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The Biology of Application

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A BIOLOGICAL APPRAISAL OF FUNGICIDE APPLICATION IN THE TROPICS

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ABSTRACT

Fungicidal spray efficiency is improved by understanding the crop target over which the active ingredient must spread or pass into. The accelerative effects of climate on crop growth, fungal activity and deposit loss makes the tropical crop target more difficult to define. Biological data helps to establish the timing and placement of protectant spray and plot the fate of deposits as they are modified by weathering and growth. Spray scheduling must be compatible with the rate of appearance of new susceptible foliage and take into account the dilution of deposits by leaf expansion. The size and shape of target will largely determine the type of sprayer which can be usefully employed, while the density of foliage and its effect on microclimate may benefit from the use of air-assisted sprayers which open up the canopy and deposit more spray on the abaxial leaf surface. Marked changes in leaf display or surface character which affect retention and deposition may be used to improve spray timing and placement, particularly if they coincide with distinct changes in susceptibility. The effect of canopy shape and structure and individual leaf display on the path of redistributed fungicide are important because spores and chemical are often redistributed together. The rapid entry of systemics is facilitated by synchronising application with the presence of actively-growing foliage, and losses are further minimised if fungicide which runs-off into the soil can be absorbed through the roots.

INTRODUCTION

Advances made in chemical potency, formulation chemistry and spray machine technology have not led to broadly-based increases in crop protection efficiency (Hislop, 1983). Spray applied to crops by traditional methods and according to established recommendations usually achieves the desired level of control, but failure to deposit a higher proportion of pesticide on target leads to inefficient control (Graham Bryce, 1977). The projection of pesticide onto crops continues to be well researched and mode of action has been elucidated for most active ingredients, but there continues to be a lack of information on how crop biology affects the deposition and fate of pesticide (Fulton, 1965). The ultimate target for fungicide is the protoplasm of the pathogen, but for practical purposes the only tangible target is the crop surface over which a protectant fungicide must spread or pass through in the case of a systemic material. In the tropics, the accelerative effects of climate on crop growth, fungal activity and deposit loss combine to increase the need for target information. The following paper combines a limited review with a practical appraisal of the crop target component of foliar spraying which is illustrated with the author's own findings and observations in the tropics.

REVIEW AND DISCUSSION

Protectant fungicides

Spray timing

Protectant sprays must be timed to precede spore germination on susceptible plant surfaces. Predictions of potential disease severity based on pathogen population, weather, host susceptibility or a combination of the three have been formalised into forecasting systems(Fry and Fohner, 1983), which are most appropriate for diseases which occur sporadically (Bourke, 1970). Tropical crop diseases are usually endemic and active unless a predictable, pronounced dry season occurs and, therefore, variations in crop susceptibility would appear to be useful parameters upon which to base spray schedules.

Tropical evergreen crops such as citrus produce new foliage as a series of seasonally-induced flushes which are susceptible to infection by a complex of pathogens (Mabbett, 1982). This growth pattern has been utilised by synchronising a minimal number of sprays, with the appearance of susceptible flushes and young fruit in the post-blossoming period, to control greasy spot (Mycosphaerella citri), melanose (Diaporthe citri) and sour orange scab (Elsinoe fawcetti) (Whiteside, 1976; Mabbett and Phelps, 1983a). For this strategy to succeed deposits must withstand tropical weathering to remain at active levels until the flush hardens and matures. The retrieval of copper at fungitoxic levels five months after application of cupric hydroxide in water-based LV sprays to grapefruit trees in Trinidad (Table 1), and the recovery of copper residues from coffee foliage in Kenya seven months after spraying (Morgan, 1970) shows that the desired levels of tenacity are easily achieved.

TABLE 1

Longevity of copper deposits from LV sprays of cupric hydroxide on grapefruit trees

Spray Method	Initial Deposit	Weathered Deposit	% Loss
LV mistblower 0.3 kg Cu^{++}/ha	2.15[a]	0.69[a]	68[b]
LV mistblower 1.0 kg Cu^{++}/ha	6.46[a]	2.70[a]	59[c]

[a] µg Cu^{++}/cm^2 of leaf surface

[b] After 4 months of complete weathering including 17 inches of rain

[c] After 5 months of complete weathering including 3.9 inches of rain

Failure to adopt this strategy in the control of leaf anthraonose of lime disrupts the normal flushing sequence because Gloeosporium limetticola also causes an acute condition called 'withertip' in which a rapidly spreading blight destroys new shoots. This causes the dormant buds to break and produce foliage intermittantly throughout the year and thus destroys the facility for synchronised spraying (Wheeler, 1969).

Only certain parts of a tree-crop canopy may be vulnerable to infection because they are within reach of inoculum splashed up from the soil. Provided that they are distinct enough to be treated in isolation, economies can be made by spot application with hand-held or knapsack sprayers. The exposed position of low-hanging cocoa pods permits protection against black pod (Phytophthora palmivora) with a high volume knapsack sprayer, and, if necessary, the open canopy of the cocoa tree allows the spot application of higher pods by using the same sprayer fitted with an extended lance. Similarly, full low-hanging oranges can be protected against infection by Phytophthora spp., which cause brown rot, by spraying to run-off with a hand sprayer, although neither type of machine could be usefully employed for the general protection of these tree crops.

Row-crop vegetables are usually sprayed at 7 to 14 day intervals with scant regard for the growth patterns and coverage needs of specific crops. Seven-day intervals can cope with the tomato disease early blight (Alternaria solani) because it does not attack the young leaves which are produced at a steady rate throughout the life of the crop (Mabbett and Phelps, 1984c), but not with angular leaf spot of cucumber (Pseudomonas syringae p.v. lachrymans) which promptly infects the rapidly-produced leaves (Mabbett and Phelps, 1976). With new cucumber leaves produced at a rate of one/vine/day and expanding by a factor of thirty to attain maturity within 10 days, many leaves are either completely unprotected or have their deposits diluted to sub-effective levels during a single spray interval. With four-day intervals each leaf receives spray once during the critical 4- to 6-day period after emergence, when most expansion has occured and before the disease takes off (Tables 2 and 3) (Mabbett and Phelps, 1984b). Cucurbits present an extreme example of deposit dilution through growth, but similar problems have been reported with other crops such as tobacco (Tapscott and Mapother, 1961).

Spray placement

The impractability of ground-based sprayers, except thermal foggers, for the protection of rubber is an obvious example of how crop biology dictates the mode of application, but there are more subtle ways in which this occurs. Hearting crops such as lettuce and cabbage suffer a shadow effect in which the side furthest from the nozzle is not covered, particularly when the angle of application is small, but the small farmer overcomes this problem by spraying the plants individually with a high volume knapsack sprayer. The Alliums (onion, garlic and chive) present difficult targets to protect efficiently because the upright and narrow, pointed leaves give a relatively small leaf area index and are difficult to wet. Electrostatic sprayers producing charged droplets (Coffee, 1979) may provide the answer in this type of crop. Droplet capture by the narrow leaves, which provide the nearest earth point, would improve control of diseases such as downy mildew (Peronospora

TABLE 2

Leaf expansion and incidence of angular leaf spot infection with increasing leaf age in cucumber

Age after unfurling Days	[a]Mean leaf area[c] cm^2	Actual leaf area as a factor of leaf area at day 1	Leaves[b] infected %
1	10.0	1.0	0
2	15.6	1.6	0
3	44.6	4.5	0
4	94.2	9.4	0
5	149.0	14.9	2
6	192.2	19.2	5
7	231.6	23.2	12
8	249.8	25.0	39
9	271.2	27.0	59
10	282.4	28.2	83
11	285.4	28.5	95

[a] Mean of 50 leaves

[b] Per cent (%) of 50 leaves, with symptoms

[c] Upper and lower leaf surface

TABLE 3

The effect of leaf age at spraying on the fate of copper deposits from LV sprays of cupric hydroxide to cucumber

Leaf age at spraying days	Leaf age at sampling[a] days	leaf size cm^2	Residue $\mu g\ Cu^{++}/cm^2$	Expansion factor	Loss factor
1[b]	1	7	5.25	-	-
	6	219	0.04	31.0	131.0
	12	315	0.03	45.0	175.0
5[c]	5	184	1.63	-	-
	10	286	1.11	1.6	1.5
	15	316	0.66	1.7	2.5

[a] Mean of six 10-leaf samples

[b] LV mistblower; Cupric hydroxide in water at 1.0 kg Cu^{++} in 175 l/ha

[c] LV mistblower; Cupric hydroxide in water at 2.0 kg Cu^{++} in 350 l/ha

destructor) and purple blotch (Alternaria porri), particularly at the leaf tips. Spray applications which give poor canopy penetration and insufficient under-leaf cover are usually incompatible with the requirements for disease control in dense-canopied tropical crops. Many infections begin inside the canopy encouraged by microclimatic humidities that are maintained for longer periods at concentrations necessary for spore germination, particularly on the under surface of the leaf. This surface is shielded from the direct rays of the sun, which reduces the likelihood of spore dessication, and offers more opportunities for stomatal entry and less resistance to cuticle cracking. Air-assisted machines such as low volume mistblowers and conventional, fan-assisted ULV sprayers are able to open up the canopy and protect the inner shell of foliage (Mabbett and Phelps, 1983a). The air-stream flips the leaves of the outer shell and allows the spray to move into the canopy (Courshee, 1967), which is so important for the protection of mature orange and grapefruit trees which otherwise present an almost inpenetrable mass of leaves, fruit and branches (Carman, 1975). By turning the leaves to face the spray stream, air-assisted sprayers deposited more fungicide on the lower leaf surface of mature grapefruit trees, but the extent to which this happened appeared to depend on the strength of the air blast and the position of the leaves in relation to the nozzle. Lower leaf surface cover provided by LV mistblower was superior to that achieved by air-assisted ULV sprayer (Table 4), and leaves situated above the nozzle were flipped upwards to expose the lower surface, while those below the nozzle were pushed in a downward direction to present the upper surface to the spray stream. These observations are supported by the work of Vigodsky and Zieslin (1970) who found the best under-leaf cover with mistblowers in rose trees was in the highest part of the plant.

TABLE 4

Differential deposition of copper from cupric hydroxide on upper and lower surfaces of grapefruit leaves following air-assisted LV and ULV sprays

Spray Method[a]	Initial Deposit	
	Upper	Lower
ULV	[b]1.51(47)[c]	1.70(53)
LV	5.29(41)	7.63(59)

[a] Cupric hydroxide ULV 0.20 kg Cu^{++}/17 l/ha and LV 1.0 kg Cu^{++}/100 l/ha, Turbair Tot and knapsack mistblower respectively.

[b] $\mu g\ Cu^{++}/cm^2$ of leaf surface

[c] Per cent deposited on respective surface

The way in which leaves respond to the air stream would certainly appear to be specific for crop and machine since it will depend on the power of the fan, the characteristic of the air blast and position of the nozzle in relation to the height and natural disposition of the leaves, as well as the elastic properties of the petiole. Courshee (1967) has pointed out that leaves may be moved to a position in which a minimal area is presented to the spray stream. Leaves of trees such as cocoa, mango and rubber which are limp and pendant in the new flush, respond more to air movements in this condition than later when they have hardened and assumed a dorsi-ventral orientation. The need for canopy penetration has been established during the assessment of the new range of electrostatic sprayers (Griffiths et al., 1981; Hislop et al., 1983) and since efficient droplet capture seems to be at the expense of canopy penetration, current emphasis is on the development and use of electrostatic sprayers with air assistance (Hislop, 1983).

The effect of leaf surface roughness on retention and deposition has been investigated on many crop species over the last thirty years. Macroroughness caused by leaf hairs and veins (Furmidge, 1962) and microroughness which is controlled by the physico-chemical properties of the cuticular waxes (Holloway, 1969) have been shown to have a marked effect on retention. Types and degree of leaf hairiness play a significant part (Rich, 1954; Wilson and Hedden, 1964) but the usefulness of most investigation has been limited by inter-crop comparison which introduces other surface factors which may affect retention. The effect of different leaf hair densities within a single crop, cucumber, have been compared and are documented in a research paper at this symposium (Mabbett and Phelps, 1985). The ability of densely-haired young leaves to build up large deposits of copper fungicide from a high volume sprayer before incipient run-off was reached would buffer the effects of leaf expansion on deposit dilution, which has been shown to be a major reason for the poor control of angular leaf spot of cucumber with LV and ULV sprays employing low doses of cupric hydroxide (Mabbett and Phelps, 1984b). Of additional benefit was the disposition of young leaves which lay flat against the vine with the abaxial (lower) leaf surface exposed, and the raised nature of the veins on this surface to form spray catchment areas between them. These factors together with increased retentive area provided by the dense matt of hairs combine to ensure the retention of large fungicide deposits on this surface, which is the main point of entry through stomata for the bacteria which cause angular leaf spot (Whitaker and Davis, 1962). Leaf veins tend to be raised on the abaxial leaf surfaces of dicotyledonous crops e.g. blackcurrant (Furmidge, 1962) though not to the same degree as on cucumber. This surface should have the greatest potential for spray retention, but other factors operating in the growing crop will combine to prevent the potential from realization. The angles subtended by the stem and petiole and lamina and petiole in most crops are such that natural leaf display tends to shield the lower surface from incoming spray and accelerate run-off.

Longevity of deposit and redistribution

Residual, protectant fungicide should have a degree of resistance to dispersion or solubilization which prevents wash off and loss to the soil, but not to the extent that it is unavailable to kill spores on the leaf where it was deposited, or on other leaves following redistribution. Tenacity, the ability to withstand weathering, is determined by the physico-chemical properties of the formulation, plant surface and the type and intensity of weathering to which the deposit is exposed (Somers, 1967). The particles of inorganic copper fungicides (Somers, and Thomas, 1956) and zineb (Rich, 1954) adhere to plant surfaces more strongly than they cohere to each other so that thinly-spread deposits with a greater proportion of particles in direct contact with the leaf surface could be expected to show higher tenacities than thicker deposits. In the light of these surface phenomena it is worth considering that the superior tenacity of ULV deposits compared with LV and high volume deposits, which was established fifteen years ago (Fuller Lewis, 1969; Smith and Johnson, 1971) may be controlled by the 'thinness' of deposit spread in addition to sticking properties of oil-based carriers. It would certainly help to explain the unusual results of Whan et al. (1983) who found that ULV deposits were less tenacious than high volume deposits when used at spray rates of 2.0 kg cupric hydroxide/25 l/ha and 0.2 kg/100 l/ha, respectively, and the curvilinear loss of LV deposit on grapefruit leaves compared with the linear loss of smaller and better distributed deposits following ULV application (Mabbett et al., 1983a). The behaviour of copper deposits on field grown tomato supports these contentions since there was no significant benefit to be gained by raising the dose of LV spray beyond 1.29 kg Cu^{++}/ha, because the marginal increases in residue were not proportional to the increases in dosage (Table 5). Such observations reinforce the view that there is little point in applying ever-increasing dosages of fungicide to combat the effects of weathering, because an increasing proportion is lost as the particles build up on each other instead of adhering to the plant surface (Mabbett and Phelps, 1984a; 1984c).

Surface factors which have been shown to affect deposit tenacity are leaf age (waxiness) in banana (Burchfield and Goenaga, 1958), loss of leaf turgidity (Fogg, 1947) and solubilising leaf exudates in apple and broad bean (Arman and Wain, 1958). The effects of hairiness have produced some conflicting results which are probably a reflection of the individual nature of hairiness between different crop plants and other surface factors. Copper deposits were more tenacious on the pubescent leaves of egg plant than the glabrous leaves of sweet pepper (Wilson and Hedden, 1964), but less tenacious on tomato and potato, which are both hairy and on cauliflower and broad bean which are smooth (Somers and Thomas, 1956). Under intense artificial rainfall copper deposits from LV applications were drastically reduced to about 20% of the initial deposit, irrespective of whether the surface was smooth (grapefruit), pubescent (tomato) or coarsely-hairy (cucumber) (Table 6). Greater inter-crop differences in deposit tenacity showed up with ULV application (Table 6) which is consistent with the behaviour expected to be shown between a lipophilic carrier and generally lipophilic plant surfaces with small but important differences in physico-chemical properties.

TABLE 5

Dosage and recovery of copper from cupric hydroxide following LV sprays to tomato

Dosage[a] kg Cu^{++}/ha	Residue[b] µg Cu^{++}/cm^2	Recovery[c] %
0.49	1.21	14.00
0.97	2.56	12.25
1.29	3.31	12.50
1.61	3.49	10.00
1.94	3.83	9.25

[a] LV knapsack mistblower at 350 l/ha

[b] Means of residues taken from six experimental units 3 to 4 days after application for four consecutive weeks

[c] Per cent recovery of Cu^{++}. Mean over four week period

TABLE 6

Loss of copper from deposits of cupric hydroxide on three leaf surface types following LV and ULV applications

Crop/ Surface type	Spray method[a]	µg Cu^{++}/cm^2 of leaf surface after artificial rainfall		
		Nil	1 in[c]	10 in[c]
Tomato/ pubescent	LV ULV	16.66(100) 1.58(100)	4.85(29)[b] 1.01(64)	3.01(18)[b] 0.70(44)
Cucumber/ coarsely hairy	LV ULV	9.02(100) 1.07(100)	3.70(41) 1.01(94)	2.27(25) 0.95(89)
Grapefruit/ smooth	LV ULV	10.49(100) 2.41(100)	5.97(57) 2.28(95)	2.33(22) 1.70(71)

[a] LV mistblower and ULV Turbair Tot applying, respectively, formulations of 2.0% w/v in water and paraffinic oil

[b] Per cent of initial deposit

[c] Intensities of 0.2 inches/min to tomato and cucumber and 1.0 inch/min to grapefruit. Drop diameter 6 mm

Fungicide deposits may be weathered by the action of rain, dew, wind and sun. Rain, which is considered the most important agent of weathering, may remove deposits by dissolving or redispersing the active ingredient or mechanically by the beating action of raindrops (Somers, 1967). Exposure to a particular type and intensity of weathering depends in part on the position of the deposit in the canopy because lower leaf-surface deposits tend to be shielded against the direct action of raindrops while deposits in the lower part of the canopy are subject to the cumulative effect of run off from foliage above. The rapid loss of copper deposit from the upper surface of grapefruit leaves under low rainfall conditions agreed with the findings of Park and Burdekin (1964) on coffee. The contrasting behaviour of deposits under heavier natural rainfall, when losses from both surfaces were comparable, or under intense artificial rainfall which caused greater erosion of lower surface deposit, agrees with the contention of these workers that heavy rain increases the erosion of lower surface deposit (Table 7). An increased amount of rain splashes, drips and rivulets affecting the lower surface during heavy and prolonged rainfall, following canopy saturation, could account for the increased erosion of lower surface deposit. Somers (1967) has suggested that deposit is lost during growth movement but there was no discernible loss of copper deposit from cucumber leaves during a ten day period , when the leaves expanded by a factor of thirty and this held true for deposits from both LV water based sprays and ULV oil based sprays (Mabbett and Phelps, 1984b).

TABLE 7

The effect of weathering type on loss of copper deposits from upper and lower surfaces of grapefruit leaves following LV sprays of cupric hydroxide

Weathering type	Initial Deposit		Weathered deposit	
	Upper surface	Lower surface	Upper surface	Lower surface
Natural; 5 months 3.9 inches rain	5.29[a]	7.63[a]	1.39(74)[b]	4.01(48)[b]
Natural; 4 months 17 inches rain	1.82	2.48	0.51(72)	0.87(65)
Simulated; 20 min. 20 inches; 1 inch/min.	7.26	14.50	3.43(53)	4.17(72)

[a] µg Cu^{++}/cm^2 of leaf surface

[b] Per cent (%) loss

Redistribution of fungicide in solution or suspension is an important vehicle for the transfer of active ingredient to other leaves which are unprotected due to deficiencies in spray distribution or because they represent post-application growth. Extension of the zone of fungicidal influence beyond the deposited particle helps to achieve whole leaf protection (Matthews, 1982), but local redistribution of fungicide over the leaves of crops such as tomato is restricted by their morphology, which in the case of tomato, gives a compound leaf made up of seven essentially separate leaflets (Mabbett and Phelps, 1984c). Morgan (1972) found that redistribution of copper from the upper to lower parts of berries was an important factor in the control of coffee berry disease. The climatic and formulation factors affecting redistribution have been considered and investigated (Hislop, 1967: Courshee, 1967: Hislop and Cox, 1970) but biological factors need to be given equal prominence. The net downward direction of redistributed fungicide means that deficiencies in coverage at the top of the canopy which are a feature of ground application to well developed citrus trees (Carman, 1975), cannot be compensated for by redistribution. In the same way coffee berry disease has been controlled by spraying the tops of trees only and relying on redistribution (Pereira and Mapother, 1972; Pereira, 1970). The bringing together of fungicide and pathogen in rainwater (Evans, 1967) is thought to play an important part in the control of coffee berry disease (Pereira and Mapother, 1972; Waller, 1972) and coffee leaf rust (Rayner, 1962). Leaf lesions of potato late blight occur most frequently at the tips and margins of leaves because the drip patterns after rainfall carry spores to these points and maintain conditions for germination (Lapwood, 1961), but redistribution of fungicide causing the build up of dense deposits at the points may equalize this effect (Goosen and Eue, 1956). Whan et al. (1983) showed that simulated rainfall redistributed cupric hydroxide to the tips and margins of tomato leaves which are particularly prone to infection by Phytophthora infestans, the causal organism of late blight of tomato and potato (Howe et al., 1982).

Systemic fungicides

These are absorbed by the plant through the leaf, stem or root surface and transported varying distances within the plant, as short as from one leaf surface to the other (trans-laminar movement) or as far as from roots to shoot apex (Bohmont, 1983). Biological demands on the application of a systemic are different but no less important than those on a protectant, and those such as benomyl which are used as systemic and protectant fungicides require an integrated appraisal. Even fungicides which are noted for their systemic curative action will have residual protectant action while they remain on the leaf surface, and 90% of foliar applied metalaxyl has been found on or in the surface of avocado leaves up to 28 days after spraying (Zaki et al., 1981). Given that curative action against established or establishing infections inside the tissue is the main function of systemics, then rapid entry into the plant thus avoiding the effects of weathering and persistence of unsightly residues on flowers and fruit should be the ultimate aim of application. For tree-crop spraying, a flush of new growth is required to intercept the spray and ensure effective absorption and recommendations for control of avocado root rot (Phytophthora cinnamomi) with foliar applications of phosetyl aluminium advise that diseased trees are cut back to encourage new growth prior to spraying (Mercer, 1984). Synchronisation of systemic fungicide sprays with the appearance of seasonal flushes in citrus could prove particularly useful for the control of foliar diseases and pathogens such as Phytophthora spp which infect collars, branches, shoots and fruit. The new lighter green leaves are conveniently situated on the periphery of the canopy, within easy reach of a knapsack mistblower and well displayed to the less penetrative spray stream of a hydraulic high volume sprayer. There is evidence to suggest that the relatively poor control of greasy spot with benomyl on grapefruit trees budded on Rangpur lime and rough lemon rootstocks was due to sparse amounts of foliage at the time of spraying caused by repeated uncontrolled attacks of greasy spot to which these combinations are known to be susceptible (Mabbett and Phelps, 1973; 1983a).

Fungicide waste through run off into the soil is a limiting factor on the efficiency of high volume protectant sprays, but systemics such as phosetyl aluminium which show downward and upward systemicity (Hill and Pirman, 1980), may not necessarily be lost. High volume applications of protectants such as iprodione at 2,000 l/ha are effective in the control of grey mould (Botrytis cinerea) on strawberry (Alford and Gwynne, 1983) but wasteful since a good proportion of spray will run off into soil. Similar applications of phosetyl aluminium at 1000 l/ha to control strawberry red core (Phytophthora fragariae) (Alford and Gwynne, 1983) are potentially less wasteful because fungicide running off into the soil becomes available for uptake by the roots. Similarly, phosetyl aluminium dripping from the peripheral foliage of avocado trees, following high volume sprays to control root rot lands in the region of the feeder roots and becomes available for absorption. Chemicals such as phosetyl aluminium or its metabolites which exert their effect by stimulating the host's defence mechanisms (Dekker, 1983) add a new biological dimension to spray application. Consideration must now be given to the site of anti-fungal substance production as well as its site of action because, for example, application of phosetyl aluminium or an equivalent material to the tapping panel of rubber trees to control black stripe (Phytophthora palmivora) would seem pointless if transportation to the leaves was necessary to stimulate an anti-fungal response.

CONCLUSION

Novel spray systems are exciting from the research point of view but full assessment of them is time consuming and is hampered by a lack of basic information on traditional systems, which are largely effective but very inefficient (Hislop, 1983). Biological data will help to define the timing and placement of spray needed to prevent pathogen entry into the crop and plot the fate of deposits as they are modified by weathering and growth. New methods of application have tended to be ignored for tropical disease control in favour of insect pest control on cotton, which being a valuable cash crop that is bombarded with pests from emergence to picking, is an attractive subject for application from both research and commercial points of view (Mabbett and Phelps, 1983b). New methods need to be assessed in the tropical situation in conjunction with consolidative work with traditional systems so that farmers in the Developing World can be offered the most cost effective option.

The mathematical and physical components of crop spraying have deterred many botanists and agronomists from becoming involved in this challenging field of work, with the result that the problem has too often been viewed from one side only rather than by integrating the ideas and expertise of crop biologists as well as spray physicists. The answer must lie in a multi-disciplinary approach to pesticide application.

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THE GROWTH EFFECTS OF CUCUMBER ON SPRAY RETENTION AND INITIAL DEPOSITION

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ABSTRACT

The effects of leaf display, vein profile and hairiness on spray retention and fungicide deposition are reported in relation to the twin problems of unprotected post-application growth and deposit dilution due to, respectively, the rapid production and expansion of new leaves. Densely-haired young leaves retained large deposits of cupric hydroxide from a high volume sprayer up to incipient run-off. These deposits were sufficiently large to buffer the effect of dilution by leaf expansion, which is a major factor contributing to poor control of angular leaf spot (Pseudomonas syringae p.v. lachrymans) with low and ultra low volume sprays. Of additional benefit was the disposition of young leaves which lay flat against the vine with their abaxial (lower) surface exposed, and the raised nature of the veins on this surface to form spray catchment areas between them. These factors, together with the increased surface area for retention provided by the dense matt of hairs, combineto ensure maximum deposition on this surface, which is the prime point of entry through stomata for the bacteria which cause angular leaf spot.

INTRODUCTION

Cucumber is grown throughout the humid tropics by small farmers for sale in local markets as a fresh salad vegetable (Mabbett, 1981). Tropically-grown cucumber plants exhibit phenomenol growth rates with new leaves produced at the rate of one/vine/day and expanding by a factor of up to thirty to attain maximum size within 10 days (Mabbett and Phelps, 1984). In the face of such growth rates protectant sprays of copper fungicide, applied weekly to control angular leaf spot (Pseudomonas syringae p.v. lachrymans) (Mabbett and Phelps, 1984), fail to protect the five new leaves/vine produced during the spray interval. Deposit levels on leaves which receive spray prior to their major expansionary phase appear sufficient. Angular leaf spot appears on the leaves four to six days after they emerge, which is the most rapid phase of expansion, and develops quickly during hot humid weather (Haas and Rotem, 1976), when the crop is able to maximise growth rates. Requirements are for shorter spray intervals and application methods which maximise deposits on young leaves and thereby buffer the effects of dilution by growth until the next application. Marked changes in leaf geometry and leaf hair density which accompany growth and develop-

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ment were investigated in relation to coverage, retention and deposition, to determine whether these biological factors could help identify the application needs for the management of angular leaf spot.

MATERIALS AND METHODS

Studies were carried out in the field and on detached leaves of Marketer and Local varieties of cucumber.

Leaf area studies

Leaf areas were calculated using predictor equations formulated from the correlation of linear dimensions with leaf area in a simple linear regression programme. The best predictor for the five-lobed leaf of cucumber was found to be length (vertical line from the insertion of the petiole to the tip of the terminal lobe) x width (distance between the tips of the two upper lateral lobes), designated LW, and the equations with coefficients of determination in brackets are as follows (Mabbett and Phelps, 1980):-

Marketer $y = -6.3985 + 0.8132x$ (99.18)
Local $y = -6.3437 + 0.8663x$ (98.70)

Leaf display studies

The change in leaf disposition with increasing age was assessed in the field on Marketer variety by measurement of i) the angles subtended by the vine (stem) and petiole, and ii) the petiole and abaxial surface of the lamina. The first six emerged leaves (representing six days growth) on ten randomly-selected vines were assessed and mean values for each angle calculated.

Leaf hairiness studies

The first 10 leaves of vines from five randomly-selected plants (Local variety) were harvested to give a range of leaf sizes. Leaves were mounted under a binocular microscope and illuminated with a side light source. A small strip of photographic film (2 x 5 cm) containing holes of diameter 2.5 mm was laid over the leaf and the hairs within the area of one hole were counted using a fine needle. Ten counts were made for each leaf, five adaxial (upper) and five abaxial (lower) and length x width (LW) measurements computed. Graphical representations were used to determine the relationships between leaf hair density and leaf size for adaxial and abaxial surfaces.

Spray retention and fungicide deposition on detached leaves

Six samples, each of 20 leaves, were harvested at random from 0.1 ha of Local cucumber. Samples varied according to leaf size and approximated to mean length x width (LW) values of 10, 25, 75, 125 and 225 cm^2. A hand-operated garden sprayer consisting of a siphon apparatus attached to 750 ml bottle was adjusted to give the finest spray possible and standardised by 25 consecutive atomisations when the bottle was full (750 ml) half full (400 ml) and almost empty (150 ml), of 0.1% kocide (Cupric hydroxide) in distilled water. The mean volumes emitted were 1.74, 1.72 and 1.73 ml and the C.V. for volume in 25 atomisations was 7.0%, 2.4% and 4.9% for the three levels respectively.

Each leaf was mounted on a sheet of plastic mesh (2 x 2 mm) fastened over a metal tray at a distance of 30 cm from the nozzle of the sprayer. Leaves were sprayed to run-off, which was indicated by the fall of two consecutive drops of liquid from the leaf when held in a vertical position by the petiole. Of the twenty leaves comprising each group, half were sprayed on the adaxial surface and half on the abaxial surface. The number of atomisations required to bring each leaf to run-off was recorded. Leaves were transferred individually to 100 ml flasks (large leaves to 250 ml wide-mouthed extraction flasks) and shaken for the appropriate time. The mesh washed with 0.06M HCl and distilled water and dried after each leaf had been sprayed.

Copper deposits were removed from leaves by a standard method (Mabbett and Phelps, 1983). Leaves were placed in appropriate-sized flasks, immersed in 30 ml of 0.06M HCl and mounted on a wrist-action shaker for 30 min. Samples were reduced and made up to 25 ml for determination of copper content using an atomic absorption spectrophotometer. Deposits were expressed as $\mu g\ Cu^{++}/cm^2$ of leaf surface and graphical representations were used to determine the relationships between retention, deposition and leaf size.

RESULTS

The vine petiole angle increased from 10° for the youngest emerged leaf to a maximum of 90° within 5 days, while the petiole lamina angle was reduced from 180° to a minimum of 135° on day three. The net result in terms of leaf display is that the emerging leaf lays flat against the vine with the abaxial surface facing outwards, but within 5 days has changed position so that it is borne at right angles to the vine with the adaxial surface uppermost (Table 1).

TABLE 1

Changes in disposition of cucumber leaves with increasing age

Position of first six leaves at top of the vine (≡ age in days)	Vine/petiole angle[#] (Degrees)	Petiole/lamina angle[#] (Degrees)
1	10	180
2	45	180
3	50	180
4	75	135
5	90	135
6	90	135

[#] Mean of ten leaves.

The curvilinear relationship between leaf hairiness and LW was transformed to a linear fit by converting LW to a logarithmic scale, $\log_{10}$ provided the best fit. Hairiness was transformed to square root hairiness to equalise the variance which was increasing along the line with a reduction in $\log_{10}$ area. The strong negative relationships showed that leaf hair density decreased as the leaf increased in size

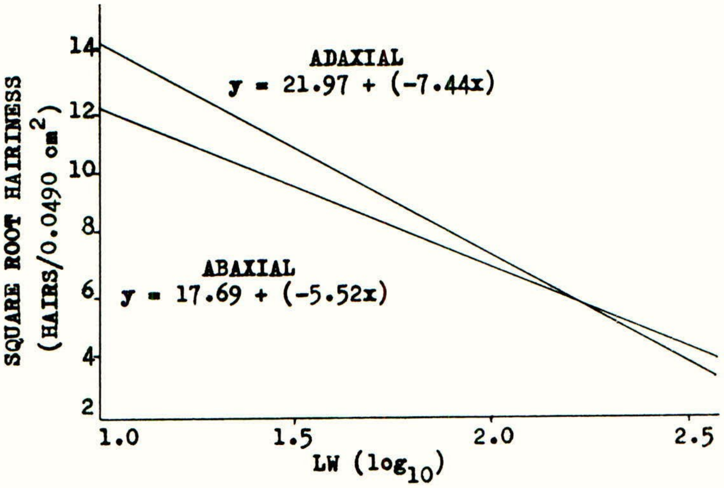

FIGURE 1

The relationship between hairiness and leaf size

TABLE 2

Simple linear regression of leaf hair density (square root of hairs/ 0.0490@ cm²) on leaf size ($\log_{10}$LW).

	Abaxial Surface	Adaxial Surface
C.D.	93.9	96.1
Equation	$y = 17.69 + (-5.52x)$	$y = 21.97 + (-7.44x)$
S.E. (a), (b)	0.10 0.20	0.11 0.21
F ratio (calc) 50 d.f.	773	1241
$(b_1 - b_2) = 1.919 \pm 0.4067$ x t 100 d.f.+++		

(a), (b) constant term and slope, respectively.

@Area within which hairs were counted.

+++Significant at the 0.1% level.

C.D. Coefficient of Determination.

TABLE 3

Relative hairiness and deposition on leaves of different size

Area[a] (cm^2)	Age[e] (days)	Abaxial Surface Hairs/leaf	Abaxial Surface Hairs/cm^2	Abaxial Surface µgm $\text{Cu}^{++}/\text{cm}^2$	Adaxial Surface Hairs/leaf	Adaxial Surface Hairs/cm^2	Adaxial Surface µg $\text{Cu}^{++}/\text{cm}^2$
2.6[d]	1	8,951[b]	3,442[b]	25.31[c]	14,056[b]	5,406[b]	19.17[c]
28.4	3	51,165	1,802	11.78	65,069	2,291	7.16
74.0	5	76,990	1,040	7.79	83,028	1,122	3.98
130.2	10	73,042	561	5.83	69,556	534	2.53

[a] Calculated from the Area Predictor Equation for Local Cucumber.

[b] Calculated from the regression equation of hairiness on leaf size.

[c] Calculated from regression equation of deposition on leaf size.

[d] Youngest emerged leaf.

[e] Estimated from position on the vine.

for both surfaces but the significant difference between the slopes (Table 2) indicated that the effect was not the same for each surface. Leaf hair density was greatest on adaxial surfaces at leaf emergence but decreased more rapidly with leaf expansion so that hair density was about the same for each surface on fully expanded leaves (Figure 1). Emerging leaves had considerably more hairs on their adaxial surface but subsequently more hairs were formed on the abaxial surface so that there were no marked differences in densities by the time leaf expansion had ceased (Table 3).

The curvilinear relationships obtained for retention, deposition and leaf size were treated as above so that simple linear regressions of retention (square root of number of atomisations at run off) and deposition (square root µg Cu^{++}/cm^2 recorded at run off) on $\log_{10}$ area were calculated (Figure 2 and Table 4).

TABLE 4

Simple linear regressions of spray retention (square root of number of atomisations at run off) and deposition (square root µg Cu^{++}/cm^2 recorded at run off) on $\log_{10}$ leaf area.

	Abaxial Surface	Adaxial Surface
<u>Retention</u>		
C.D.	73.33	82.45
Equation	$y = 3.9367 + (-0.6446x)$	$y = 3.3471 + (-0.7694x)$
S.E. (a), (b)	0.0298 0.0515	0.0269 0.0470
F ratio(calc) 57 d.f.	156.66	267.82
$(b_1 - b_2) = 0.1248 \pm 0.0698$ x t 114 d.f. N.S.		
$(y_1 - y_2) = 0.5896 \pm 0.0401$ x t 114 d.f. +++		
<u>Deposition</u>		
C.D.	88.28	91.14
Equation	$y = 5.6690 + (-1.5404x)$	$y = 5.0584 + (-1.6398x)$
S.E. (a), (b)	0.0430 0.0744	0.0387 0.0677
F ratio (calc) 57 d.f.	429.16	586.01
$(b_1 - b_2) = 0.0994 \pm 0.0578$ x t 114 d.f. N.S.		
$(y_1 - y_2) = 0.6107 \pm 0.0579$ x t 114 d.f. +++		

(a), (b) constant term and slope, respectively.
N.S. not significant at the 5% level.
+++ Significant at the 0.1% level.
C.D. Coefficient of determination.

The four regressions showed strong negative relationships as spray retention and deposition of copper/cm^2 decreased with an increase in leaf size and the slopes were not significantly different because retention and deposition were affected by leaf size in the same way for

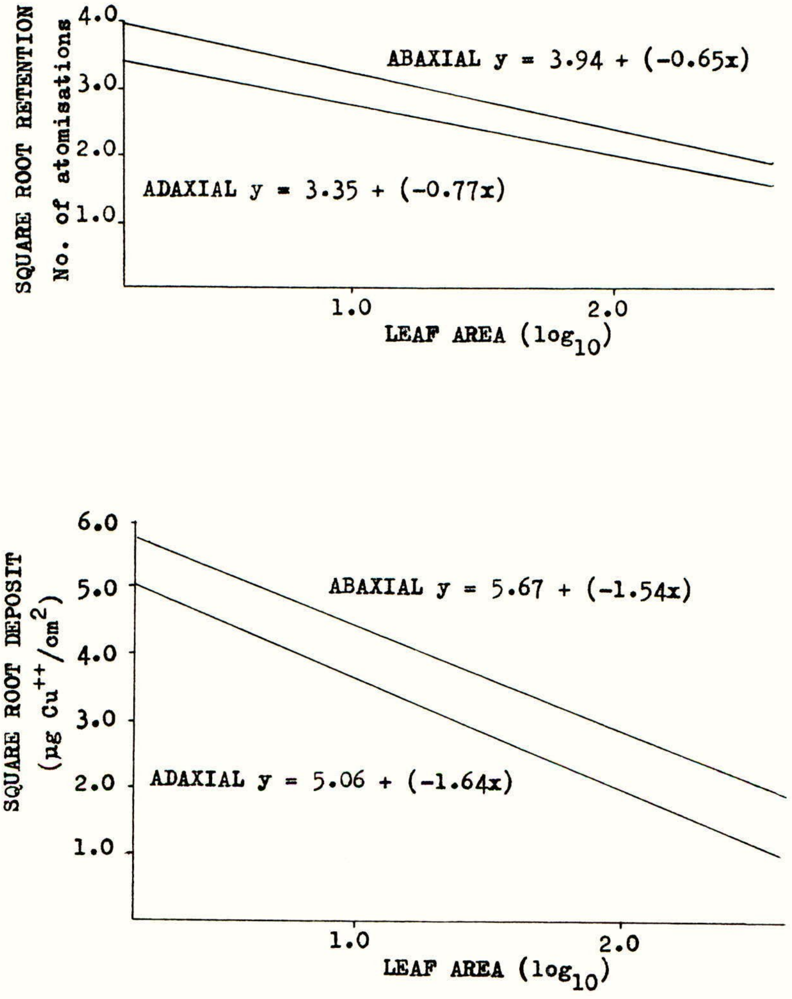

FIGURE 2

The relationships between spray retention, deposition and leaf size for abaxial and adaxial leaf surfaces.

adaxial and abaxial leaf surfaces. The slopes were significantly apart showing that the abaxial surface retained more liquid and higher deposits than the adaxial surface of leaves of equivalent size. As expected there was a significant correlation between spray retention and fungicide deposition at run-off for the whole range of leaf size. One day old leaves (2.6 cm^2) were more densely hairy by factors of 10.1 and 6.1 and held more deposit/cm^2 by factors of 7.6 and 4.3 than 10-day old leaves (130 cm^2) for, respectively, adaxial and abaxial surfaces (Table 3).

DISCUSSION AND CONCLUSIONS

Foliar hairiness has been investigated in relation to spray retention and deposition (Rich, 1954; Wilson and Hedden, 1964) but the usefulness of many investigations has been limited by inter-crop comparisons which introduce other surface factors. The studies reported here measured changes of retention within a single crop species which permit more precise comparisons. The relationship between leaf size and hair density was mirrored by remarkably similar relationships between leaf size and retention and leaf size and deposition, which suggests leaf hair density as a major factor controlling spray retention in cucumber. The ability of smaller, densely-haired leaves to retain more spray before run-off occured is presumably due to an increased surface area for liquid retention. The effect was similar for both leaf surfaces but abaxial surfaces held more spray over the complete range of leaf size. This appeared to be related to the raised profile of the veins on the abaxial surface forming inter-veinal gulleys which act as spray catchment areas. On adaxial surfaces veins are situated in depressions to give raised inter-veinal areas which accelerate run-off, factors which have been previously recorded to affect retention by blackcurrant leaves (Furmidge, 1962). Veins tend to be raised on the abaxial leaf surface of most dicotyledonous crops but not to the same extent as in cucumber. This surface should therefore have the greatest potential for spray retention but the angles subtended by the stem and petiole and petiole and lamina in most crops are such that natural leaf display tends to shield the abaxial surface from incoming spray, but this is not so for cucumber leaves for up to three days after emergence.

Reduced spray intervals will minimize the number of leaves which remain unsprayed but will not solve the problem of dilution of deposit to ineffective levels unless very large amounts of active ingredient can be deposited on leaves at the pre-expansionary stage. Low and ultra low volume spray systems providing well distributed, but relatively small, initial deposits were unable to reduce angular leaf spot to acceptable levels because deposits were diluted to sub-effective levels by leaf expansion (Mabbett and Phelps, 1984). The results of these investigations indicate that morphological characteristics of young leaves increase the retention of spray from high volume applications to run-off which helps to buffer the effects of future leaf expansion. Of additional significance is the disposition of young leaves which lay flat against the vine with their abaxial surface exposed, and the raised profile of the veins on this surface to form spray catchment areas between them. These factors together with the increased surface area for retention provided by the dense matt of hairs combine to ensure maximum deposition on this surface, which is the prime point of entry through stomata for the bacteria which cause angular leaf spot (Whitaker and Davis, 1962; Umekawa et al., 1981).

In Trinidad, cucumbers are grown in rows on cambered beds and, as the plants begin to vine, the growing points radiate from the planting hole. In practice, adequate control may be achieved by high volume applications, using a knapsack sprayer, which are directed every four days at the tips of the vines until the crop foliage completely covers the ground and individual plants are no longer discernible. Additional whole crop sprays could be made as necessary to compensate for losses due to weathering. Previous studies indicated that minimum deposit levels of 1 µg Cu^{++}/cm^2 are required to maintain protection (Mabbett and Phelps, 1984). The present work shows that young leaves can accumulate sufficient deposit from run-off spraying to buffer the effects of a 25-fold dilution. This was achieved with a low (0.1%) concentration of Kocide (Cupric hydroxide) and projected losses through weathering could be compensated for by increased concentration. The control of angular leaf spot in tropically-grown cucumber may present one of the few examples where reduced volume systems applying small but well distributed deposits are neither necessary or desirable.

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SPRAY FACTORS AND FUNGICIDAL CONTROL OF APPLE POWDERY MILDEW

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ABSTRACT

Data from a number of field experiments are summarised with regard to the quantities of fungicide deposited at sites susceptible to mildew infection, by different methods of spraying, and to the degrees of subsequent infection. It is shown that although reduced volume (c. 50 l/ha) application of partially-controlled drop sizes often deposited as much or more pesticide than higher volume (500-800 l/ha) hydraulic nozzle spraying, control of mildew was usually best with the latter. Higher volume applications covered larger proportions of target foliage and this may have led to improved efficacy, even though systemic fungicides were often used. Data from controlled laboratory and glasshouse studies generally supported this conclusion, as do recent findings of other workers.

Although the logistic advantages of reduced volume spraying are recognised, it is suggested that growers should not use the technique to reduce fungicide doses. Practical control of mildew calls for a managed and supervised approach in which dose and volume rates are varied according to tree type, foliage density, inoculum intensity and weather conditions.

INTRODUCTION

Dessert apples are a high value crop and constitute a complex spraying problem. They are susceptible to a wide range of pests and diseases, each with a different life cycle and vulnerable stages at different tree growth stages and affecting different host sites. The spraying season is generally a four month period during which time approximately twenty applications of several different chemicals could be applied at 7-14 day intervals. During this extended season, the total plant surface area may show a 4- or 5-fold increase. In the U.K., the commonly grown cultivar Cox's Orange Pippin is susceptible to powdery mildew (*Podosphaera leuchotricha* (Ell. and Everh.) Salm) and this susceptibility combined with climatic factors, makes the effective control of this disease a persistent crop protection problem.

Hislop (1983) reviewed the general state of the art of top fruit pest and disease control and concluded that there was now little relevance in using former high volume spraying practices (up to 2000 l/ha). He pointed out that most insect pests are now relatively easily controlled with volumes reduced to about 50 l/ha, largely as a result of experiments done at Long Ashton Research Station (Cooke *et al*. 1976). However, he concluded that disease control was generally more difficult and suggested that moderate to severe infections of apple mildew were rarely, if ever, adequately controlled with reduced volumes (c. 50 l/ha). This was despite the application of modern potent systemic fungicides applied every seven days throughout the growing season. This opinion is somewhat at variance with the experience of Gunn (1980), although both are agreed that there is a need to improve the logistics of apple mildew control.

The purpose of this paper is to provide an update on the subject of apple mildew control and to report recent field and laboratory work designed to analyse the apparent failure of reduced volume spraying. Space limitations preclude detailed presentation of work done pre- 1980 but a comparison of our findings and those of others, in particular Umpleby (1984) and Butt et al (1984) is made, and some tentative conclusions drawn. A major problem in interpreting the work done on this topic in recent years is the variety of application techniques used, and although the biological consequences have been reported, very often full valid comparisons were lacking. Furthermore, rarely was any attempt made to analyse spray deposition, thus inhibiting logical interpretation of the results.

The theory behind reduced volume and in particular controlled droplet application techniques (CDA) which are sometimes incorrectly regarded as synonymous (Hislop, 1984), is that the maximum number of small spray droplets which are potentially well retained by foliage are available from a minimal small spray volume. Because many modern pesticides are systemic, good retention and distribution on the target of these should compensate for small total surface coverage. Indeed, it was expected that use of ULV/CDA techniques would probably deposit more pesticide on the foliage than high volume applications where run-off might occur. The assumption was that if a greater proportion of the pesticides could be retained on targets, then not only would logistics be more favourable, but also that there should be a possibility of decreasing dose rates, with a concomitant saving to the grower and a reduction of off-target contamination. Previous work (Herrington et al. 1981) had indicated that only approximately 30-50% of the applied fungicide was retained on the trees sprayed at 2250 l/ha.

MATERIALS AND METHODS

Field Experiments

Orchard sites

Between 1979 and 1984, experiments on Cox's Orange Pippin were done at Long Ashton Research Station and by the Agricultural Development and Advisory Service staff at Luddington Experimental Horticultural Station. Trees were c. 3.5 - 4 m high and planted 4.6 x 2.7 m (Experiments A & F) / 5.5 x 4.6 m (Experiment B) / 5.5 x 3.1 m (Experiment C) / 4.0 x 1.9 m (Experiment D) and 4.2 x 2.5 m (Experiment E), spacing on MM 106 rootstocks.

Treatments

Experiment A: In 1979 an experiment was conducted to test ULV/CDA post-blossom spraying on different levels of primary inoculum. A dormant season spray of a non-ionic surfactant 3825 g a.i./ha + bupirimate 1125 g a.i./ha (Dormakil I.C.I. Plant Protection PLC) was applied at the recommended rate in 2250 l/ha (hand applied) to half the trial area. The whole area then received three pre-blossom sprays, applied conventionally (1130 l/ha) of benomyl at 565 g a.i./ha (Benlate 50% a.i. WP du Pont). Eleven post-blossom sprays at weekly intervals were applied to two replicate plots of winter-treated or non-treated areas; these contained a mixture of binapacryl (Morocide 50% a.i. E.C. Hoechst) and pyrazophos (Afugan 30% a.i. E.C. Hoechst) either at the recommended doses of 383 g a.i./ha and 158 g a.i./ha in 2250 l/ha (hand applied), or at 1/5th dose rate applied using a K.E.F. air-blast sprayer fitted with four electrically driven spinning discs (Micron Ulva).

Experiment B: In 1980, a similar experiment to 1979 was done with large and small primary mildew infestations which were treated with 15 weekly post-blossom applications of a bupirimate 275 g a.i./ha (Nimrod 25% a.i. E.C. I.C.I. Plant Protection PLC) /triadimefon 40 g a.i./ha (Bayleton

25% W.P. Bayer) programme. A K.E.F. air blast sprayer with improved air flow characteristics was used to apply recommended rates of fungicide in 820 l/ha with hydraulic nozzles or 1/2 dose rates at 54 l/ha using 6 Micron X7 air-propelled stacked rotary disc atomisers.

Experiment C: Between 1981 and 1984, experiments were done by ADAS at Luddington Experimental Horticultural Station (details of the layout and programmes are described elsewhere by Umpleby (1984)). Deposit data were obtained in 1981 and 1982, details of which are given later.

Experiment D: In 1981, a field experiment at Long Ashton Research Station investigated the efficacy of oil based sprays using the fungicide bupirimate (I.C.I. Plant Protection PLC experimental formulation) at recommended rates (175 g a.i./ha) and at 1/2 dose rates. These were applied by hand using experimental air-shear equipment (Herrington et al. 1983a) and compared with a water-based formulation (Nimrod 25% E.C. I.C.I. Plant Protection PLC) applied at 50 l/ha at full and half rates and full rate at 500 l/ha. Except for one interval of 14 days, there were 11 weekly applications.

Experiments E and F: Preliminary studies in 1981 showed that deposition could be approximately doubled when droplets are electrostatically charged; four I.C.I. 'Electrodyn' nozzles were fitted to a Drake and Fletcher Commandair sprayer to apply 40 g a.i./ha of oil based fenarimol (I.C.I. Plant Protection PLC experimental formulation) at 1 l/ha. The same sprayer was also equipped with 3 fan-driven rotary cage atomisers (Micronair AU 7000 units) applying 200 or 500 l/ha of the same dose of water dispersed fenarimol (Rubigan 12% E.C. Elanco). A second experiment (F) used two hydraulically driven Micronair AU 4000 units, applying 200 l/ha, which were mounted to give a turbulent air flow in the trees. This method was compared with a standard laminar type air flow mist blower (K.E.F.) at 500 l/ha. Again, the full dose of fenarimol was used. Each treatment was applied on a weekly schedule from the 4 June to the 6 August.

Biological Data

The incidence of primary mildew was recorded on blossom clusters and breaking terminals from each of the experiments to give a background level of primary disease pressure. Secondary mildew was recorded in the first seven leaves of vegetative shoots from each of six trees per treatment block.

Deposit Measurement

A. Quantitative

Deposit data for experiments B C E and F were obtained by taking samples from the first suitably expanded leaves on extension shoots from 3 replicate trees in 2 spray blocks. Trees were divided into seven sampling sites and two replicates were taken from each tree position, i.e. top (1), middle centre (2), inter-tree south (3) north (4), inter-alley east (5) west (6), and base (7).

Data for experiments B and C are based on analyses of captan deposits applied at a dose of 500 g a.i./ha (Captan 50% W.P. I.C.I. Plant Protection PLC). Data for experiments E and F were obtained for all methods of spraying on three occasions by using fluorescent tracers. Uvitex OB (optical brightener) 3 g a.i./ha and fenarimol supplied by I.C.I. was used for the 'Electrodyn' applications, and an emulsifiable concentrate of Uvitex (10 g a.i./ha) was added to the aqueous fungicide applications on the first two occasions. This tracer was extracted from the leaf discs with hexane (aromatic free) containing 5% acetone. Water soluble fluorescein (BDH, 200 g a.i./ha was used in the third aqueous fungicide spray assessment and was extracted in 0.1 M phosphate buffer (pH 7.0) containing 0.05% Triton N101 wetting agent. Fluorescence was measured using a Perkin-Elmer 2000 spectrophotometer. Uvitex was measured at 426 nm after excitation at 363 nm and fluorescein was measured at 510 nm after excitation at 449 nm. Photodegradation of tracers in the field (Sharp, 1974) was minimized by sampling all plots within 15 minutes of spraying. In order to facilitate direct comparisons within and between treatments all deposit data were corrected to a standard application rate of 100 g a.i./ha.

B. Qualitative

Qualitative distribution of spray within the tree was on experiments E and F using Uvitex OB or Tinopal (Ciba-Geigy) fluorescent tracers. Two extension shoots from each of the seven sample sites (as above) were removed from 3 replicate trees. Upper and lower surfaces of young leaves were examined using an Optomax Image Analyser, and the percentage cover per unit area was recorded.

Droplet Spectra

Experiment A: Droplet spectra produced by electrically driven spinning discs (Micron Ulva) were examined under static conditions with a Malvern Particle Sizer. With a disc speed of 6000 rpm and a feed rate of 150 ml of water/minute, the VMD was 78 μm (± 5). NMD values varied between 15 and 30 μm.

Experiment B: The droplet spectra produced by the stack of seven 5.5 cm cupped discs were tested in a wind tunnel where they could be driven by propellors, as they would be when fitted to a mist blower, and where drop production in an air stream could be examined using a Particle Measuring System analyser (PMS). With a wind speed of 31.3 m/s rotational speed was 7800 rpm and with a feed rate of 200 ml/min, a VMD of c. 90 μm was obtained. However, different atomisers behaved erratically and results were variable.

Experiment D: The air-shear atomisers produced droplets with VMDs ranging between 21 and 49 μm (Western, 1983).

Experiments E and F: The hydraulic nozzles produced a VMD of 221 μm, the AU 4000 rotary cages (6000 rpm and 1.5 l/min) gave a VMD value of 155 μm, while the AU 7000 units (5000 rpm and c. 1 l/min) gave a VMD of 192 μm. R values for the rotary cages (i.e. $\overline{\text{VMD}}$/NMD) varied between 4.2 and 6.5. The 'Electrodyn' nozzles at 30 kv and a feed rate of 6.5 ml/min produced droplets with a VMD of 42 μm and an R value of 1.45.

Laboratory Studies

Laboratory studies using an experimental track sprayer have been done to examine the interacting effects of droplet size, droplet number and dose of fungicide sprays on disease control. Initial tests were carried out with glass-house grown marrow plants (*Cucurbita pepo*) sprayed with bupirimate (Nimrod 25% E.C. I.C.I. Plant Protection PLC) (Herrington and Baines, 1983b). This work was extended to apple mildew on glasshouse grown apple seedlings. Sprays of aqueous bupirimate containing 1×10^{-5} to 6×10^{-3} g a.i./ml were applied in drop sizes ranging from 120 to 250 μm and numbers ranging from c. 5 to 50/cm^2.

RESULTS AND DISCUSSION

Table 1 summarises the effects of a winter eradicant spray (Hislop *et al*. 1978) on the level of primary mildew recorded in the spring for experiments A and B, while Table 2 summarises the mean amount of secondary mildew recorded on experiments A to F for the various spray appliecation methods. Table 3 is a summary of the deposit data recorded on experiments B, C, E and F and of cover data from experiments C, E and F.

TABLE 1

Primary mildew (%) on blossom clusters and extension shoots with and without winter eradicant treatments.

Experiment A		Experiment B				Subsequent Summer Application Volumes
% Blossom clusters		% Blossom clusters		% Extension shoots		
+	-	+	-	+	-	
0.25	2.7	0.48	4.71	6.1	25.2	0
0.25	5.0					2250
		0.64	2.23	1.72	16.0	800
0.25	7.75	3.73	3.17	1.07	2[illegible].0	55

\+ = with winter eradicant   - = without winter eradicant

Comparison of the data in Table 1 with the corresponding secondary mildew data in Table 2 clearly illustrates that reduced volume spraying was less effective when disease incidence was high. In contrast, large and medium volume spray applications were generally effective irrespective of disease pressure. Therefore, disease pressure is an important factor in determining the likely effect of various application techniques. Examination of the data in Table 3 shows that except for the low volume (*c*. 50 l/ha) application in experiment B and the 200 l/ha application in experiment E, the doses of fungicide deposited from reduced (55 l/ha) and very small (1 l/ha) volume applications are either similar to or greater than those from high volume application. But the results in Table 2 show that mildew control usually decreases with reducing spray volumes. This too was the clear result of the ADAS trial reported by Umpelby (1984). Two possible reasons for this decrease in control with reduced volume spraying are evident from the data in Tables 3 and 4. First, reducing volumes inevitably reduces coverage (not to be confused with drop frequency per unit area) of susceptible foliage. This is difficult to measure accurately and the value given for percentage cover achieved with the large volume application in experiment C is an underestimate as it was recorded on water sensitive paper which was in places oversaturated. In experiments E and F a soluble fluorescent tracer (Tinopal, Ciba-Geigy Ltd) was used to measure cover but this too presented problems in measurement because it was difficult to obtain sufficient contrast in large volume applications. Thus, we believe that in general, reducing spray volumes ten-fold (i.e. from 500 to 50 l/ha) resulted in a four-fold reduction in coverage. Secondly, it is evident from the coefficients of variation in Tables 3 and 4 that reduced volume spraying is more variable in both quantity of deposit (dose) and quality (cover) compared with larger volume spraying. Similar conclusions are reached by

Cooke *et al.* reported elsewhere in these proceedings.

TABLE 2

Mean percentage of secondary mildew recorded on young foliage of extension shoots.

Nominal Application Volume (1/ha)	Fungicide Dose	Expts. A		B		C	D	E	F
		1979		1980		1982	1981	1984	
		+	-	+	-	+	-	-	-
0	0	35a	55a	56a	69a		25a	56a	44a
2250	1	5b	2b						
500-800	1			2b	5b	2	3b	29b	24b
"	0.25					8			
200	1							37bc	27b
55-110	1					8	3b		
"	0.5			10c	20c		5b		
"	0.25					30			
"	0.2	17c	42c						
1-5)	1						4b	42c	
")oil	0.5						6b		
")	0						13c		

\+ = with winter eradicant   - = without winter eradicant
No significant difference between treatments with same suffix (P = 0.05).

The results presented here are necessarily abbreviated. However, they indicate that in contrast to early hopes, rotary atomisers have not generally produced controlled spray drop sizes, although volume median diameters were smaller than those from conventional hydraulic nozzles and had a smaller scatter about the mean. For various practical reasons, some rotary atomisers (e.g. Micron X7) have not performed as expected and in some work were replaced by low-throughput hydraulic nozzles (e.g. the Spraying Systems' TX3 and TX4 nozzles used by Umpelby, 1984). The rationale behind this step was provided by Allen *et al.* (1978) who showed that smaller drop sizes were more effective for the control of apple mildew than larger average drop sizes when spray volume was constant and relatively large. Moreover, recent work (Butt *et al.* 1984) indicated that when drop size is kept constant and reasonably small, increasing spray volumes from *c.* 50 to 600 l/ha by using different numbers of low-throughput hydraulic nozzles (TX3) generally decreased mildew infection. Since doses of fungicide deposited were the same for all application volumes, Allen (private communication), like ourselves, concluded that dose was not the only factor affecting mildew control.

TABLE 3

Deposit data for different tree aspects from different spray application methods. Data are expressed as mean values ng/cm^2 based on an application rate of 100 g a.i./ha.

Sampling Position in Tree	Experiment B 1980		Experiment C 1981			Experiment C 1982		Experiment E 1984			Experiment F 1984	
	KEF 820*	MICRON X7 54*	COMMAND-AIR 550*	MICRON X7 55*	TX3 55*	COMMAND-AIR 550*	TX3 55*	MICRON-AIR 500*	AU7000 200*	'ELECTRODYN' 1*	KEF 500*	MICRONAIR AU 4000 200*
Top	169	131	138	164	165	100	106	112	69	332	62	165
Middle	119	45	111	171	216	103	263	80	45	29	65	58
Base	160	40	161	262	205	106	238	79	43	41	83	28
Inter tree	253	108	136	134	184	113	236	119	76	82	141	123
Inter alley	208	107	206	167	189	132	212	115	81	178	157	133
Overall mean	196	92	156	171	190	114	204	105	63	132	114	109
Coefficient of variation (%)	35	104	36	53	40	14	38	40	48	95	81	95

*Application volume l/ha.

TABLE 4

Cover data for different tree aspects from different spray application methods. Data are expressed as mean percentage cover/cm^2 of combined upper and lower leaf surfaces.

Sampling Position In tree	Experiment C** 1981			Experiment E‡ 1984			Experiment F‡ 1984	
	COMMAND-AIR 500*	MICRON X7 55*	TX3 55*	MICRON-AIR 500*	AU 7000 200*	'ELECTRODYN' 1*	KEF 500*	MICRONAIR AU 4000 200*
Top	6	2	4	12	7	0.5	6	1
Middle	7	3	5	11	4	0.2	7	3
Base	9	5	3	7	4	0.2	10	2
Inter tree	8	3	4	11	6	0.2	11	3
Inter alley	10	3	4	11	6	0.5	9	3
Overall mean	8.4	3.8	4.8	10.4	5.4	0.3	8.6	2.3
Coefficient of variation (%)	47	79	71	59	71	81	47	61

*Application volume l/ha.

**Experiment C - water sensitive papers.

‡Experiments E & F - fluorescent tracer 'Tinopal'.

In our experience, only the 'Electrodyn' atomiser produces near-monodispersed droplet sizes in an orchard sprayer's air-stream. Very small volume applications (e.g. as low as 1 l/ha) while not particularly effective in controlling mildew (e.g. experiment E), did not show the complete failure which might have been expected from the results of earlier 50 l/ha applications and our general rationale about the volume/control relationship. We attempted to examine the 'Electrodyn' system in 1983 but we had virtually no mildew. In contrast, the degree of mildew control achieved by any spray system examined in 1984 was poor. At one time we thought that this might have been due to the development of resistance by the pathogen to fenarimol (as reported for cucurbit mildew by Huggenberger, 1984) but this now seems unlikely because unrelated fungicides also performed poorly at Long Ashton in 1984. The reasons for the poor control thus remain unclear.

The general conclusion that coverage of the target is an important aspect influencing mildew control in the field is to some extent parallelled by the laboratory work reported by Herrington and Baines (1983b). This early work was done with a systemic fungicide (bupirimate) and marrow mildew, but has now been extended to apple mildew. In an attempt to make the work more relevant to the field situation, where infection can occur at any time between spray applications, Herrington, (in press), has shown that bupirimate appears to be a better protective fungicide (i.e. applied pre-inoculation) than as an eradicant material (applied post-inoculation). While the importance of dose in producing these effects was demonstrated, it was also shown that an eight-fold increase in volume deposited (i.e. doubling drop size from 140 to 280 µm), whilst keeping dose and drop number constant, enhanced curative action and, to a lesser extent, protection.

CONCLUSIONS

In practice, spraying large volumes of liquid, although usually effective, is time-consuming. Reduced volume spraying could be more efficient in labour terms, and in terms of the use of pesticide if a larger proportion of that sprayed is retained by the tree. Thus, we believe there is a case to be made for reduced volume (and perhaps reduced dose) in certain circumstances. Pest control in orchards is often perfectly satisfactory with reduced volumes and doses (Cooke *et al*. 1976; Umpleby, 1984). It can also succeed for mildew control when infection conditions are unfavourable. The following guide-lines are suggested:-

1. Carry-over of inoculum from one year to the next should be kept to a minimum, either by a thorough spray programme the previous year, by cutting out infected material in the spring or with the use of a winter eradicant spray.
2. The level of primary mildew in the orchard (and surrounding orchards) should be measured.
3. The initial spray programme should take account of early disease pressure, the relatively low leaf area index and the weather. Under conditions unfavourable to disease development (e.g. cold spells) spray volumes could be reduced. Fungicide doses can also probably be reduced in higher volume sprays if inoculum pressure is small.
4. Monitor infection at frequent intervals throughout the season and act quickly to discourage disease build-up (Butt, 1977).
5. Generally be prepared to increase spray volumes progressively as the leaf area increases. Remember that these strategies only relate to mildew control. The need to spray against apple scab and for pests will sometimes over-ride these suggestions.

These suggestions take account of the need for growers to reduce inputs improve the logistics of spraying and hopefully to improve timeliness of applications. However, growers have to remember that in the U.K. there are no label recommendations for reduced volume/dose spraying, and that there are no safety clearances for these techniques.

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A COMPARISON OF ALTERNATIVE SPRAY TECHNIQUES IN CEREALS

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ABSTRACT

Traditional techniques of hydraulic spraying together with use of the right pesticide produce good biological effects resulting in cost-effective yield benefits. This effectiveness however is offset by known wastage of spray to the ground and the risk of the potential environmental effects. Theoretically, some novel application methods can be more efficient because they contain a measure of control on the drop spectra produced, therefore potentially more effective and safe. Information relating to these aspects is dependent upon detailed physical, chemical and biological studies, but there are few valid data.

An attempt has been made scientifically to examine interacting factors associated with spraying techniques and to study a subject that in the past has suffered a preponderance of ad hoc studies. The paper describes a 2 year multidisciplinary study of cereal spraying, utilising spinning disc, rotary cage, electrostatic aqueous and electrohydrodynamic methods of atomisation, and the comparison with various types of flat fan nozzles commonly used in standard farm practice.

In all studies the hydraulic nozzle system was generally the most biologically effective but in terms of spray retention, wasteful. The addition of charging on some lower volume hydraulic nozzles increased efficiency of spray retention. Low volume CDA applications tended to be less effective biologically compared to the conventional hydraulic systems and did not always reduce wastage. All methods of spraying produced a yield gain and the benefit if correlated with the improved factors of logistics and timeliness associated with some novel techniques, could be advantageous. For general acceptance however, further evaluation and improvement may be necessary.

INTRODUCTION

Spraying chemicals for control of pests, weeds and diseases is recognised as an inefficient means of application (Matthews, 1981). This is based on calculations of theoretical dose requirements compared to the much larger quantities used in practice. Although not quantified absolutely a large proportion of pesticide is not deposited on the target but is wasted (Graham-Bryce, 1977). The Seventh Report of the UK Royal Commission on Environmental Pollution (Anon, 1979) suggests that although spraying is essential to maximise food production, environmental pollution must be reduced.

Despite these problems it cannot be denied that conventional hydraulic nozzle delivery systems, using the highly potent pesticides available, achieve good biological results normally culminating in cost-effective yield benefits. It is not surprising therefore that in recent years attempts have been made to produce a delivery system which is both effective and efficient. The grower is now faced with farming literature extolling the virtues of alternative delivery systems. He may choose low volume techniques which improve the logistics and timeliness, enabling him to spray a greater area more quickly with machinery that can traverse the land in adverse conditions. He may soon be able to spray electrostatically, theoretically improving deposit retention on the crop and also reducing drift. But are the claims associated with these novel methods valid; are they infact more effective, efficient and safe? As Fulton (1965) pointed out there exists a lack of fundamental information about where and in what form sprays are deposited, to achieve a particular degree of biological action. Laboratory studies have been, and are being made, on factors affecting spray efficacy (Frick, 1970; Hislop & Baines, 1980; Scopes, 1981; Merritt, 1982ab; Herrington, 1984) but interpretation and application of this data into a practical field situation is difficult. Some recent attempts have been made (Arnold & Pye, 1981; Cooke et al. 1981; Griffiths et al. 1981; Hislop et al. 1983) to evaluate certain delivery systems under field conditions, but a full understanding of the requirements for maximum efficiency and effectiveness is still lacking.

This paper describes a multidisciplinary approach involving physical, chemical and biological assessments of both novel and conventional methods of application with an attempted correlation of the data obtained. The work involved fungicide and herbicide applications to cereals utilising spinning disc, rotary cage, electrostatic hydraulic and electrodynamic atomisers and the comparison with conventional hydraulic flat fan nozzles. The study was based on two years work but to avoid unnecessary repetition and complexity, detailed data are presented for 1984. Where applicable reference and discussion are made to the relevant work of 1983.

MATERIALS AND METHODS

According to availability and design of equipment some field trials were conducted on 12 m x 50 m plots and some on 3 m x 25 m plots. All equipment was tractor mounted and ground speeds were mainly 8 kph for the large plots and 7 kph for the smaller.

Micronair rotary cages

Seven Micronair AU 5000 rotary units were fitted to a 12 m boom (Ransome Micronair 700 sprayer) and for both herbicide and fungicide programmes two application rates of 40 and 90 l ha^{-1} were used at 160 and 240 kPa pressure respectively. The variable restrictor units were set at 3 and 5 respectively. For herbicides, a cage rational speed of 2000 rpm was used at an angle of 15° from the horizontal and for fungicides, 3000 rpm at an angle of 30°. Typical drop spectra are shown in Table 1.

Spinning discs

The 12 m boom was supplied by CDA Ltd., and was fitted with 10 belt driven Micromax discs at 120 cm spacings. For herbicides an application rate of 40 l ha^{-1} was used at a disc speed of 3000 rpm and for fungicides 10 l ha^{-1} at 5,500 rpm. In this treatment full and half doses of herbicide and fungicide were examined.

Electrostatic hydraulic nozzles (ES System)

Six Spraycare (ES) electrostatic units were mounted on a 3 m boom in order to apply electrostatically charged and uncharged aqueous sprays for both fungicides and herbicides. The system utilised induction charging

(Power Farming, Feb. 1984). The application volumes for each pesticide were 70 and 200 l ha^{-1}, using Spraying System Tee Jet 8001 nozzles for the smaller rate and 8003 for the larger, both at c. 300 kPa pressure. The nozzle spacing was 50 cm and the height above the crop adjusted to 50 cm. For each experiment both sets of nozzles were operated with and without electrical charging. Typical drop spectra for charged and uncharged modes are given in Table 1.

Electrodynamic spraying

Fungicide applications were done using an experimental 3 m Electrodyn boom originally designed by ICI Plant Protection Division. The boom was fitted with six centrally mounted generators (50 cm spacing) each containing a nozzle designed for atomisation of oil formulations by electrical energy. Holes situated on either side of the generators permitted air assistance (provided by a centrifugal fan) in the form of a curtain on both sides of the nozzles. The nozzle tip distance was optimised at 43 cm from the boom and 40 cm from the top of the crop. Flow rate of oil formulation was controlled by a 12v precision variable speed pump and for 2 l ha^{-1} calibrated to delivery 0.19 ml $nozzle^{-1}sec^{-1}$. Atomisation voltage was set at 40 kv.

Conventional hydraulic nozzles

Pesticides were applied conventionally at volume rates of 100 and 200 l ha^{-1} using Lurmark Kematal 110° flat fan nozzles. For the smaller volume F110-015 type were used and for the larger F110-03, both at 300 kPa pressure. Nozzle spacing was 50 cm and the height above the crop set at 35 cm. These types of nozzles were used on both the 3 and 12 m booms.

Fungicide experiments

For the small plot (3 m x 25 m) trials winter barley (cv. Sonja) was sprayed on two occasions, 10 April (GS 30-31) and 9 May (GS c. 57). On both dates a mixture of an experimental triazole fungicide (flutriafen, ICI) and carbendazim (125 g + 200 g) ha^{-1} were used, formulated specifically for oil and aqueous spraying. In 1983 the same triazole fungicide was used and the spray timing was similar. In the 12 m plots winter barley (cv. Igri) was sprayed with prochloraz + carbendazim (405 g + 225 g) ha^{-1} 'Sportak Alpha' at GS 31 and propiconazole + tridemorph (125 g + 250 g) ha^{-1} 'Tilt Turbo 375 EC' at GS 39. For hydraulic nozzles and spinning disc atomisers, half doses were included in the trial. In 1983 triadimefon + carbendazim (125 g + 250 g) ha^{-1} 'Bayleton BM' was used at GS 31 and the second spray consisted of propiconazole (125 g ha^{-1}) 'Tilt' to the same variety of winter barley (Igri).

Herbicide experiments

In the 12 m x 50 m plot trials, a commercial mixture of ioxynil (252 g) + bromoxynil (252 g) as potassium octanoate esters + mecoprop (2016 g) ha^{-1} 'Swipe 560SCW' was used in 1984 on the winter wheat crop (cv. Avalon) whereas in 1983 winter barley (cv. Igri) was sprayed with bifenox + mecoprop (188 g + 463 g) ha^{-1} 'Ceridor'.

Deposit analysis

Deposits were measured quantitatively by fluorescence spectrophotometry utilising a method developed by Cooke & Hislop (to be published). The tracer used was Uvitex OB (Helios) incorporated in the oil formulations (2 or 2.5 g l^{-1}) and as an emulsifiable concentrate (1% w/v) added to the aqueous tank mix. Tank samples were taken at the nozzles to check the concentration of the tracer. Extraction from plant components was achieved using aromatic free hexane containing Analar acetone (5% v/v). The acetone was added in order to maintain at least 95% extraction efficiency even if the plant samples were not completely dry. For the fungicide programme 30 plants per treatment were sampled at each of the two growth stages. Each plant was analysed individually and at the early growth stage (30) subdivided into four components and at the later stage (57) divided into 5 as shown in Fig. 1.

In the 12 m boom trials it was necessary to make up large volumes in the spray tank. In these circumstances it was expedient because of cost to use the water soluble sodium salt of fluorescein for deposit analyses. Although more susceptible to photodegradation than Uvitex OB, sampling was completed within 15 minutes to minimise this effect.

Biological evaluations

In the fungicide programmes disease assessments were made for *Rhynchosporium secalis* (Oudem.) J J Davis, *Erysiphe graminis* DC *f.sp. hordei* Merat (mildew), *Drechslera teres* (Sacc.) Shoemaker (net blotch), *Puccinia hordei* Otth (brown rust) and concomitant green leaf area. In the herbicide programmes regular assessments taken in marked sample areas were done to monitor initial wilt, kill or post treatment recovery of weeds.

RESULTS AND DISCUSSION

Table 1 is a summary of drop spectra obtained from some of the atomisers assessed. Examination of these values indicates the wide spectrum of drop sizes obtained from hydraulic nozzles, the larger orifice 8003 types being potentially the most wasteful in terms of large drops produced (16%). The 110° nozzles at the 100 l ha^{-1} rate (110-015) produced the largest potentially driftable component (11%). At the other end of the volume scale was the electrodynamic (ED) method of atomisation where a high degree of control of drop size was obtainable yielding R (VMD/NMD) values close to unity. Although not shown, manufacturers claims for the spinning disc are R values approximating to 1.5 providing flow rates and disc speed are matched. The rotary cage atomisers produced a narrower spectrum than the hydraulic counterparts and therefore theoretically offer advantages. An interesting facet of this table were the values determined for the 80° nozzles in the induction charged and uncharged modes. The higher rate 8003 nozzles showed no significant differences with or without charging whereas the 8001 (70 l ha^{-1}) type gave a significant decrease in the smaller and larger drops produced. The significance of these values was demonstrated in fungicide deposits obtained on plant components, especially at the later growth stages (Table 2). Although not used in these trials the drop spectra obtained from the smallest 800067 nozzles were also assessed and exhibited a much more

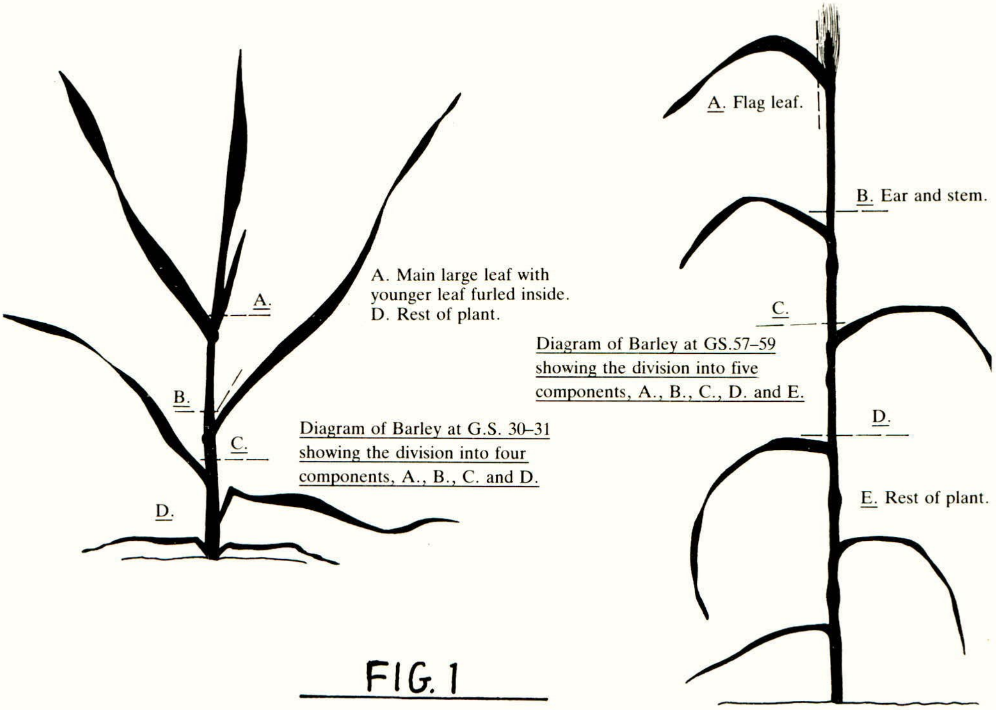

FIG. 1

Diagram of Barley at G.S. 30–31 showing the division into four components, A., B., C. and D.

Diagram of Barley at GS.57–59 showing the division into five components, A., B., C., D. and E.

dramatic effect with respect to charging; there was a 2% reduction in small drops and a small reduction in large drops. These nozzles were used in a former trial (Hislop et al. 1983) but adopting the internal charging technique developed by Marchant & Green (1982).

Fungicide deposits were measured at the two growth stages as stated previously, but in order to keep this report brief only the data for GS 57-59 are shown. Full data will be presented in a future publication. Tables 2 and 3 represent deposit values found on the two varieties of barley, Sonja and Igri. The absolute values shown may not be too informative but the associated coefficients of variation (CV) shown in brackets do express a measure of uniformity of spray deposit; the higher the value the less uniform the distribution and the more likely that some parts may be overdosed at the expense of underdosing of others. In both tables the hydraulic nozzles, especially those used for the highest volume (ca. 200 1 ha^{-1}) exhibited the lowest CV values at all levels of sampling. They also demonstrated the inherent properties of evenness of deposition and penetration due to the wide spectrum and associated momenta of the drops produced. The most wasteful however was shown by the uncharged 80°

TABLE 1

Drop spectra obtained from various atomisers measured with a Malvern 2200 particle sizer

Atomiser	VMD	NMD	R (VMD/NMD)	% Vol. <50μ	% Vol. >350μ
Hydraulic F110-015 (Kematal) 300 kPa	141	15	9.4	11	4
Hydraulic F110-03 " "	181	19	9.4	8	12
Hydraulic 80067 uncharged 300 kPa	134 }*	26 }*	5.1 }*	9 }*	0.8
Hydraulic " charged "	139 }	34 }	4.1 }	7 }	0.5
Hydraulic 8001 uncharged "	159 }*	31 }*	5.1 }*	6 }*	3 }*
Hydraulic " charged "	158 }	38 }	4.1 }	5 }	2 }
Hydraulic 8003 uncharged "	205	31	7	5	16
Hydraulic " charged "	208	31	7	5	16
Rotary Cage 90 1 ha^{-1} 3000 rpm	142	43	3	5	0.2
Rotary Cage 40 1 ha^{-1} "	152	51	3	4	0.3
Electrodynamic 2 1 ha^{-1}	75	72	1	not measured	0

* indicates significantly different at $P = 0.05$

nozzles by virtue of the coarser nature of droplets produced at the 200 1 ha^{-1} rate which was also amplified by the low value (49%) for capture (Table 2). Charging of the hydraulic nozzles at the 200 1 ha^{-1} rate compared to uncharged tended to give lower CV values and achieved greater deposition at the base of the crop with a subsequent greater spray capture. Charging at the 70 1 ha^{-1} rate produced larger deposits in the uppermost plant parts, presumably due to enhanced capture of electrostatically charged smaller drops resulting in an increased total capture (73% cf. 57%). This phenomenon was not found in the deposit analyses made at GS 30-31. However, these capture values are tentative since they are based on an estimated target tiller population of 8 x 10^{6} ha^{-1}. The correct procedure for a mass balance study would be to measure total deposits retained by the crop over a known area and those reaching the ground. The analytical techniques involved are complex especially with respect to recovery from soil, but this aspect will be examined in future studies. At the growth stage 57-59 protection of the flag leaf and ear may be a more important factor than protection of lower plant parts. The Electrodyn demonstrated its high charge to mass ratio (q/m) properties; despite air assistance, much greater deposits were found on the ears, in agreement with previous results (Hislop et al. 1983). This was also reflected in a very high mean capture value (112%) but because the CV values were large (88-240), this figure ranged from ca. 60-140%. The rotary cage at both volumes at GS 31 exhibited high CV values similar

TABLE 2

Spray deposition on barley (cv. Sonja) GS 57-59 (3 m boom)

Treatment	ng/cm^2 Uvitex on plant components A (Flag leaf)	B (Ear + Stem)	C	D	E	% Capture*
Hydraulic 100 l ha^{-1}	135	82	44	25	18	58
(F110-015)	(57)	(38)	(42)	(36)	(57)	
Hydraulic 200 l ha^{-1}	97	104	44	30	26	67
(F110-03)	(68)	(43)	(34)	(32)	(48)	
Hydraulic 70 l ha^{-1} uncharged	96	82	42	22	12	57
(8001)	(41)	(42)	(48)	(69)	(94)	
" " charged	120	124	35	17	8	73
(8001)	(45)	(59)	(51)	(76)	(101)	
Hydraulic 200 l ha^{-1} uncharged	102	68	30	23	16	49
(8003)	(81)	(39)	(41)	(46)	(40)	
" " charged	97	82	44	29	23	65
(8003)	(37)	(50)	(49)	(30)	(31)	
ED 40 kV 2 l ha^{-1}	111	474	17	6	9	112
(Air assisted)	(132)	(88)	(105)	(113)	(240)	

Deposits recovered are based on 100g Uvitex ha^{-1}. Values in brackets are coefficients of variation (CV). *Capture based on an estimated tiller population of 8 x 10^6 ha^{-1}.

TABLE 3

Spray deposition on barley (cv. Igri) GS 57-59 (12 m boom)

Treatment	ng/cm^2 fluorescein on plant components A (Flag leaf)	B (Ear + Stem)	C	D	E	% Capture*
Hydraulic 180 l ha^{-1}	90	97	48	25	24	68
(F110-03)	(53)	(32)	(38)	(55)	(66)	
Rotary Cage 40 l ha^{-1}	54	139	21	15	12	67
	(110)	(109)	(80)	(81)	(76)	
Spinning Disc 10 l ha^{-1}	37	83	17	10	11	43
	(79)	(54)	(68)	(61)	(55)	

Deposits recovered are based on 100 g fluorescein ha^{-1}. Values in brackets are coefficients of variation CV).
* Capture based on an estimated tiller population of 8 x 10^6 ha^{-1}

to those shown in Table 3 for the 40 l ha^{-1} rate and lacked the effective partitioning of spray throughout the crop canopy, shown by the hydraulic nozzles. Similarly the spinning disc suffered from the same non-uniformity and lack of penetration assumedly due to the low momenta and near mono-disperse nature of the droplets produced. It also exhibited the

TABLE 4

Mildew, green leaf area and yield recorded on winter barley (cv. Sonja)

	1984			1983	
Treatment	Mildew % (2nd leaf)	Mean* GLA %	Yield (t/ha)	Mean* GLA %	Yield (t/ha)
Hydraulic 200 l ha^{-1} (F110-03)	0.4^{a}	39^{ab}	7.9^{a}	39	6.5
Hydraulic 70 l ha^{-1} (8001) charged	0.5^{a}	39^{ab}	7.8^{a}	-	-
Hydraulic 70 l ha^{-1} (8001) uncharged	0.6^{a}	28^{abc}	7.8^{a}	-	-
Hydraulic 100 l ha^{-1} (F110-015)	0.4^{a}	39^{ab}	7.7^{a}	37	6.2
Hydraulic 200 l ha^{-1} (8003) charged	0.8^{a}	39^{ab}	7.7^{a}	-	-
Hydraulic 200 l ha^{-1} (8003) uncharged	0.9^{a}	45^{a}	7.6^{a}	-	-
Electrodynamic 2 l ha^{-1} (Air Assisted)	5.8^{b}	25^{bc}	7.6^{a}	33	6.1
Unsprayed	33^{c}	7^{d}	6.0^{b}	2	5.2

Values with the same superscript in the same column are not significantly different ($P = 0.05$)

* Mean values for flag and second leaf

least total capture (43%). At this point it may be appropriate to suggest that the pursuit of mono-dispersed droplets <u>per se</u> associated with controlled droplet application (CDA) technology may be undesirable because of the attendant lack of partitioning into a crop.

The exceptionally dry weather conditions of 1984 inhibited disease development, only mildew being of any significance. Therefore, at later growth stages, only this pathogen was recorded in detail together with the attendant green leaf area (GLA) on the flag and second leaf. Tables 4 and 5 demonstrate the excellent relationship between the levels of mildew, GLA and yields. A similar relationship was found for the 1983 trials. The most salient conclusion drawn from examination of both tables was that a high volume 110^{o} nozzle system is always the best treatment, although in terms of yield, not always statistically different from the others. This phenomenon mirrors that of the deposit CV data (Tables 2 and 3) where the wide fan (110^{o}) high volume (ca. 200 l ha^{-1}) produced the best distribution and penetration patterns. Another important deduction was that all treatments, even if disease pressure was low produced yield benefits above those of unsprayed controls, possibly from some 'phytotonic' effect. Therefore, although high volume applications are apparently the most biologically effective other factors must be considered. Cost-effectiveness is of prime importance to the grower; if input costs can be reduced by lowering volumes hence improving the logistics and timeliness and still achieve an acceptable yield gain, there remains a case for ULV/CDA appliction techniques. However, caution should be exercised because if a residual pest, disease inoculum or weed population is allowed to build up over several seasons, conditions in a subsequent year could favour a rapid development to such a degree that no pesticide or method of application will succeed. Hence, there is a pre-requisite for careful farm management.

The data shown in Table 5 include half dose treatments. Again the high volume rate (180 l ha^{-1}) is generally better than ULV/CDA methods, normally associated with dose reductions. However, it is noteworthy that in this lower disease year (1984) the half-dose spinning disc treatment was as effective as the full dose spinning disc treatment. A similar effect was noted in some of our earlier work (Hislop et al. 1983). This may be a function of concentration, where the drops also contain surfactants and additives up to 20 times greater than a conventional system, perhaps having a deleterious effect on plant development at the higher dose.

TABLE 5

Mildew, green leaf area and yield recorded on winter barley (cv. Igri) (12 m boom)

Treatment	Mildew (%) (2nd leaf)	1984 Mean** GLA(%)	Yield* (t/ha)
Conventional 180 l ha^{-1} (F110-03) Full dose	1^a	9^{6a}	7.7^a
Conventional 90 l ha^{-1} (F110-015) Full dose	2^a	93^b	7.4^{ab}
Rotary Cage 90 l ha^{-1} Full dose	1^a	89^b	7.2^{ab}
Conventional 180 l ha^{-1} (F110-03) Half dose	11^b	79^c	7.2^{ab}
Spinning disc 10 l ha^{-1} Half dose	16^{bc}	66^{de}	7.0^b
Conventional 90 l ha^{-1} (F110-015) Half dose	3^a	82^c	6.9^{bc}
Spinning disc 10 l ha^{-1} Full dose	24^c	73^{cd}	6.7^{bc}
Unsprayed	48^d	54^c	6.4^c

Values in the same column with the same superscript are not significantly different ($P = 0.05$)

* Treatments ranked according to yield, values corrected to 15% moisture.

** Mean values for flag and 2nd leaf.

Table 6 summarises deposit data and reduction of broad leaved weed species obtained from the 12 m boom delivery systems examined in 1983 and 1984. Again there is an apparent volume relationship: the 180 l ha^{-1} rates gave the best control associated with high deposit and low CV values on the targets. Similar results were also obtained with an experimental herbicide in small plot experiments sprayed with the 3 m boom fitted with electrostatic and non-electrostatic hydraulic nozzles. Another aspect of the enhanced biological effect associated with increased application volumes, are the differences found between the 90 and the 40 l ha^{-1} rates using rotary cages, especially in 1984. The spinning disc treatment in 1984 was significantly worse than both hydraulic treatments whereas in 1983 only the half dose spinning disc was inferior.

It must be emphasised that these results and conclusions are drawn from a limited 2 year study (although similar deductions were reported by Hislop *et al*. (1983). Further fundamental and field research programmes are necessary to establish a more adequate data base.

TABLE 6

Spray deposition of fluorescein on two weed species and reduction of total weed species

12 m boom trials 1984 w/wheat (cv. Avalon) 1983 w/barley (cv. Igri)

	1984			1983	
	ng/cm^2			ng/cm^2	
Treatment	Parsley	Pansy	% Reduction	Pansy	% Reduction
Hydraulic 180 l ha^{-1}	216 (27)	216 (42)	83^a	180 (27)	92^a
Rotary Cage 90 l ha^{-1}	93 (46)	82 (37)	69^{ab}	65 (110)	61^b
Hydraulic 90 l ha^{-1}	239 (37)	184 (33)	56^b	69 (45)	86^a
Spinning disc 40 l ha^{-1}	147 (85)	187 (84)	39^c	108 (97)	79^a
Spinning disc 1/2 dose 40 l ha^{-1}	-	-	-	-	64^b
Rotary cage 40 l ha^{-1}	62 (86)	56 (77)	36^c	165 (54)	58^b

Deposits based on 100g fluorescein ha^{-1}.
Values with the same superscript do not differ significantly ($P = 0.05$).

Our evidence suggests that at the present time no delivery system is more effective than the standard method of application. Some application methods can be more efficient than the standard in terms of quantity of pesticide retained on the crop, but this does not necessarily lead to enhanced performance. This lack of enhancement is probably due in part to the problem of identifying the true sites of action of some of the materials used and the qualitative aspects of resultant deposits. The efficiency of spraying has also to consider other factors such as labour inputs, farm management, timeliness, non-target deposition and possible environmental side effects. In certain situations alternative delivery systems have very real logistical advantages and where appropriate label recommendations exist, a change to lower volume spray systems, could reduce costs and not lose a significant proportion of the yield benefits.

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