1977)
Chlorfenpropmethyl			
2, 3, 6-TBA			
loxylnil/bromoxynil	5–20 (CDA equipment) to	High volume is more effective	
	165–200 (hydraulic		
	sprayer)		
Dicamba	10 (CDA)	Worse than, same as, conventional	Ayres (1976)
	20 (CDA)		
	220 (hydraulic)		
Glyphosate	30 to 100	Low volume is more effective	Campbell, Fellowes, Shears (1984)

Other reports have indicated slightly less control with low-volume CDA boom-spray applications with $250 \mu\text{m}$ droplets at 20 L ha^{-1} (Bailey and Smartt, 1976; Wilson, 1976; Bailey *et al.*, 1978). Extensive field tests comparing a vertically mounted rotary disc (Giroget) with hydraulic nozzles showed that the two application methods gave comparable control of weeds, insects, fungi, and were effective with growth regulators (Morel, 1985).

Translocated herbicides, such as the phenoxyacetates and benzoates, are generally not volume dependent. However, where crop tolerance is marginal, higher volumes are needed. Conditions for optimum retention on a target are complex and difficult to define and, with little information available on this aspect of the spraying operation, appropriate decisions are difficult to make.

Resultant effectiveness of the deposit

Once droplets have been retained on the plant, the effectiveness of the herbicide is influenced by its persistence, droplet size, spacing, location on the plant (placement) and absorption.

Persistence The persistence of the herbicide on the target and its availability to the plant can be influenced by factors such as rain, dew, wind, breakdown by hydrolysis, degradation by visible and ultraviolet radiation, and bacterial degradation (Marrs and Seaman, 1978). Bayer and Lumb (1973) have considered herbicide availability, particularly in relation to transport through the plant's cuticle, while Davis *et al.* (1976) suggested that extraneous material on leaf surfaces may also influence herbicide availability.

Droplet size and spacing The distribution of herbicide on the target can influence the level of control obtained. In particular, droplet size, spacing, concentration and location on the plant are important. Droplet size was first examined by Smith (1946) who reported that large droplets (560 μm) of aqueous 2,4-D were more effective on kidney beans than small droplets (30–70 μm). Unfortunately, the technique used would have been detrimental to the deposition of small droplets.

Later, Behrens (1957) concluded that droplet spacing was most important and that except for some minor effects, droplet size, spray volume and herbicide concentration had no direct influence on plant response. He suggested that, where water was the spray diluent, eleven droplets per square centimetre approached the optimum. In contrast, no response to droplet size was obtained in a similar study by McKinlay *et al.* (1972) on cotton (*Gossypium hirsutum*) but on sunflower (*Helianthus annuus*), 100 μm droplets of 2,4-D amine were 3.1 times more potent than 200 μm and 6.3 times more so than 400 μm droplets. They concluded that an increase in dosage is equally effective whether it is achieved either by increasing spray concentration or by increasing the number of droplets per unit area or both.

Evidence of physiological isolation of large droplets of concentrated herbicide has been obtained by Way (1969) and Richardson (1983). They showed that large droplets and high concentrations of MCPA and 2,4-D respectively caused severe localised necrosis resulting in poorer control. Thus, small droplets (100–200 μm) spaced relatively closely (10–30 cm^{-2}), using moderate herbicide concentrations, are necessary for optimum results with the phenoxyacetic herbicides. Further work is needed on woody plants and, in particular, with droplets less than 100 μm in diameter.

At a very low volume rate (5.5 L ha^{-1}), McKinlay *et al.* (1974) found that smaller droplets (100 μm) of paraquat on sunflower produced more damage than larger droplets (350 μm), but at a higher volume rate (22 L ha^{-1}); droplet size did not appear to be important. Similarly with paraquat, droplet sizes in the range 128–300 μm did not affect its activity on cotton (Buehring *et al.*, 1969). On *Portulaca oleracea* (pigweed) decreasing the droplet size from 600 to 300 μm and increasing the volume from 47 to 281 L ha^{-1} increased control at both 0.28 and 0.67 kg ha^{-1} (Buehring *et al.*, 1973). Thus the parameters for optimum spray application with paraquat vary from species to species.

Effectiveness varies not only with the herbicide used, but also the weed species sprayed, so if a range of herbicides is to be used against a range of weeds in differing situations with one sprayer, a nozzle that produces a range of droplet sizes, possibly from 100–300 μm is needed. Further information is essential so that the droplet spectra can be optimised for a wider range of herbicide/weed situations. This is especially the case if a narrow droplet-size range is to be used, as with CDA. It is also necessary to know whether there are any relationships between the age of the plant and droplet distribution and whether the upper and lower leaf surfaces provide similar results for herbicide-droplet distribution. The latter aspect, and the significance of droplets less than 100 μm , must be understood if predictions of the value of electrostatic spraying techniques are to be made.

Placement The placement or location of the herbicide on the target is of considerable importance. Blackman *et al.* (1958) concluded that phenoxyacetic herbicide retained by young cotyledons contributes less to the growth inhibition of linseed (*Linum usitatissimum*) than an equivalent deposit on true leaves.

In *Avena fatua* (wild oats), barban was more effective when applied to the base of the first leaf than in other areas (Holly, 1960). Similar results have been reported by Neidermyer and Nalewaja

(1974) for plants with one to two leaves, and Coupland *et al.* (1978) for plants with one to four leaves, while Moser *et al.* (1976) using plants with one to two leaves showed that the same amount of Avenge, Mataven, benzoilprop ethyl and Hoegrass placed either on the growing point or on the base of the plant provided the greatest reduction in dry weight. Coupland *et al.* (1978) also found that glyphosate was more effective on the lamina base than on the leaf tips on *Agropyron repens* (couch grass). As spray placement affects biological efficacy, experiments are needed to find which equipment produces the most effective deposit. Further information is also needed on the relationship between physiological age, plant morphology and surface structure and herbicide efficacy.

Spray drift

Loss of herbicide from a treated area can result from movement of droplets during the spraying operation or of vapour after the spraying operation. Loss from aircraft is generally greater than loss from ground equipment because of higher release height and turbulence from the aircraft wake.

Spillman (1982) suggests that to minimise drift from aircraft, nozzles that produce a narrow spectrum of droplets with a volume median diameter of $225\text{ }\mu\text{m}$ could be fitted. He found that one of the best nozzles was a hydraulic flat fan (8005) set at 45° down and backwards. He also suggested that spraying should be done when the atmosphere is turbulent. In high-wind conditions the aircraft should not fly lower than one-fifth its span (approximately 2 m) in order to minimise movement of the spray cloud into the wing-tip vortices.

Atmospheric conditions The problem of spray drifting from aircraft spraying operations has been recognised for at least 40 years. Brooks (1947) reported off-target damage caused by calcium arsenate and commented that the aircraft mainly flew in early morning, obviously during temperature inversions, which would account for the damage off-target. Hartley (1959) also mentioned spraying in inversion conditions and points out that inversions can lead to movement of high concentrations of pesticide. Measurements of drift under inversion and lapse conditions were made by Akesson *et al.* (1964) who clearly showed that most drift occurred when inversion conditions existed. This is also supported in data collected by Yates *et al.* (1974) who used a stability ratio to describe atmospheric conditions, and showed that drift was lowest when the atmosphere was unstable. Spillman (1982) has described in detail the effect of turbulence on droplet movement from aircraft and has concluded that $225\text{ }\mu\text{m}$ droplets are required for optimum performance.

Losses Losses of herbicide were measured by Grover *et al.* (1972) in field trials that clearly showed that 3 to 4% of the applied butyl ester of 2,4-D was lost as droplet drift and 25 to 30% as vapour drift. When the low volatile diethylamine salt of 2,4-D was sprayed no vapour drift could be measured. Maybank *et al.* (1978) demonstrated that 30 to 60% of the initial 2,4-D butyl ester application can drift as a vapour in the two hours following application, while the corresponding figure for 2,4-D octyl ester is 10 to 15%. Droplet drift was between 1 and 8% of the initial application for ground rigs and 20-35% for aircraft spraying. Loss of herbicides from ground sprayers has been considered in detail by Combella (1981) and was mainly governed by droplet size, height of release and climatic conditions.

Drift control Drift of herbicides from aircraft can be controlled to some extent by adjuvants. A variety of materials have been tested, with varying degrees of success. Gratowski and Stewart (1976) found that the additives Accutrol, Foamspray and Lodrift reduced drift but also reduced herbicide effectiveness. Similar results were obtained with hydroxyethyl cellulose materials and

Nalco-Trol where low-shear nozzle and low airshear positions (D6 back) were used (Yates *et al.*, 1975). The more complex issues of drift control have been discussed by Yates *et al.* (1974) and include atmospheric stability and micro-meteorological conditions, atomisation and droplet spectrum and oil content of the spray.

SPRAYING EFFICIENCY

EFFICIENCY OF BOOM SPRAYERS

Boom sprayers are generally very inefficient although acceptable results are regularly produced in the field. When stationary, an efficient boom sprayer should give uniform distribution across the swath. This can readily be tested in the field using an improvised patternator. The boom must be at the correct height and be operated at the pressure recommended by the nozzle manufacturer. Tests on growers' booms (with single-orifice fan nozzles) using a field patternator have shown that variation in spray collected can be as great as +132 to -96% of the mean, while the majority range between 40-60% (Combella, 1984). If the sprayer is providing a satisfactory level of control, the pesticide dose rate must be high enough to allow for these variations in accuracy.

Improving efficiency

Nozzle performance Careful selection and frequent testing of nozzles are necessary. For example, when the coefficient of variation for distribution across the swath was reduced to less than 12% on farmers' boom sprayers when stationary, a reduction in herbicide dose rate of 12.5% was possible in limited tests without loss of weed control (Combella and Richardson, 1985).

While uniformity of distribution is not commonly determined, flow rate is often measured. This practice is to be encouraged, although variation in flow rate between nozzles at the time of the test can be misleading if the nozzles are uniformly worn. Such nozzles may give within 5% of the average flow rate for the nozzles tested, yet have very poor distribution characteristics. Nozzles should be discarded when flow rate exceeds the rate when new by 10%.

Another nozzle performance characteristic that must be considered is the droplet spectrum produced under the prevailing operating conditions. While it is particularly important to know the volume of small droplets (i.e. those less than 100 μm) that are likely to drift, this information is not readily available.

Nozzle selection Nozzles selected for a boom sprayer must produce an even distribution, have the desired droplet spectra and flow rate, minimise the effects of boom instability, and possess good wear characteristics. A nozzle that gives as low a volume of small droplets as possible should be selected for spraying in areas near to susceptible crops in order to minimise the risk from spray drift. In general, the proportion of small droplets increases as the spray angle increases (Figure 10.1) for any given orifice size, as the pressure increases (Figure 10.3), and as the orifice size decreases (Figure 10.2). On aircraft, nozzles should be selected on the basis of durability and arranged in such a way as to give uniform distribution and provide as low a drift hazard as possible.

Nozzles should be selected to give the lowest volume rate that will consistently give adequate weed control with minimum environmental hazard. This can be as low as 30-50 L ha⁻¹ when applying glyphosate for minimum tillage practices. To minimise vertical-boom instability, 110° nozzles are preferred as they allow greater boom movement before distribution is affected.

Nozzle wear Durability of the nozzle should also be considered as rates of wear are high when wettable powders are used. For example, after 40 hours operation using a wettable powder, flow rates through brass nozzles had increased dramatically (Table 10.2). However, when emulsifiable concentrates and suspension concentrates were used, flow-rate changes were much smaller. These tests do not take into account variation in water quality, which also affects wear rate. Tests in Australia have generally shown the injected-moulded acetal-plastic nozzles to be the best if cost, droplet spectra, distribution and flow-rate characteristics are all considered when emulsifiable concentrates and suspension concentrates are to be used. When wettable powders are used, hardened stainless steel and certain sintered-alumina nozzles are recommended.

Table 10.2 Percentage increase in flow rate of single-orifice flat fan nozzles at 300 kPa after 40 hours (Combella, 1984)

Nozzle	Nozzle material	Spray material		
		Wettable ^a powder	Suspension ^b concentrate	Emulsifiable ^c concentrate
Albuz Brown	Sintered alumina	0.8	2.7	-3.2
Delevan LF15	Nylon	14.7	0.7	-0.9
Hardi 4110-10	Acetal plastic	11.4	0.5	-1.5
Lurmark F110-01	Acetal plastic	10.5	5.0	1.9
Spraying Systems 110-01	Brass	65.4	5.5	4.5
Spraying Systems 110-01	Hardened stainless steel	2.5	1.9	0.6
Spraying Systems 110-01	Stainless steel	16.0	1.9	1.9
LSD (<i>P</i> = 0.05)		3.0	N.S.	3.0

^aWettable powder—'Gesaprim 80' 4.5 kg in 50 L.

^bSuspension concentrate—'Gesaprim 50' 7.2 L in 50 L.

^cEmulsifiable concentrate—'Ulvapron' 2 L in 50 L.

Boom design To minimise the effect of boom instability on distribution, the boom must be stable in both the vertical and horizontal planes. The Gimbal and Universal Mount linkage designs developed by the National Institute of Agricultural Engineering in the United Kingdom not only reduce horizontal boom movement, but also keep the boom parallel to the ground. In contrast, the commonly used self-levelling systems merely ensure that the boom remains horizontal so the system must be locked when traversing slopes or it will accentuate uneven boom height. The use of springs and dampers on booms has improved their stability.

Careful design is essential for booms supported by wheels toward their ends. In particular, the load on the wheels should be very low if the structure is light, or the structure should be strong enough to withstand the stresses encountered when the wheel traverses uneven ground.

Spray output The aim of all sprayer manufacturers should be to make the spraying operation as simple and as foolproof as possible. This is best achieved by relating output to ground speed, i.e. metered spraying. There are various methods of achieving this aim, although each has its limitations. The common fault with all systems is the time lapse between the change in ground speed and the change in output.

The most commonly used systems, which employ a positive-displacement pump either driven by a ground wheel or directly connected to the tractor's power take-off, reduce the error to a minimum. As flow rate through a nozzle is related to pressure by a square root function, a doubling in flow rate (i.e. doubling ground speed) is accompanied by a four-fold increase in pressure. Unfortunately, as the pressure increases so the small droplet component and thus drift increase. To help contain drift these systems should have a pressure gauge fitted so that they may be operated between 200-350 kPa (Wills and Combellack, 1984).

Attempts have been made to overcome the pressure-increase problem by injecting the herbicide into the diluent, which is maintained at constant pressure in the spray line. While such systems have considerable merit, their major drawback is the time taken for the new dose to reach the nozzles. Development of these units using injection points close to the nozzles is warranted.

FUTURE DEVELOPMENTS

Further improvements in boom design will occur. On current ground sprayers, stability in both vertical and horizontal planes needs to be improved. Spray output will be related to ground speed on more sprayers.

Variations in droplet trajectory, such as the spray sheet being projected horizontally (i.e. parallel to the ground), have been assessed at the Keith Turnbull Research Institute (Richardson, 1986) because they offer the chance to increase retention especially on grass weeds and also overcome some of the effects of boom instability. Theoretically, when hydraulic nozzles are pointed vertically at the target, droplet capture on vertical weeds is disadvantaged compared with that on flat weeds. Results are encouraging, but further tests are necessary (Combellack and Richardson, 1985). The use of aerofoils to increase droplet capture through turbulence also needs serious consideration as increases in capture of 20-110% have been measured in turbulent air streams (R.G. Richardson, unpublished data).

A narrow droplet-size spectrum is required if precise spray application is to be achieved. Theoretically, delivery of such a spectrum could achieve minimum loss due to droplet drift and give the most effective target coverage. Production of this type of spectrum has been a common goal of a number of research workers. For aircraft, Yates (1981) reported tests with piezoelectric micro-jet spray nozzles also known as laminar airfoil nozzles. These were developed from a pulsed-jet system (Schneider and Hendricks, 1964) that generated a single stream of uniform droplets into a multiple-stream nozzle by Yates and Akesson (1978). Tests with these nozzles (Yates, 1981) showed that a narrow droplet spectrum is produced and suggested that this resulted from jet break-up and in-flight coalescence of satellite droplets. Virtually all droplets less than 200 μm are eliminated and hence drift is well controlled. Further development and subsequent commercialisation of these units should be encouraged. Another nozzle under consideration for use on aircraft is the variable geometry venturi or bifoil nozzle (Parkin and Newman, 1977). This device has been developed to enable ultra low volumes, down to 0.36 L ha^{-1} , to be applied as a coarse aerosol spray. They were designed to operate over an air-speed range of 210-230 km hr^{-1} which is unsuitable for most rotary nozzles as they sometimes develop dangerous vibrational modes at these speeds. Development of these nozzles will assume greater significance if the speed of commonly used aircraft increases. Further developments of piezoelectric nozzles have been described by Stent *et al.* (1981) who have incorporated an induction charging system to prevent coalescence of droplets in flight. Although these authors have been investigating the use of these nozzles on ground sprayers, a number of practical

drawbacks have been identified such as the small orifices, which lead to filtration problems, and the high cost of each unit.

Electrostatic charging of sprays applied by either ground or aircraft offers theoretical advantages, especially enhancement of deposition of the spray and reduction of droplet drift. Development of an effective unit for aircraft began with a rotary nozzle (Carlton and Isler, 1966). Two significant findings resulted from this work: (1) the rotary nozzle is suitable for experimental work and is capable of producing a charged water-based spray from aircraft; and (2) a charge of an opposite polarity on the airframe was induced by the spray-charging process. Carlton (1968) then showed that this latter effect rendered the spray-charging devices ineffective and concluded that spray charging by a gaseous ion-emission technique may be the most promising when compared with the dual power supply and polarity-reversal techniques. However, later studies (Carlton and Bouse, 1977) showed that corona discharging took place at low levels of spray-charging voltage and was first noticed at the wing tips. The authors considered that this latter effect was a disadvantage as it enhanced the possibility of the mobile negative air ions combining with the positively charged spray material. They suggested that the discharge point must be separated as far as possible from the charged spray plume and in later work demonstrated the value of this technique (Carlton and Bouse, 1978). Deposition of charged spray can exceed its uncharged counterpart by 800% and reduce spray drift (Carlton and Bouse, 1980).

Development of systems suitable for ground-operated sprayers followed a rekindling of interest in the early 1970s. Since that time a corona-discharge system based on a rotary nozzle has been developed (Arnold and Pye, 1980), which charges conventional water-based sprays using a 30-50 kV charge. An induction-charged rotary-disc nozzle system has also been developed (Marchant, 1985). In this system the charging electrode rotates with the disc and the operating voltage is significantly lower at 1.5 kV. Two systems of induction-charge spray from hydraulic nozzles have been developed. Law (1978) used a twin fluid nozzle in which a conventional water-based spray liquid is passed over an embedded electrode charged to 2-10 kV. This system has been extensively evaluated (Law and Lane, 1981) but has not been commercialised due to problems with power requirement for an adequate air flow. Marchant and Green (1982) developed a system that charges the spray and then attracts the small drift-prone droplets onto electrodes. Commercial evaluation of a modified form of this unit indicated no consistent increase in effectiveness (Pay, 1985; Phillips and Harrington, 1985). However, its usefulness in reducing spray drift was not measured.

In another system a non-conductive liquid is charged at 20-25 kV as it leaves the nozzle (Coffee, 1979). Power requirements are about 100 mW per nozzle. The mutual repulsion between different parts of the liquid overcomes the surface tension so that the liquid first forms ligaments and then breaks up into ostensibly mono-sized droplets. This system known as the 'Electrodyne' has been extensively field tested and results have been particularly encouraging with insecticides (Pascoe, 1985). However, weed control has been variable (Parham, 1982), particularly if spray penetration through a dense canopy is necessary where air assistance is required (Durand *et al.*, 1983). Thus, while charged sprays have improved deposition, and in certain circumstances reduced drift, penetration into the canopy has been reduced. Further evaluation of these systems is warranted as they offer significant advantages over conventional systems.

Spray canopies and/or air deflectors offer a means of reducing drift and increasing spray deposition on plants. One of the early attempts to utilise the airstream and thus turbulence, was reported by Courshee (1959) who found that drift was generally reduced. Since that time most

of the work has centred on reducing drift using some form of deflector (Smith *et al.*, 1982) or canopy (Rogers and Ford, 1984). Work in Australia is attempting to manipulate the airstream to increase droplet capture. This follows observations made by Combellack and Richardson (1985) who noted that spray capture was increased in the wake of a spray vehicle probably as a result of turbulence. Tests showed that droplet capture is often improved if the spray sheet is projected horizontally. If this technique proves practical it will obviate the need for improving vertical boom stability as well as increasing deposition and reducing drift. Finally, initial tests have shown that as speed increases from 4 to 20 km hr⁻¹ droplet capture is improved (Richardson and Combellack, 1985, unpublished). Further consideration of the effect of sprayer speed, droplet sizes and trajectory on the collection efficiency of sprays is required.

Spray output needs to be more efficiently related to ground speed. The development of a chemical injection sprayer is considered the most appropriate system. One major problem with such a unit has been the time lag between speed change and dose-rate change at the nozzle (Vidrine *et al.*, 1975). However, more recent work suggests that this problem is solvable (Reichard and Ladd, 1983). Another problem is the change in pesticide viscosity with a change in temperature, which results in changes to pump output and hence dose rate (Gebhard *et al.*, 1984). When such a system has been developed it is suggested that multi-tank versions should be used to selectively apply herbicide mixtures.

Chemical savings of 70-80% are possible if an appropriate herbicide is applied only to a weed that occurs in patches, e.g. *Raphanus raphanistrum* (wild radish), *Avena fatua* (wild oats), rather than spraying a mixture over the entire area. Attempts to develop a sprayer that is able to spray weed patches by differentiating between weeds and bare ground have been unsuccessful to date. It may be necessary, therefore, to map the weeds using a physical mapping technique. Because of the potential savings offered by this system, further development is considered important.

Developments of controlled-droplet application techniques will continue. However, results so far have been slightly less reliable than for hydraulic nozzles. This reflects either too low a drop density or poor canopy penetration. Therefore, further development of the vertically mounted spinning disc ('Girojet') is warranted as this unit has provided equally as reliable control as hydraulic nozzles (Morel, 1985).

Volumes of application will decline to less than 50 L ha⁻¹; in some situations down to 20-30 L ha⁻¹. Greater emphasis will be placed on all aspects of operator safety. Reduced boom heights will be made possible due to droplet trajectory changes. Faster working rates will be possible due to the use of lower volumes and improved boom suspension systems, thus permitting more timely application of sprays.

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