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AIR-ASSISTED CROP SPRAYING: AN INTRODUCTORY REVIEW

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ABSTRACT

Forced air streams are invaluable as a method of constraining, transporting and depositing sprays for crop protection. Machinery developed for air-assisted spraying ranges from small low-powered hand-held devices for use in enclosed environments, through motorised knapsacks to large heavy duty equipment used to spray bush, vine and tree crops, and broadacre ground crops. The volume and speed of air issuing from the machines vary widely and are largely functions of the power supplied. While both the volume and velocity of air are important, it is generally agreed that for tree spraying the volume to air speed ratio should be large in order to counteract the effects of natural air movements and displace the stagnant air in the canopy. When air is used to atomise sprays, velocity is critical. Spray liquid volumes and droplet size interact strongly with air quality and target morphology: coarse sprays of high liquid volume are inappropriate for air-assisted applications.

INTRODUCTION

Artificially induced air currents are used in many diverse operations involving the application of liquid agrochemical products to crops. Although these practices are often well established and sometimes well documented, I know of no recent comprehensive review.

Terms such as 'air-blast spraying', 'mist blowing', 'concentrate spraying' and 'air-carrier sprayers' abound in the literature and often appear to be synonymous. Unfortunately, such terms can be misleading because they are poorly defined and often imply something more or less specific about the technique. For example, air-blast spraying implies that a large volume of air is employed, but sometimes the volume involved is relatively small but the velocity might be high. On the other hand, mist-blowing suggests that the spray droplets involved are small, but often this is not quantified and in some instances they could not be classified as mists. For these and other obvious reasons, I prefer in this review to refer to all of these techniques as air-assisted spraying. By so doing I am in accord with the title of this symposium, but more importantly I imply nothing specific about the techniques, except that air in some way helps the spraying process. My primary objective is to outline the ways in which spraying can be assisted by the use of artificially induced air flows in order to provide a background for the presentations which follow.

To engineers, air is a fluid and not surprisingly behaves similarly to water. To move air we have to apply pressure and this consumes energy. The moving air has to be contained, ducted and delivered. For our purposes, air is usually considered an incompressible fluid at the outlet. Unfortunately, air unlike water is not easily visible so measurements of velocity and volume are usually made indirectly (e.g. Ower & Pankhurst, 1977). Since we usually use some sort of fan to move air, readers interested in their construction, behaviour and performance should consult specific texts (e.g. Osborne, 1966). However, for most crop protectionists, adequate descriptions of the types of fans used in spraying machines and factors affecting their performance according to the 'Fan Laws' are provided by Matthews (1979). The behaviour of a stream of air issuing from most air-assisted sprayers is complicated by sprayer motion and natural air currents (see under Tree spraying) but is usually described by turbulent jet theory which has been discussed and developed recently by Brazee *et al.* (1984)b. Graphic representation of the velocity fields illustrating the rate of decay of an idealised air jet is given by Fraser (1958) and Potts (1958).

HISTORICAL INFORMATION

Before spraying of agrochemicals started a little more than a hundred years ago, the few products then available were often dusted on to crops with a current of air generated by bellows. According to Large (1940), the first simple air-assisted sprayer was probably developed in France for the application of Bordeaux mixture to vines in about 1885. This device also used bellows to produce an air stream which was directed towards the end of a gravity fed drip pipe thereby effecting some liquid atomisation and projection of the droplets towards the vines. An accessible and comprehensive history of 'concentrate spraying' up until about 1960 is given by Rose (1963) and includes many valuable photographs illustrating machinery development. Particularly innovative and advanced for its time was the 'Strawsoniser' shown at the Paris Exhibition of 1889. Advertised as being suitable for draught by animals such as horses, mules, oxen, this machine generated 'high speed' air jets via a compressor driven by the land wheels and was said to be adaptable for spraying ground or tree crops. According to Rose (1963) this machine was exported to many countries, including the USA, where much early practical development of tree sprayers was to take place, culminating in 1937 in the introduction of the first successful large 'air-blast' tree sprayer. Brann (1956) reports that the first types used a four-bladed aircraft propeller but that this was replaced by an axial flow fan in the early 1940s and that by 1945 this 'Speed Sprayer', as it was known, was in commercial use in all the main fruit growing areas of the United States. Transfer of this technology to commercial orchards in Europe was delayed by the second world war, but a high volume air-blast sprayer which became known as the 'Autoblast' was introduced in 1944. Later modifications to this machine led to early experiments in reducing spray volume rates. Kearns & Morgan (1953) stated that it was 'essential to use fans capable of producing large volumes of air of sufficient velocity to lift the foliage and thus ensure underleaf coverage with droplets, without inducing damage'. Three years later, Brann (1956) concluded his review by stating 'We cannot go on solving the problems by building larger machines with more air blast. Progress lies in the direction of more efficient application of the power we are now using through a better understanding of the factors involved in getting the toxicant from the tank to the plants.' Marshall *et al.* (1963) appear to be amongst the first workers to discuss the merits of air volume *versus* air velocity but stated that in Canada both were important and suggested values for them when spraying trees planted *c.* 9 m apart. However, it was some 10 years later before much science came to the 'art' of tree spraying (Randall, 1971) as discussed later.

The history of air-assisted spraying has not developed as a logical progression even though most of the requirements for droplet production, transport, impaction, etc. were well understood earlier (Brown, 1951; Potts, 1958; Fraser, 1958). This was because much machinery development was *ad hoc* and often preceded the development of the most suitable pesticides, or an integrated understanding of physical, chemical and biological factors involved. For example, the pulse jet was discovered in 1906, but pesticidal thermal fogs were not examined until 1940 and the 'Todd Insecticidal Fog Applicator' was not produced until 1945. The 'Swing Fog Pulse Jet Applicator' dates from about 1950 (Brown, 1951; Rose, 1963). The ground crop 'Strawsoniser' was preceded in 1945 by the seemingly sophisticated air-assisted row crop 'Agro' sprayer using air-shear nozzles designed and built in England by ICI and Ransomes, Sims & Jefferies (Anon, 1946). Although it is reported that this machine underwent considerable testing and development at the great cost of *c.* £10,000 (Holmes, 1952) little is published about it and only a small number were sold, and only now are we seeing a revival in this technology.

Other high points in the history of air-assisted spraying are noteworthy. Around 1949 the Dutch firm Keikens Dekker produced a back-mounted 'mist-blower powered by a small lightweight 2-stroke engine and machines of this type are in world-wide use today for small volume, small droplet spraying. In the same year, Edward Bals produced a small volume sprayer using a spinning disc atomiser to give control over spray drop sizes and a hand-directed head designed to provide for controlled drift of the droplets dispersed by air generated by a paddle fan driven by a small air-cooled 4-stroke engine (Rose, 1963).

TREE, BUSH AND VINE CROP SPRAYING

Tree crops - particularly apples - have been the subject of much study as regards air-assisted spraying. Over the years since about 1940, terms such as high- and low-volume spraying abound in the literature with their significance changing with the capacity of machines to handle differing volumes and the varying size of trees. For example, Potts & Garman (1950) recorded that high-volume might mean the application of *c.* 7000 l/ha by hydraulic devices to deciduous woodland, or *c.* 5000 l/ha of apples, but that with 'mist-blowers' the application might be as low as 100 l/ha. Today, citrus plantations in Spain, for example, still receive up to 9000 l/ha via hand applications, or less than 400 l/ha via air-assisted equipment (Juste *et al.*, 1990). But many apple plantations in the UK are currently being treated with only *c.* 50 l/ha. The nonsense of using volume rates per unit area of ground as a description of a treatment variable in apple orchards was highlighted by Morgan (1964) and by Hall & Reichard (1978). The latter authors pointed out that tree volume per unit area of ground might vary at a particular season by about two orders of magnitude depending upon planting distances and morphology. At some spray times, the trees are bare but at others they are covered with dense foliage.

Enthusiasm for very small volume, air-assisted spraying of trees probably originated in the USA as early as 1928 (Potts, 1958) and as a result of early work on aerial spraying. In England, the work of Moore in the late 1940s (Moore, 1958) using neat lime sulphur as an apple fungicide had a similar stimulatory effect, and encouraged the National Institute of Agricultural Engineering (NIAE) to develop in 1951 an intense programme of research on air-assisted tree spraying which lasted for some 25 years. At first this revolved around building an experimental orchard sprayer capable of atomising about 30 l/h of spray with a droplet volume median diameter of *c.* 70-90 μm, considerably smaller than those used previously (Byass *et al.*, 1960). The sprayer had centrifugal fans delivering *c.* 2 m^3/s of air at 2,800 rev/min fan speed consuming *c.* 16 kW of power, and novel air shear nozzles. Byass & Weaving (1960) reported studies of this equipment and its application to fruit spraying in comparison with applications at *c.* 800 l/ha, and concluded that subject to control of pest and diseases being satisfactory, doses deposited were similar for the two applications but that work rates were increased by *c.* 50% with the lower volume applications. In addition, cover by deposits was greater for the concentrate sprays per unit volume applied. For both volume applications there was a marked reduction in deposits at the tops of trees as the season progressed. The conclusion from orchard work in this period was that insect and mite control from the lower volume/small drop applications was often inferior to that from application at about 600 l/ha using somewhat coarser sprays from good hydraulic pressure nozzles, but that there appeared to be little or no advantage of increasing volume rates further. Mean leaf deposits were similar over a wide range of drop sizes with losses to the ground decreasing and airborne ones increasing with reduced drop size (Byass & Charlton, 1963).

Byass and colleagues at NIAE then spent some years developing equipment and techniques suitable for the study of air and spray distribution in apple trees of varying sizes which were used by Randall (1971) in classical field work as a prelude to model wind tunnel studies (Hale, 1975, 1978). In the field work the trees were planted on a 7.3 m x 7.3 m square and were *c.* 7 m high. Three single sided sprayers of 7.5 kW theoretical air power with differing characteristics, *viz.* 1.53 m^3/s at 90 m/s, 2.46 m^3/s at 68 m/s and 7.67 m^3/s at 41 m/s were examined at travel speeds of 3.2 and 6.4 km/h. The results clearly indicated the superiority of high-volume low-velocity air and suggested that ground speed depended on wind conditions and tree spacing. However, as previously indicated (Marshall *et al.*, 1963) air velocity should be sufficient to move the foliage although in contrast to the latter authors, axial flow fans were considered more suitable than centrifugal squirrel cage fans. The seemingly simple theoretical requirement of replacing the air within the trees with spray-laden air and the best way to do this is rarely stated clearly (Marshall *et al.*, 1963; Matthews, 1979) but depends greatly on tree size. To a large extent Randall's work was hampered by the short time the trees were in full leaf and by variable weather conditions. Thus, a model approach (Hale, 1975; 1978) was well justified. This used one-twelfth scale trees (full scale planting 7.3 x 7.3 m) and sprayers in a wind tunnel using wind speeds up to *c.* 16 km/h with the machines travelling at between 3.2 and 8.1 km/h into, with and across the wind. A complex series of measurements were possible under controlled conditions. Although it was not possible to scale down the spray drop sizes used, the results were generally as measured by Randall and held in all wind conditions examined. Wind effects increased rapidly as the distance from the air centre increased. It was suggested that air flow performance improved as the output is increased up to a value of about 1.7 m^3/m of forward travel after which improvements are small in relation to increase in output. Therefore, if the spraying speed was 6.4 km/h, the sprayer would need an air output of *c*. 10 m^3/s per side; this is impossible even for axial flow fans of a practical size. A compromise solution was to build a single sided sprayer with an output of 9.4 m^3/s to test the wind tunnel predictions in an orchard planted at 7.3 m x 7.3 m. The fan used was 1.2 m diameter and although orchard measurements were close to model predictions further development was not pursued as it was considered more important to adapt the results to the hedgerow type of plantation with rows planted at 4.5 m apart reducing the distance from the machine air centre to the rear of the tree to about 3.5 m (Hale, 1978). After experimentation in collaboration with Drake & Fletcher Limited, a commercial sprayer (the 'Commandair') was built in 1975 using a 1 m fan and total air output of *c*. 17 m^3/s at *c*. 21 m/s. For comparison, Marshall *et al*. (1963) had suggested air velocities of *c*. 45 m/s and volumes of *c*. 7 m^3/s for spraying trees of between 9-10 m diameter and *c*. 6-7 m tall. As a result of much detailed field experimentation they also pointed out that when smaller air speeds were used, regardless of volume, parts of the tree close to the air vents were oversprayed. Furthermore, when smaller air volumes were used the tops of mature trees were underdosed, regardless of air velocity. The importance of air vent geometry relative to the trees and travel speed (1.5-3.2 km/h) was also highlighted. One of the most practical descriptions of sprayer specifications, including details of air capacity requirements for trees of differing heights and for varying travel speeds similar to those discussed above, is given for South African orchards (apple and peach) by Hugo & Preez (1977). In the USA much similar work has been reported (Hall *et al*., 1975; Fox *et al*., 1982; Brazee *et al*., 1984a) while the effects of induced air movements from sprayers on atomisation were also measured using modern laser technology (Reichard *et al*., 1978). The same measuring technique was used by Parkin & Wyatt (1980) to demonstrate the effects of nozzle orientation relative to high speed air jets in a wind tunnel, although this topic and the general effects were well known previously (Potts, 1958).

Almost all the air-assisted tree spray research discussed so far has related to air flows diverging from sprayers using axial flow fans with the air necessarily turned through 90° to aim it at trees lateral to the sprayer. Much energy is lost when air is turned in this way and commercial machines with two axial fans angled in opposite directions with straight-through air flow have been built, but received little attention in recent years possibly because of higher costs. On the other hand, machines with cross flow fans have been developed for specific spray tasks, e.g. treating bush fruit (Sharp, 1980) and vines (Bäcker, 1983), although their potential advantages were recognised earlier. These sprayers produce a column of laterally displaced air which is easily and effectively directed at adjacent targets. Compared with axial and centrifugal fans the air flow is less turbulent, but fan efficiency is lower. Rearward spray angle is varied by rotating the vertical fan housing. Gohlich (1985) showed that a 45° angle of attack to lateral targets may be advantageous. Since these fans are often driven hydraulically, rotational speed and output are constantly variable. In one commercial unit, fans *c*. 1.5 m long x *c*. 0.3 m wide are claimed to displace *c*. 2.7 m^3/s at 30 m/s, but the fan speed quoted is ambiguous. In vine spraying upward spray drift is greatly minimised. A prototype tree sprayer using stacked cross flow fans capable of being adjusted to tree shape and rotary atomisers developed at Michigan University has given very encouraging deposit distributions (Van Ee *et al*., 1984). An alternative approach to air-assisted spraying in which air is also moulded to the contours of the tree, bush or vine with smaller air moving units driven by hydraulic or electric motors and fitted with rotary cage atomisers. These devices move only small amounts of air but the distance travelled is short and energy is not dissipated so quickly. Perhaps more importantly, they can be aimed to produce converging air streams which create turbulence in the target canopy and improve spray deposition (Furness & Val Pinczcevski, 1985; Beattie *et al.*, 1989).

Electrostatic air-assisted fruit spraying is of considerable interest because charging the spray drops can improve their capture and distribution over targets (Moser *et al.*, 1983). Commercial electrostatic sprayers have been available in some countries - particularly Australia - for at least six years, but their advantages (if any) are poorly documented. A prototype machine was developed at Long Ashton in 1984 in collaboration with Drake & Fletcher Limited, using the embedded electrode charging technique of Law (1978), and showed promise as a method of increasing spray capture and reducing spray drift. An improved version of this machine will be described later in this symposium (J. Allen).

Irrespective of the type of air-assisted sprayer used, an appreciable proportion of the applied spray cannot be accounted for as deposits (Herrington *et al.*, 1981). Applications made with 50 l/h, or less, clearly need small droplets to provide sufficient numbers, and it is obvious that hydraulic nozzles producing small numerical median diameter values are unsuitable because of in-flight evaporation and low impaction efficiencies. Rotary atomisers producing a narrower droplet size spectrum are an obvious choice for small volume spraying (Matthee & Thomas, 1974; Jones *et al.*, 1974) but they have not consistently increased deposit recoveries (Herrington *et al*,. 1981). Pest and disease control with such applications ranges from good to mediocre (Cooke *et al.*, 1976; Umpelby, 1984; Cross & Berrie, 1990). However, as in all spray applications, efficiency depends upon good management and requires continuous assessments of pest and disease incidence and flexible spray programmes (Hislop, 1987).

Tropical plantation crops often present particular problems for automatic air-assisted spraying because of unsuitable spacing/morphology, difficult terrain, elevated air temperature (exacerbating in-flight droplet evaporation) and the high capital cost of machinery. However, in such circumstances small portable air-assisted sprayers have been used with some success, e.g. in Cacao for the control of capsids (Clayphon, 1971). These sprayers are usually powered by 2-stroke engines of less than 100 cm^3 capacity. Volumes of air displaced are small - *c.* 0.1-0.3 m^3/s, but velocities relatively high - *c.* 60-80 m/s, facilitating air-shear atomisation although rotary atomisers are also used, and the equipment has the advantage of being hand-directed. Vertical throw in still air is a maximum of about 10 m but horizontal throw downwind is considerably greater. Spraying (or dusting) rubber trees in Ceylon requires air-assisted machines with a vertical throw of up to 26 m, and yet sufficiently small and light to be portable (Lloyd, 1963). Not surprisingly, it was concluded that portable sprayers have little hope of being effective, especially where there was an under-canopy. An alternative to this approach is to use fogging machines with gas jets (not strictly spraying), as discussed by Matthews (1979), and to rely on specific atmospheric conditions to retain the pesticide cloud in the tree canopy.

Rarely has air-assisted spray machinery been developed specifically for use in tropical plantation crops, although a power sprayer with about a 4-5 m high air duct for spraying down on to banana foliage is an exception.

GROUND CROP SPRAYING

Potts (1958) succinctly states that 'Applications to low-growing vegetation require different apparatus and application techniques than is required for trees. Good distribution and deposition from top to bottom of plant and on the undersides of the leaves is of utmost importance. This necessitates an air blast and fine atomisation for best penetration and distribution.'

The necessity for using air-assistance universally in ground crop spraying is arguable, but it is obvious that if volume rates are reduced, smaller spray droplets than currently used are desirable and the fate of these has to be controlled. As a bonus, we hope for better distribution of pesticides, the opportunity for reducing dose rates and improved logistics possibly associated with more spray days and better timing of applications.

As indicated earlier, air-assisted ground crop spraying is not as novel as many would believe. However, much of the equipment described for early work in North America (Potts, 1958) could constitute an environmental hazard since distances from the air outlets to targets were often considerable.

Perhaps the most elegant method for producing air-assistance to sprays, without the use of fans or other power consuming machinery, is the use of an air foil boom to improve deposition and reduce spray drift (Göhlich, 1979, 1985). However, the only machinery I know of to use this concept is the 'windproof' shielded sprayer made in Canada.

The Agro sprayer of *c.* 1945 (see Historical Section) used fan-generated air ducted in a hollow boom and delivered close above and within crops from air-shear nozzles. Although the biological results were encouraging the equipment was considered too expensive for commercial production (D.A. Harris, Personal Communication). But photographs indicate a striking similarity between it and the Danfoil sprayer due to be discussed at this symposium and which is a very close relative of the American 'Sprafoil' machine (Anon., 1984). The main features of the 'Sprafoil' are a centrifugal fan delivering air through a hollow tapered boom to 69 nozzles each spaced at 20 cm. Air velocity at each nozzle is *c.* 67 m/s effecting atomisation of metered liquid flow across an airfoil distributor. Total fan output was *c.* 9 m^3/s: 13.5 kW was required to power the fan and pump. Compared to overlapping flat fan nozzles, spray distributions were poor and atomisation was judged unsatisfactory at application rates above about 120 l/h at 9.7 km/h. However, as a reduced volume sprayer it was as effective in weed control as a standard (non-air assisted) sprayer and in contrast to the latter gave some underleaf spray deposition when there was no wind. Spray drift was not measured.

Air-shear atomisation was also a feature of experimental high clearance machines examined for spraying cotton in Israel (Zucker & Zamir, 1964). A centrifugal fan delivered air via a hollow boom to nozzle outlets at *c.* 1 m spacing at a rate of *c.* 0.1 m^3/s and with an initial velocity of

88 m/s. In comparison to the standard equipment of the time using cumbersome drop legs, the air-assisted equipment performed well at reduced volume rates even though the spray was relatively coarse (VMD = 228 μm). A very low-volume (*c*. 1 l/ha) experimental air-assisted electrostatic spray system using ICI's 'Electrodyn' atomisers producing small highly charged controlled drop sizes showed considerable promise for spraying cereal crops (Hislop *et al*., 1983). Air-assistance produced usefully modified patterns of spray deposition, but this exciting development was not pursued for commercial reasons. Other electrostatic air-assisted ground crop sprayers have produced large improvements in the efficiency of pesticide deposition but adoption of these technologies has been very slow (Hislop, 1988).

Commercial air-assisted sprayers available in Europe now are the 'Degania Sleeve Boom' and the 'Hardi Twin' machines, both of which use axial flow fans and inflatable bags to duct air along the length of the boom. Since these sprayers will be discussed in detail by following contributors, only a few comments are included here. The Degania sprayer was developed in Israel as a small volume-small droplet applicator and thus uses hollow cone nozzles. Air issues from circular 4 cm diameter outlets at 8 cm centres with a mean velocity of 31 m/s with a p.t.o. velocity of 540 rev/min and a fan blade angle of 40°. Air velocity 30 cm below the outlets had a mean value of *c*. 10 m/s (Miller, 1987). In contrast, the Hardi machine has a long-slot air orifice suitable for use with flat fan nozzles. Both slot and nozzle angles can be varied 30° either side of vertical. Field experiments with the Degania were done in 1987 and 1988 (Cooke *et al*., 1990) with some encouraging results, but it was concluded that while air-assistance can reduce drift and improve spray deposition, matching air-flow and equipment parameters to crop morphology for optimum performance was difficult. The Hardi machine also reduces drift and might also improve deposit distributions (Taylor & Anderson, 1989). Further work with both machines is currently in progress sponsored by the UK Home-Grown Cereals Authority. Fundamental studies are also currently in progress at Long Ashton and the AFRC Institute of Engineering Research.

Flexible air ducts which can be adjusted to suit row crop morphologies are a feature of several sprayers and when properly adjusted can improve spray deposition, but details of air volume/velocity requirements are largely lacking. Attempts to use small boom-mounted rotary cage devices (see Tree spraying) for cereal spraying were discouraging (Cooke *et al*., 1986) although they may be more effective in vegetable and small fruit row crops (Bode, 1988). Small air volume assistance (*c*. 0.05 m^3/s) of very fine sprays, with or without electrostatic charging has also been used in glasshouse applications and has some merit over more conventional application techniques (Sopp & Palmer, 1990).

GENERAL COMMENT

The use of air to constrain, direct and impact sprays on targets is common practice in many fruit crops, and is invaluable in situations where the same spray droplet spectrum would not behave similarly without assistance. Since forced air currents are particularly suitable for transporting smaller spray droplets (*c*. 40 μm to *c*. 150 μm) the use of this type of spectrum has led to economies in spray volumes, improvements in retention on targets and reductions in waste. The use of atomisers which minimise the range of droplet sizes produced is logical but has to be suitable for the task. However, it is imperative that air-assisted sprays are matched to target morphologies. For example, some orchard sprayers used today are based on specifications derived many years earlier. It is not uncommon to see these machines treating hedgerow plantings with spray issuing over a 180° arc so that, despite advice to the contrary, some is pushed wastefully and dangerously towards the sky.

To a considerable degree, many air-assisted sprayers have been developed on the basis of experience, intuition and trial and error. Some prototypes never reached maturity for reasons which had little to do with overall performance. Compromises between design features and specifications, power requirements, cost and ease of use are common. Inevitably some equipment meets requirements better than others of a similar type. The rational scientific development of equipment is laudable, but expensive and often protracted. Great care is necessary to ensure that objectives are clearly defined with regard to proposed usage. The hope that air-assisted ground crop spraying will improve efficiency is based on sound logic, but whether or not commercial machinery is suitable remains to be seen. It would be sad indeed if we only used the air so expensively moved to control drift which we made worse by using finer sprays! Manufacturers and researchers have to avoid 're-inventing the wheel', while understanding that problems remain to be solved, particularly in tropical countries. Unfortunately, the costs of research and development relative to market expectations are often unfavourable. In some instances it will be preferable to modify the morphology and plantings of larger crops/plants rather than try to develop sprayers to suit existing conditions.

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REFERENCES

Anon. (1946) *Farm Implement and Machinery Review* May 1st, 61-62.

Anon. (1984) Sprafoil model PT4583 field sprayer. *Evaluation Report*, **350**. Prairie Agricultural Machinery Institute, 10 pp.

Bäcker, G. (1983) Cross-flow fans for vineyard spraying. *Landtechnik*, **38**, 159-162.

Beattie, G.A.C.; Broadbent, P.; Baker, H.; Gollnow, B.; Kaldor, C.J. (1989) Comparison of conventional medium to high-volume and high-volume sprayers with a low-volume sprayer for the control of Black Spot, *Guignardia citricarpa* Keily, on Valencia Orange. *Plant Protection Quarterly*, **4**, 146-147.

Bode, L.E. (1988) Air-assist, air-foil and air-curtain sprayers. *Weed Technology*, **2**, 88-93.

Brazee, R.D.; Fox, R.D.; Reichard, D.L. (1984a) Theory of air-sprayer fan deflection by crosswind flow. *Ohio State University Special Circular*, **110**, 47 pp.

Brazee, R.D.; Fox, R.D.; Reichard, D.L.; Hall, F.R. (1984b) Mathematical theory of the Air-Sprayer Turbulent Fan Jet. *Special Circular*, **109**. Ohio State University, Ohio Agricultural Research and Development Center, USA.

Brann, J.L. (1956) Apparatus for application of insecticides. *Annual Review of Entomology*, **1**, 241-260.

Brown, A.W.A. (1951) Equipment developed for the application of insecticides. *Insect Control by Chemicals*, 337-466. New York, John Wiley.

Byass, J.B.; Charlton, G.K. (1963) The effect of spray concentration on distribution of chemical and the resultant pest and disease control in dessert apple orchards. *Journal of Agricultural Engineering Research*, **8**, 277-286.

Byass, J.B.; Weaving, G.S. (1960) A low-pressure air-blast nozzle and its application to fruit spraying. II. Application factors in the use of concentrated fruit tree sprays. *Journal of Agricultural Engineering Research*, **5**, 179-199.

Byass, J.B.; Weaving, G.S.; Charlton, G.K. (1960) A low-pressure air-blast nozzle and its application to fruit spraying. I. Development of the equipment. *Journal of Agricultural Engineering Research*, **5**, 94-108.

Clayphon, J.E. (1971) Comparison trials of various motorised knapsack mist blowers at the Cocoa Research Institute of Ghana. *Pest Articles and News Summaries (PANS)*, **17**, 209-225.

Cooke, B.K.; Herrington, P.J.; Jones, K.J.; Morgan, N.M. (1976) Pest and disease control with low doses of pesticides in low and ultra low volumes applied to intensive apple trees. *Pesticide Science*, **7**, 30-34.

Cooke, B.K.; Hislop, E.C.; Herrington, P.J.; Western, N.M.; Jones, K.G.; Woodley, S.E.; Chapple, A.C. (1986) Physical, chemical and biological appraisal of alternative spray techniques in cereals. *Crop Protection*, **5**, 155-164.

Cooke, B.K.; Hislop, E.C.; Herrington, P.J.; Western, N.M.; Humpherson-Jones, F. (1990) Air-assisted spraying of arable crops, in relation to deposition, drift and pesticide performance. *Crop Protection*, **9**, 303-311.

Cross, J.V.; Berrie, A.M. (1990) Efficacy of reduced volume and reduced dose rate spray programmes in apple orchards. *Crop Protection*, **9**, 207-217.

Fox, R.D.; Reichard, D.L.; Brazee, R.D. (1982) A model study of the wind on air sprayer jets. *Ohio State University Research Circular*, **272**, 25-28.

Fraser, R.P. (1958) The fluid kinetics of application of pesticidal chemicals. *Advanced Pest Control Research*, R.L. Metcalfe (Ed.), Vol. **11**, New York: Interscience, 1-106.

Furness, G.D.; Val Pinczewski, W. (1985) A comparison of the spray distribution obtained from sprayers with converging and diverging airjets with low volume air assisted spraying on citrus and grapevines. *Journal of Agricultural Engineering Research*, **32**, 291-310.

Göhlich, H. (1979) A contribution to the demands of reduced application rates and reduced drift. *Proceedings, British Crop Protection Conference - Pest and Diseases*, **3**, 767-775.

Göhlich, H. (1985) Deposition and penetration of sprays. *Application and Biology: Monograph No. 28*, E.S.E. Southcombe (Ed.), Croydon: British Crop Protection Council Publications, 173-182.

Hale, O.D. (1975) Development of a wind tunnel model technique for orchard spray application research. *Journal of Agricultural Engineering Research*, **20**, 303-317.

Hale, O.D. (1978) Performance of air jets in relation to orchard sprayers. *Journal of Agricultural Engineering Research*, **23**, 1-16.

Hall, F.R.; Forsythe, H.Y.; Jones, M.B.; Reichard, D.L.; Fox, R.D. (1975) Comparison of orchard sprayers for insect and disease control on apples, 1966-1969. *Ohio State University Research Bulletin 1078*, 22 pp.

Hall, F.R.; Reichard, D.L. (1978) Keeping pesticide application on target. *Fruit Grower*, June, 21-23.

Herrington, P.J.; Mapother, H.R.; Stringer, A. (1981) Spray retention and distribution on apple trees. *Pesticide Science*, **12**, 515-520.

Hislop, E.C. (1987) Requirements for effective and efficient pesticide application. In: *Rational Pesticide Use*, K.J. Brent and R.K. Atkin (Eds), Cambridge: Cambridge University Press, 53-71.

Hislop, E.C. (1988) Electrostatic ground-rig spraying: an overview. *Weed Technology*, **2**, 94-105.

Hislop, E.C.; Cooke, B.K.; Harman, J.M.P. (1983) Deposition and biological efficacy of a fungicide applied in charged and uncharged sprays in cereal crops. *Crop Protection*, **2**, 305-316.

Holmes, E. (1952) Factors limiting crop protection progress. International Conference: *Some Crop Protection Problems in World Agriculture*, 1951. London: Plant Protection Limited, 85-89.

Hugo, F.J.C.; Du Preez, N. (1977) Orchard sprayers. *The Deciduous Fruit Grower*, **27**, 410-423.

Jones, K.G.; Morgan, N.G.; Russell, J.H. (1974) Experimental spraying equipment for ULV application in top fruit. *Pesticide Application by ULV Methods. Monograph No. 11, British Crop Protection Council*, 143-151.

Juste, F.; Sanchez, S.; Ibanez, R.; Val, L.; Garcia, C. (1990) Measurement of spray deposition and efficiency of pesticide application in citrus orchards. *Journal of Agricultural Engineering Research*, **46**, 187-196.

Kearns, H.G.H.; Morgan, N.G. (1953) Fifty years of fruit spraying methods and machinery. *Science and Fruit*, T. Wallace and R.W. March (Eds), Bristol: J.W. Arrowsmith, 265-275.

Large, E.C. (1940) *The Advance of the Fungi*, London: Jonathan Cape, 488 pp.

Law, S.E. (1978) Embedded-electrode electrostatic-induction spray-charging nozzle: theoretical and engineering design. *Transactions of the American Society of Agriucltural Engineers*, **21**, 1096-1104.

Lloyd, J.H. (1963) Problems of applying sprays and dusts to mature *Havea* rubber in Ceylon. *Journal of Agricultural Engineering Research*, **8**, 240-251.

Marshall, J.; McMechan, A.D.; Williams, K. (1963) Low-volume air-blast spraying in British Colombia orchards 1957-1962. *Canada Department of Agriculture, Publication 1191*, pp. 18.

Matthee, F.N.; Thomas, A.C. (1974) Low and ultra-low volume spraying of deciduous fruits. *The Deciduous Fruit Grower*, March 1974, 74-79.

Matthews, G.A. (1979) *Pesticide Application Methods*, London and New York: Longman, Ch. 8, 158-181.

Miller, P.C.H. (1987) An air-assisted ground crop sprayer - measurements of the air flow distribution. *AFRC Institute of Engineering Research, Divisional Note 1417*, 19 pp.

Moore, M.H. (1958) Concentrate spraying - fungicidal aspects. *SCI Monograph No. 2: Spraying Techniques in Agriculture*. The Comparison of High- and Low-Volume Spraying Techniques on Fruit and Ground Crops. London: Society of Chemcial Industry, 3-14.

Morgan, N.G. (1964) Gallons per acre of sprayed area. *World Crops*, June, 64-65.

Moser, E.; Schmidt, K.; Metz, N. (1983) Elektrostatische auflandung von spritzflussigkeiten fur den Chemischen Pflanzenschutz im Obstbau. *Erwerbsobstbau*, **9**, 220-228.

Osborne, W.C. (1966) *Fans*. Oxford: Pergamon Press.

Ower, E.; Pankhurst, R.C. (1977) *The Measurement of Air Flow*, 5th Edn. Oxford: Pergamon Press.

Parkin, C.S.; Wyatt, J.C. (1980) The measurement of drop spectra in agricultural sprays using a particle measuring system's optical array spectrometer. In: *Spraying Systems for the 1980s*, J.O. Walker (Ed.), Monograph no. 24, British Crop Protection Council, 241-249.

Potts, S.F. (1958) *Concentrated Spray Equipment, Mixtures and Application Methods*, Caldwell, New Jersey: Dorland Books, 598 pp.

Potts, S.F.; Garman, P. (1950) Concentrate sprays for application by mist blowers for control of forest, shade and fruit tree pests. *Circular 177, Connecticut Agricultural Experiment Station*, 19 pp.

Randall, J.M. (1971) The relationship between air volume and pressure on spray distribution in fruit trees. *Journal of Agricultural Engineering Research*, **16**, 1-31.

Reichard, D.L.; Hall, F.R; Retzer, H.J. (1978) Distributions of droplet sizes delivered by orchard air sprayers. *Journal of Economic Entomology*, **71**, 53-57.

Rose, G.R. (1963) *Crop Protection*. London: Leonard Hill (Books) Ltd, Second Edition.

Sharp, R. (1980) The cross-flow concept - how it was developed. *The Grower*, June 5th, 27-28.

Sopp, P.I.; Palmer, A. (1990) Deposition patterns and biological effectiveness of spray deposits on pot plants applied by the Ulva fan and three prototype electrostatic sprayers. *Crop Protection*, **9**, 295-302.

Taylor, W.A.; Anderson, P.G. (1989) The use of air assistance in a field crop sprayer to reduce drift and modify drop trajectories. *Brighton Crop Protection Conference - Weeds*, **2**, 631-639.

Umpelby, R.A. (1984) Pest and disease control with medium and reduced volume spraying of apples, Luddington 1981-1984. *British Crop protection Conference - Pests and Diseases 1984*, **3**, 1075-1082.

Van Ee, G.R.; Ledebuhr, R.L.; Potter, H.S. (1984) Development of a CDA/air carrier sprayer. *Paper No. 84-1507, American Society of Agricultural Engineers, New orleans, December 1984*, 8 pp.

Zucker, A.; Zamir, N. (1964) Air carrier sprayers for cotton. *Journal of Agricultural Engineering Research*, **9**, 188-193.

PATTERNATION OF SPRAY MASS FLUX FROM AXIAL FAN AIRBLAST SPRAYERS IN THE ORCHARD

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ABSTRACT

As part of a larger study by ADAS and AFRC to determine the fate of orchard sprays and reduce environmental and operator contamination due to spray drift from orchard sprayers, 23 experiments measuring spray deposits on test tube brush artificial targets were done to estimate and patternate spray mass flux from an axial fan airblast sprayer in a modern intensive Bramley orchard (tree height = 2.0 m) at Brogdale Experimental Horticulture Station, Faversham, Kent, in summer and autumn 1989. Three standard application methods, viz 500 l/ha using large orifice HC nozzles directed to the tree target, 120 l/ha using small orifice HC nozzles similarly positioned, and 50 l/ha using Micron X1 spinning disc nozzles positioned to generate a 'full arc' of spray as is done in commercial practice were investigated, as well as adjustments to nozzle position and reductions in rotational speed of the air fan.

The three standard application methods chosen all generated large amounts of spray at heights greater than 2.0 m, above the top of the tree target, even though for the 500 l/ha and the 120 l/ha methods the nozzles were apparently directed at the tree target. Such emissions are likely to produce high levels of spray drift in unfavourable wind conditions. The 50 l/ha full arc spraying method was worse than the other two spraying methods in this respect. For all three spraying methods the uppermost nozzles generated the bulk of the spray above 2.0 m. Careful positioning of the spinning disc nozzles significantly improved the pattern of spray flux from the 50 l/ha application method. Reducing the rotational speed of the fan by 40% gave a spray plume better suited to the tree target. A general conclusion of the work is that axial fan air-assisted sprayers are poorly suited to modern intensive orchards.

INTRODUCTION

Axial fan, radial flow air blast sprayers are used almost exclusively in the UK for tree and bush fruit spraying. They were designed many years ago for spraying large, densely foliated, trees often with an overhanging canopy (Byass and Carlton, 1965; Randall, 1971). However, more recently more intensive orchards have generally been planted commercially with much smaller (less than 2 m tall), more closely spaced trees. The bulk of commercial orchards are still sprayed with conventional medium volume rates (*circa* 200-500 l/ha) using large orifice hollow cone hydraulic nozzles, but an increasing portion are sprayed at lower volumes (100-150 l/ha) using small orifice hydraulic nozzles or at very low volumes (50 l/ha) using Micron X1 spinning disc nozzles (Cross, 1988).

The work reported here is a small part of a larger collaborative study being undertaken by ADAS and the AFRC to measure and mathematically model the fate of sprayers from orchard sprayers in different meteorological conditions. Theoretical considerations (Walklate, 1991) indicate that the height and droplet size distributions of the spray aerosol generated by sprayers at source determines their efficiency and spray drift potential.

The experiments reported here were done to establish a simple and rapid method for patternating spray mass flux emissions from orchard sprayers in the field and examine those generated by typical commercial application methods in current widespread use.

METHODS

A total of 23 experiments measuring spray mass flux patterns generated by different spray application methods were done in an apple orchard (cv Bramleys seedling, 4.5 x 3.0 m plant spacing on dwarfing M9 rootstocks, tree height = 2.0 m) at Brogdale Experimental Horticulture Station in summer and autumn 1989.

The same model of axial fan orchard air-blast sprayer, the Commandair (first model, non-enhanced), was used throughout. Treatments were different spray aerosols (ie. methods of spraying) comprising different volume rates, spray qualities and directions of emission, produced by different nozzles mounted in different positions on the sprayer, as shown in table 1. The first 11 experiments compared the standard Medium Volume (MV), Low Volume (LV) and Very Low Volume (VLV) sprayer configurations, experiments 12 to 18 the effects of the nozzles on the lower half of the spray boom only (see table 1), and experiments 19 to 23 the effects of reducing air fan rotational speed with the LV and MV standard configuration.

Table 1. Application methods used as treatments

Treatment	Volume rate	Nozzle make	Pressure (bar)	VMD (microns)	Relative Span	No. of nozzles
MV	491	D5-25	6.8	250	0.9	14
LV	107	TX4	6.8	150	0.7	14
VLV	47.6	Micron X1	-	90	0.7	8

Note: For the MV and LV treatments, nozzles were fixed in positions 4,5,6,7,8,9, and 10 to direct the spray at the tree target, attachment points counting from the bottom (No.1) to the top (No.12). Nozzles in positions 8,9,and 10 were switched off in experiments 12-18. For the VLV treatment, nozzles were fixed in positions 2,5,8 and 11 to form a full radial arc of spray. Those in positions 8 and 11 were switched off in experiments 12-18.

The water soluble visible dyestuffs Lissamine Green and Orange G were used as tracers throughout. Eight passes were made with each application method down the full length of the same orchard alley. Twelve (experiments 1-11) or six (experiments 12-23) 4.0 m tall vertical masts each with nine nylon-fibre test tube brushes fixed at

0.5 m intervals from 0 to 4.0 m in height were used for sampling the spray flux. Three replicate masts were placed immediately between the passing sprayer and the first target row of trees, three immediately behind the same trees. This was done on both sides of the alley in experiments 1-11 (hence 12 masts), but only on the downwind side for the remaining experiments. The test tube brushes used had bristles which formed a rough cylinder 60 mm long and 28 mm in diameter. The surface area of each brush was approximately 18.5 cm^2. They were chosen because previous work showed they had a high capture efficiency for spray drops of a wide range of sizes. The deposits of dye on the brushes were extracted in 15 ml of water and their optical density at the absorbance peak for each dye determined with a scanning spectrophotometer. Comparison with standards allowed the concentration and hence the amounts of each dye to be accurately determined. The percentage of the spray emitted from the applicator deposited per cm^2 of brush bristle surface was then calculated, and analysis of variance done.

RESULTS

The height distributions of spray deposits on the test tube brush artificial targets, expressed as percentages of emission from the applicators, are shown in the histogrammes in figures 1-4. In figures 1 and 2 measurements at 1.0 m intervals only are shown for clarity.

DISCUSSION

The deposits on the artificial targets may be regarded as measures of relative spray mass flux. Sprayer efficiency is likely to be optimal when the spray flux directed towards the tree target is maximised. The vertical profile of spray emitted should be matched to the tree canopy width and density, so that the largest amounts of spray are targeted to the widest, densest part of the tree. The tree itself may be regarded as a filter, so maximisation of the difference between deposits on targets in the 'in front' and 'behind' tree positions is desirable. Minimising spray drift potential is likely to be best achieved by minimising spray emission above the top of the trees, ie. at heights greater than 2.0 m in the Bramley orchard at Brogdale Experimental Horticulture Station where this work was done.

The results (figure 1) show that the three standard application methods all generate large amounts of spray at heights greater than 2.0 m, even in the case of the standard MV and LV spraying methods, where nozzles were positioned on the spray boom to best target the trees being sprayed. The gradual attenuation of deposits with increasing height up to 4.0 m indicate that the spray plume is considerably taller than 4.0 m, and that much taller sampling masts would be necessary to sample the whole plume. The VLV full arc spraying method appeared significantly worse than the LV and MV methods in this respect.

In the experimental orchard, maximum canopy width and density occurred at a height of about 1.0 m. The relative proportions of spray flux entering and emerging from the target tree at this height are similar for the three standard methods (figure 2).

The results also clearly show that the uppermost nozzles on the spray boom generate the bulk of the spray above 2.0 m, and that careful positioning of the spinning disc nozzles, so that they are directed to the tree target, significantly improves the performance of the ULV application method (figure 3).

Reduction in the rotational speed of the air fan was done only with the MV and LV spraying methods, but it clearly showed that reducing fan speed by 40% gave a spray plume better suited to the tree target (figure 4). The extreme of switching off the fan altogether illustrates the importance of air assistance in aiding spray penetration in apple orchards.

A general conclusion of this work is that axial fan air assisted sprayers are poorly suited to modern intensive orchards where tree height does not normally exceed 2.0 m. They were designed originally for much larger, taller trees with an overhanging canopy structure. The spray aerosol they generate is too large and poorly directed.

However, they remain most suitable for fruit farms where there is a range of types of orchard plantings, because of their inherent flexibility and simplicity, and hence their low cost. For modern intensive orchards considerable improvements in sprayer efficiency will be achieved by more accurate targeting of the spray aerosol. Such machines will be the fourth generation of orchard sprayers.

REFERENCES

Byass, J.B. and Carlton, G.K. (1965) Spraying techniques for orchards of standard trees. J. Agric. Engng. Res., 10, 60-69.

Cross, J.V. (1988) New trends in orchard spraying. Bulletin OEPP/EPPO, 18, 587-594.

Randall, J.M. (1971) The relationship between air volume and pressure on spray distribution in fruit trees. J. agric. Engng. Res., 16, 1-31.

Walklate, P.J. (1991). A simulation study of pesticide drift from an air-assisted orchard sprayer. In these Proceedings.

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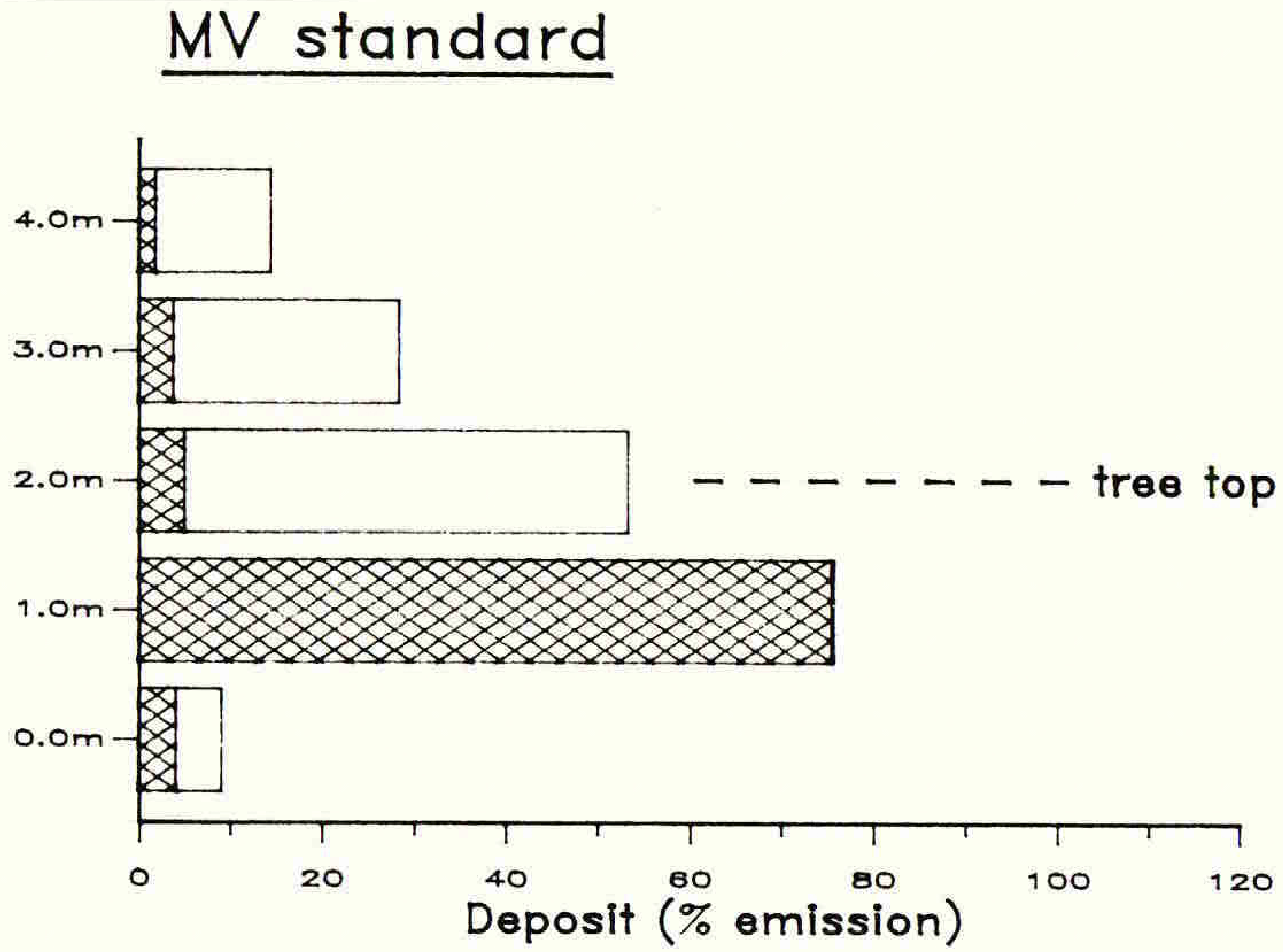
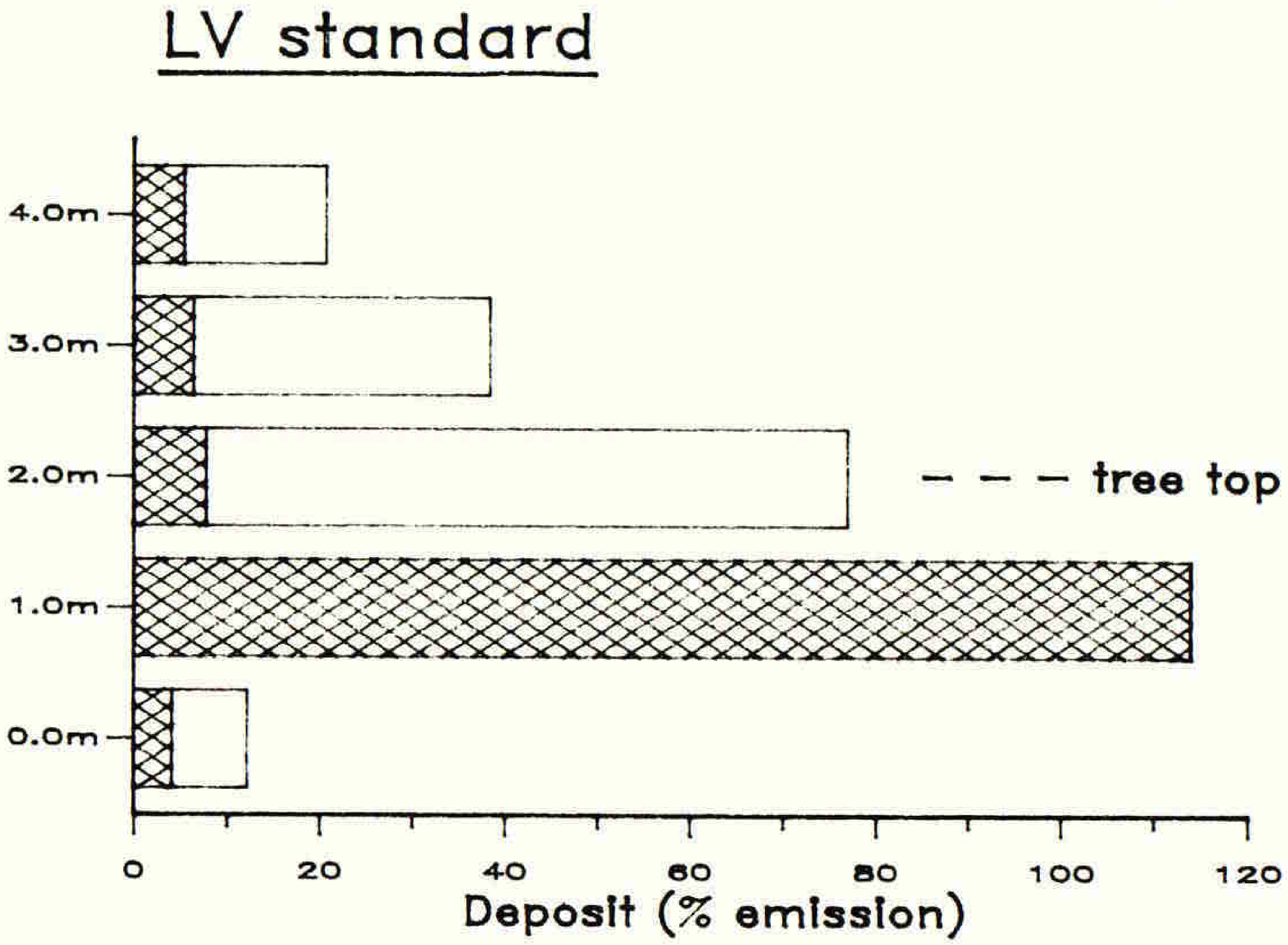




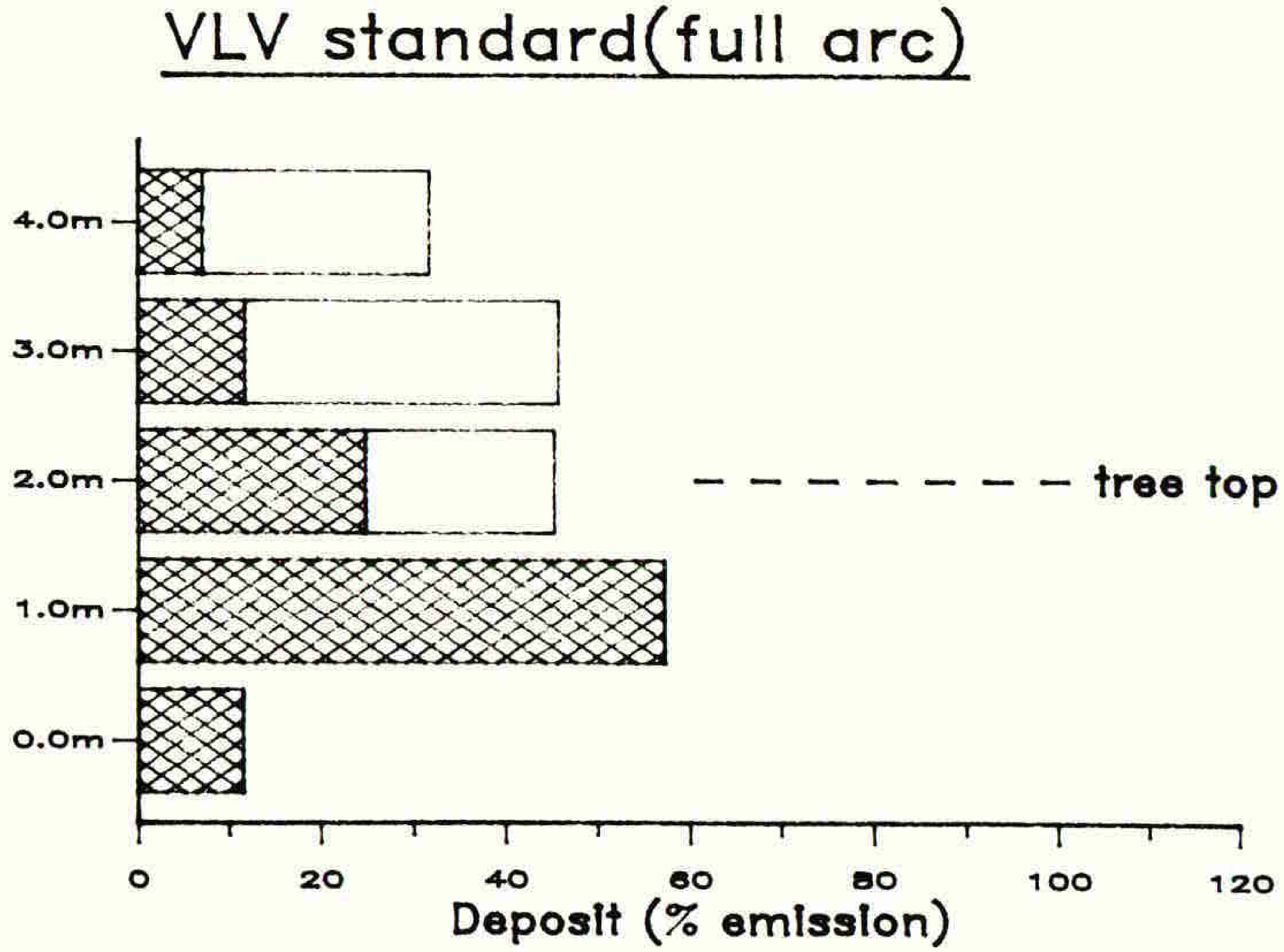


Figure 1. Vertical profiles of spray deposits on artificial targets placed between the sprayer and the tree expressed as percentages of spray emission in experiments 1–11. Hatched areas are the portion contributed by nozzles on the lower half of the spray boom as estimated in experiments 12–18.

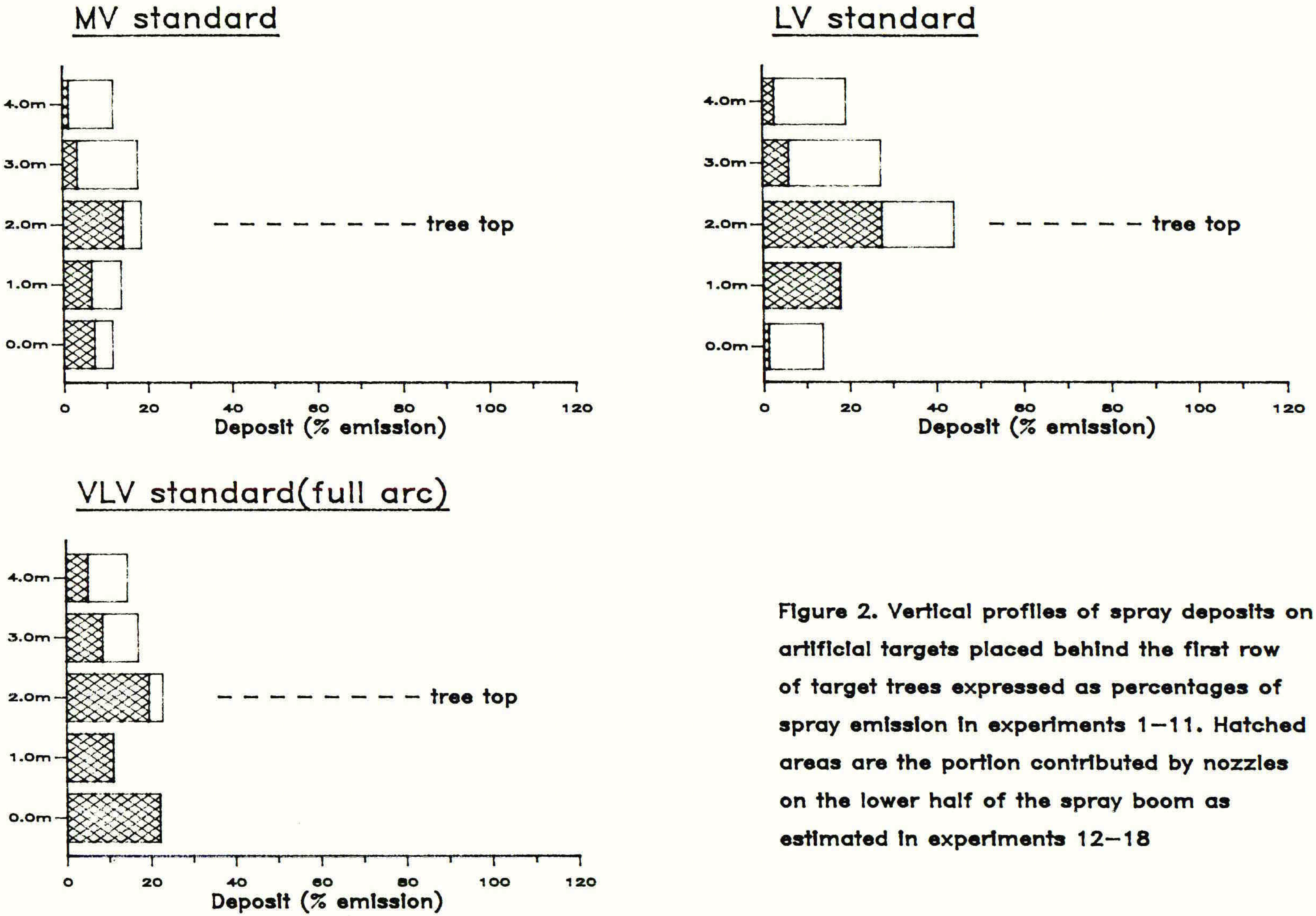


Figure 2. Vertical profiles of spray deposits on artificial targets placed behind the first row of target trees expressed as percentages of spray emission in experiments 1–11. Hatched areas are the portion contributed by nozzles on the lower half of the spray boom as estimated in experiments 12–18

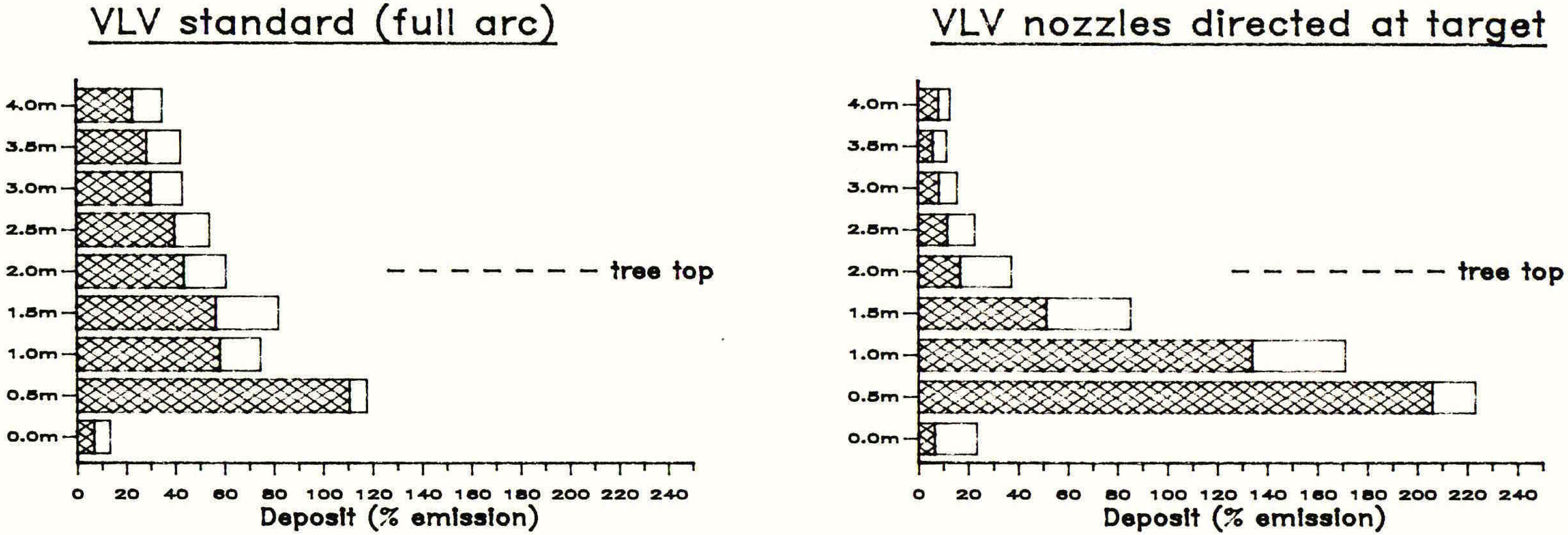
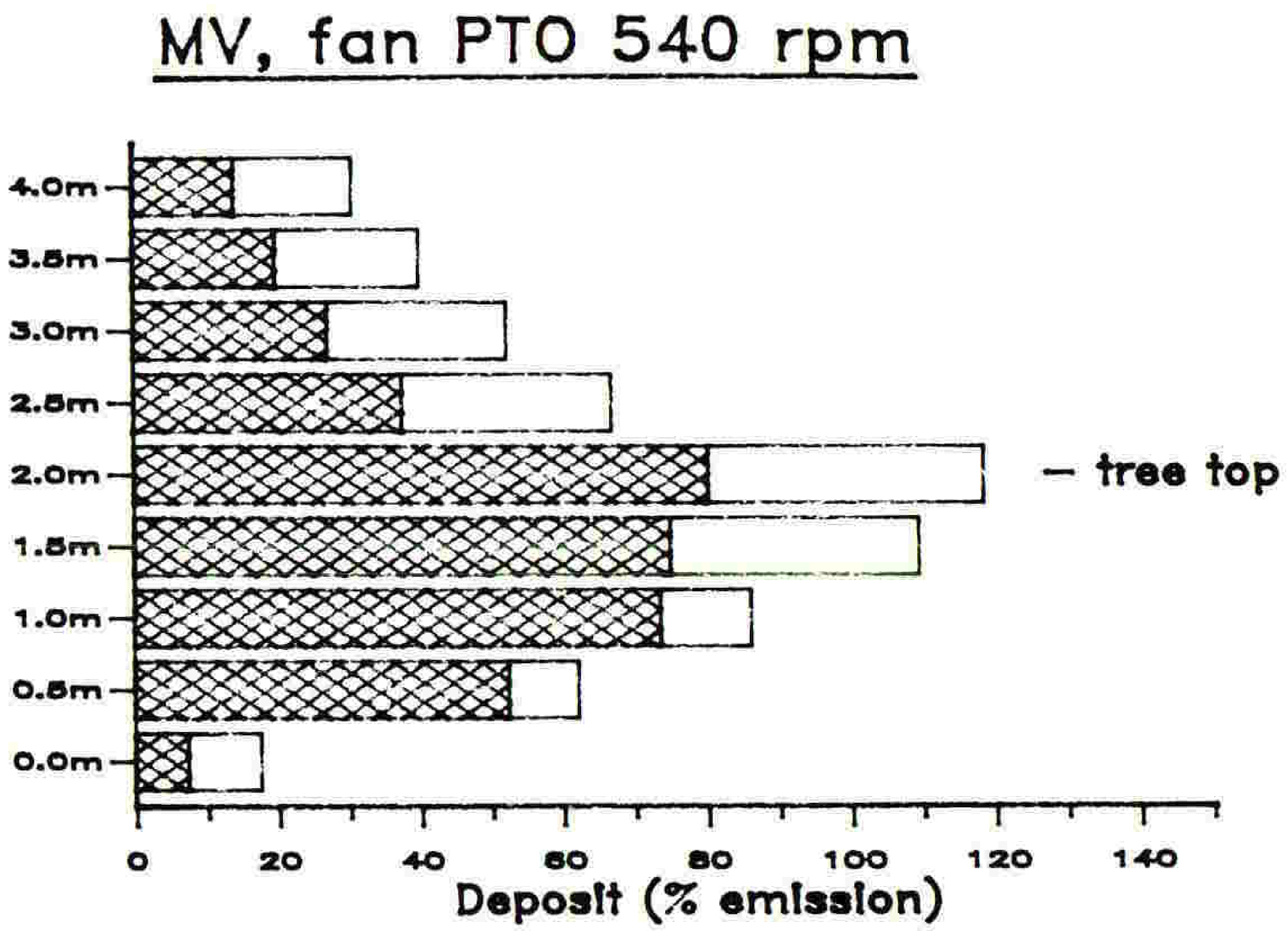
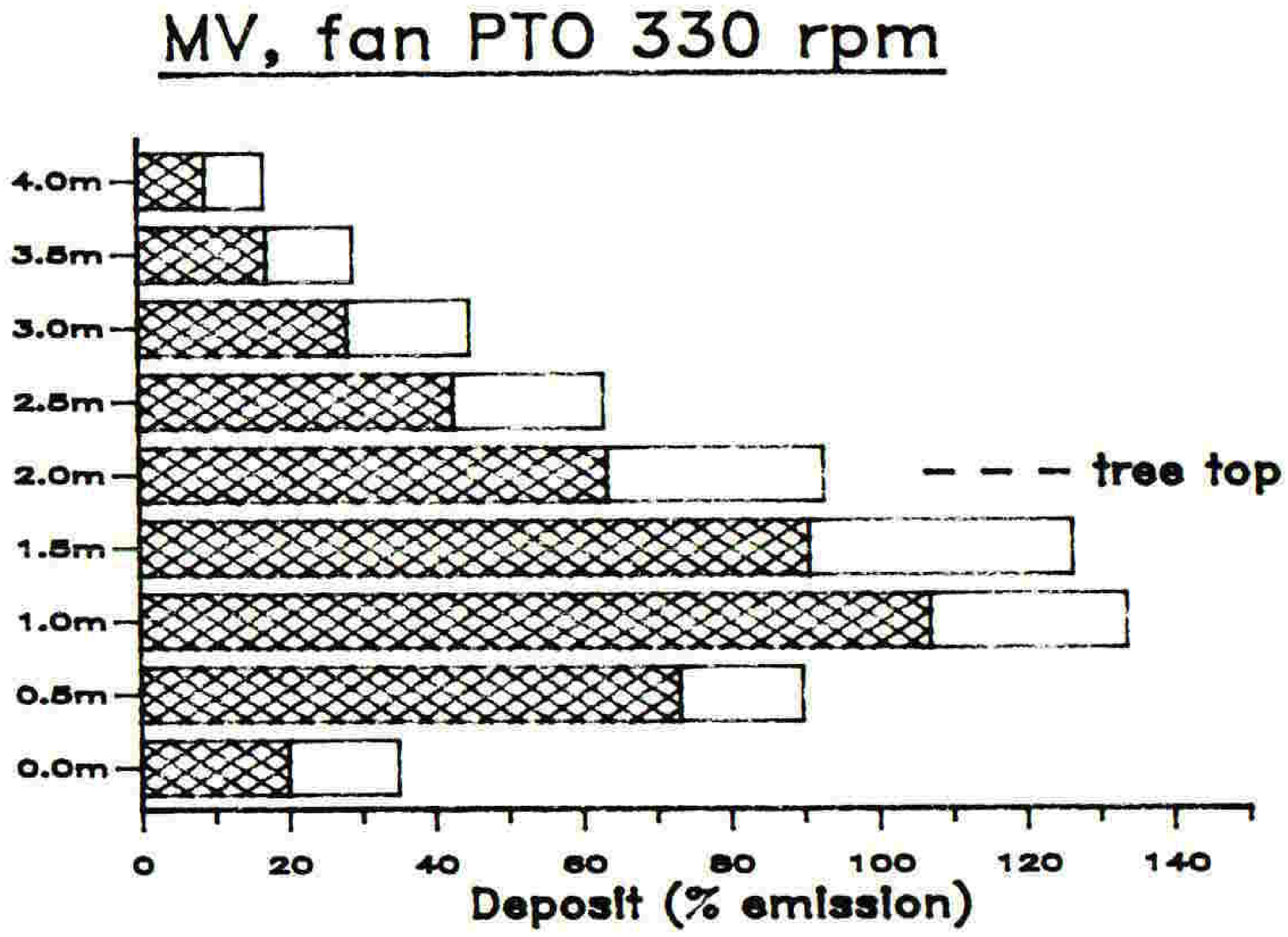


Figure 3. Vertical profiles of spray deposits on artificial targets in experiments 12–14. Hatched bars are for targets between the sprayer and the tree, clear bars are for targets behind the tree.





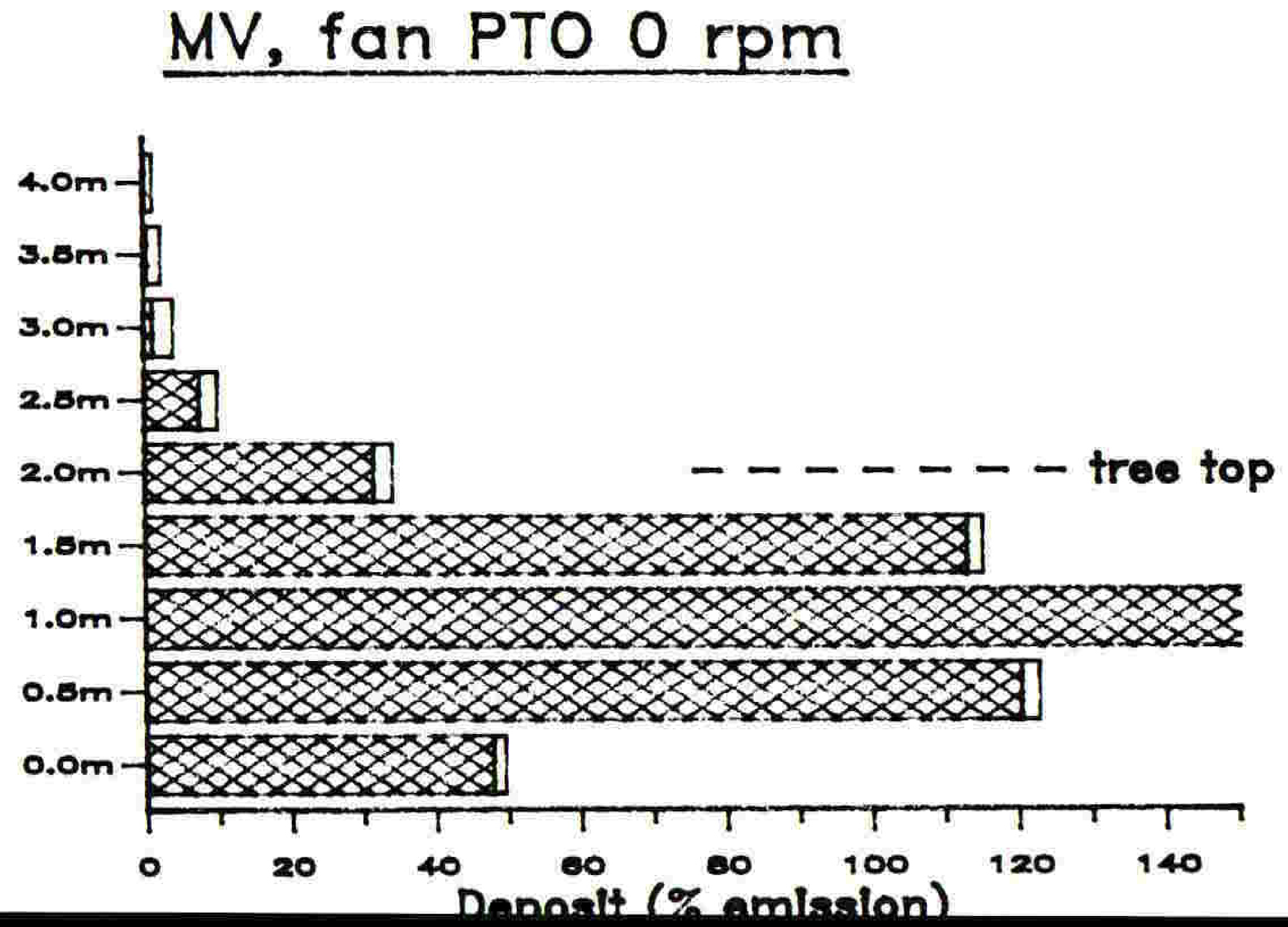


Figure 4. Vertical profiles of spray deposits on artificial targets in experiments 21–23, where rotational speed of the air fan was adjusted. Hatched bars are for targets between the sprayer and the tree, clear bars are for targets behind the tree.

DEVELOPMENT CRITERIA FOR AN AIR-ASSISTED GROUND CROP SPRAYER

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ABSTRACT

The criteria for designing a novel field crop sprayer are discussed. Along with modifications made as a result of field experience while developing the machine for commercial production.

INTRODUCTION

Agricultural spraying has always been a fertile field for new ideas and inventions, from time to time new spraying systems have been introduced to improve the farmer's position in his continuing war with pests for domination of field crops. Parallel with mechanical improvements, the chemical industries are continuously researching and developing new and more effective products. The farmer needs a combination of the best of the two fields in order to achieve optimal spraying results.

In the spraying of fruit trees, air assisted sprayers are well known and this method will continue to be used in the forseeable future. Even electrostatic sprayers use air blast to achieve better penetration into the foliage. Air assisted sprayers have also been used for some time in field crops but their effectiveness has been limited. The way in which manufacturers used the air in these sprayers was to direct the air in a specific direction, sometimes using a special nozzle. Consequently the results achieved along the full length of the boom varied enormously.

Degania sprayers, established in 1952 was always aware of the insufficiency of conventional sprayers. The number of applications required and the quantity of chemicals used on a field sometimes cancelled out the profitability of the crop, not to mention the damage done to the surrounding ecology. Ten years ago, following much research, planning and development, the prototype of the inflatable air assisted sprayer was put into work as an experimental machine. Since then we have made numerous changes but the basic system remains the same.

The targets set at the beginning of the project were:

1. To increase the penetration of the spray material into the crops;
2. To increase the coverage of the leaf - on both sides;

3. To reduce the number of applications required;
4. To reduce spray drift;
5. To increase the available time for spraying (i.e., to enable spraying even in adverse, windy conditions);
6. To allow use of conventional nozzles;
7. To achieve smaller drops;
8. To eliminate the necessity of spraying with the boom at a constant height above the crop.

DEVELOPMENT

During the years 1981, 1982, trials were carried out with a prototype machine. The results achieved were much better than anticipated. In early 1983, three machines were built and put to work in three different areas of Israel, under the supervision of the Department of Agriculture. In the same year, the first commercial experiments were carried out - A comparison of results achieved by conventional sprayer, aircraft spraying, and air assisted sprayers. The tests were carried out simultaneously in three different regions on commercial cotton fields. The superiority of the air assisted sprayer, was immediately evident and after the second spray application, the owners of the fields asked that all three fields be sprayed with the air assisted sprayers because of the poor penetration achieved by the conventional sprayer and the aircraft spraying.

The excellent results of this experiment convinced Degania Sprayers that the air assisted sprayer was a viable commercial product and so, in the second half of 1983, we began to manufacture the sprayers for the commercial market.

Why was the air assisted spraying system so dramatically better than other systems? After many, many hours of work in the field, collecting information and examining it, we feel we have the correct answer. The deciding factor in the effectiveness of a spraying system is the behaviour of each spray droplet from the moment it emerges from the nozzle until it reaches its target.

The best way to spray is to break up the spray material, using a minimal amount of water, into the smallest drops possible, which will give the best coverage. This is far from easy to achieve as from the moment the drop leaves the nozzles, it is effected by three things: wind, temperature and time. In a conventional sprayer, the pressure in the spray line forces the drops out of the nozzle at a speed which throws them a maximum of 30 cm. After that, the drops are on their own as they begin the long descent under the pull of gravity. Strong winds will blow the droplets off course; the longer the drops are in the air and the hotter it is, the more vaporisation occurs. The result is that only a proportion of the spray droplets reach their target and by this stage they have little momentum, so they impact on the first leaf with which they have contact.

Nobody was satisfied with this behaviour. However, the solution was sought in trying to improve the nozzles in order to achieve equal drop size all along the boom. Degania sprayers looked for the solution in giving extra power to the droplets (by the wind blast), so that they would reach their target in the shortest time possible and give the maximum coverage on impaction, without the need for absolute uniformity of drop size.

As the whole system was new, we had no knowledge as to how to work with the machine in different crops and under different conditions. In order to have this knowledge by the time sprayers were ready for marketing, we carried out non-stop trials with the sprayers, working on different crops under varying conditions, all over Israel. The things to which we needed answers were:

1. Overcoming drifting;

2. Reducing the amount of chemicals applied;

3. Optimal boom height;

4. Most suitable nozzle type;

5. Optimal application rate;

6. Optimal drop size;

7. Required air velocity;

8. Working conditions in different crops.

The results received from all the trials we carried out, exceeded our expectations. Today, after ten years of experience working with the air assisted sprayer, Degania Sprayers is in a position to give answers to almost any question or problem concerning field crop spraying - both in Israel and other countries.

The following combination of parameters are probably the most important for the effectiveness of the spray. Wind velocity and volume, nozzle type and spacing and boom height.

Fan Capacity

On an air assisted sprayer, the air is the most important parameter. The down draft from the sleeve must be even along the length of the boom having uniform velocity and volume. Any difference in one of these parameters will change the result. The capacity of the fan has to be sufficient to meet these requirements.

Nozzle Type

Air assisted sprayers will work very well with all kinds of nozzles and application rates, but the greatest advantage is to spray with low volumes that air assisted can offer. We recommend working with low volumes, and the best results we have achieved are with cone jet nozzles with their wide range of working pressure and drop size. The way the cone jet is made ensures minimum blockage of the nozzles.

Nozzle Spacing

On air assisted sprayers the pattern of the nozzles is disturbed by the air, therefore we cannot use nozzles in the conventional way because it will leave strips without spray at all. To ensure maximum equal distribution along the boom, it is necessary to work with the right spacing. In Degania Sprayers we use 25 cm.

Boom Height

The boom height is of major importance with these kinds of sprayers. We need to leave enough height spacing between the crop and the sprayer for proper entrainment of the drops by the air, and mixing the airstreams coming out from the sleeve. The boom should not be too high as this will cause excessive drift.

SUMMARY

The air assisted sprayer uses an air blast to force the spray droplets into the crop, in the shortest time possible, overcoming the external effects of wind and reducing the effects of temperature to a minimum, while achieving maximum leaf coverage. The application rates achievable are very low - between 20-100 litres per hectare depending on crop type and spraying conditions.

In short, the system allows the farmer to spray under almost any conditions, reduce the amount of spray chemicals and number of applications and receive excellent results.

DEVELOPMENT OF PRACTICE-ORIENTED CONTROL TEST METHODS FOR ORCHARD SPRAY MACHINES BY MEANS OF A VERTICAL TEST STAND

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ABSTRACT

In fruit-, vine-, and hop-growing, plant protection is usually conducted with air-assisted sprayers. Among others it is necessary to know the vertical distribution of the liquid portion in the two-phase-flow to rate the efficiency of plant protection. In order to segregate the components of the two-phase-flow the lamellate spray-seperator has been developed. For several crop-types a distribution pattern has been determined in field experiments. By varying the nozzles and nozzle-angles on the air-assisted sprayers a nominal distribution pattern was determined using the lamellate spray-seperator and was verified in orchards. As a result of these tests nozzle arrangement tables were derived, making possible a crop specific adaptation of the blower sprayer's vertical distribution pattern.

INTRODUCTION

The application of plant-protective agents in fruit-, vine-, and hop-growing requires both the vertical distribution and the horizontal distribution of the active agents. Compared to field application this distribution occurs in a larger extent in three dimensions. Therefore, air-assisting is usually used to bridge over the distance between the nozzles and the target zones. By the air-flow the liquid particles are transported to the trees or shrubs.

For instance the vertical oriented foliage of a fruit trees decreases continuously with the tree height with isolated leaves or branches at the tree-top. In most cases approximately the same active agent deposit at all parts of the plant has to be applied. For this reason the spraying must result in a differing active agent distribution depending on the tree dimensions. Furthermore, in contrast to field application the tree dimensions do not change during the vegetation period. Only the flow resistance varies from unleafy trees to leafy trees with fruits. All that can be considered by means of sprayer adaptation to the culture with regard to sort-typical growth-differences. That implies that effective and efficient plant protection in three-dimensional cultures with minimized active agent losses (soil, air, water) only can be ensured if the treatment meets those special demands.

The spraying industry offers a wide range of sprayers to the farmers providing numerous feasibilities to adapt the sprayer to the culture. Up to now, only in exceptional cases vague producer recommendations exist for adjusting the sprayer to different cultures. The lack of measured vertical distribution patterns of the sprayer's two-phase-flows is responsible for that.

In the agricultural practice various tree types are treated under identical sprayer adjustment. That causes considerable fluctuations of the active agent quantities and can result in unnecessary environment-loads. Also in future several crop-types obviously will be cultivated by one farm. That necessitates a very simple and fast manner to adapt the sprayer to the culture.

MEASURING THE DISTRIBUTION BY MEANS OF THE LAMELLATE SPRAY-SEPERATOR

The distribution pattern of field-sprayers simply is determined in a horizontal plane with a 'sprayer-plate'. In contrast to that, the distribution pattern of air-assisted sprayers for trees has to be determined in a vertical plane. In addition, the liquid particles of the two-phase-flow have to be seperated. For this task a 'lamellate spray-seperator' has been developed at the Technical University of Berlin, Institute of

Agricultural Engineering. That allows the nearly complete seperation of the liquid particles (Fig. 1).

The elements of the spray-seperator are commercial drop-seperator-lamellae consisting of plastic. The lamellae are also used in air-conditioning plants and in process engineering to clean fumes.

Mode of operation of the spray-seperator

The shape of the lamellae forces the two-phase-flow to change its direction. The carrier air follows this change without let or hindrance. On the other hand, the liquid particles maintain their direction because of effective inertia forces and bounce against the lamellae (Fig. 2). The eliminated fluid is transported into the two phase-seperation-chambers of a lamella by the air flow's drag forces . The lamellae are slightly inclined with reference to the horizontal. Therefore, the fluid flows out laterally from the drop-seperator following the lamella shape and is collected in 18 height sections of 25 cm each using graduated cylinders.

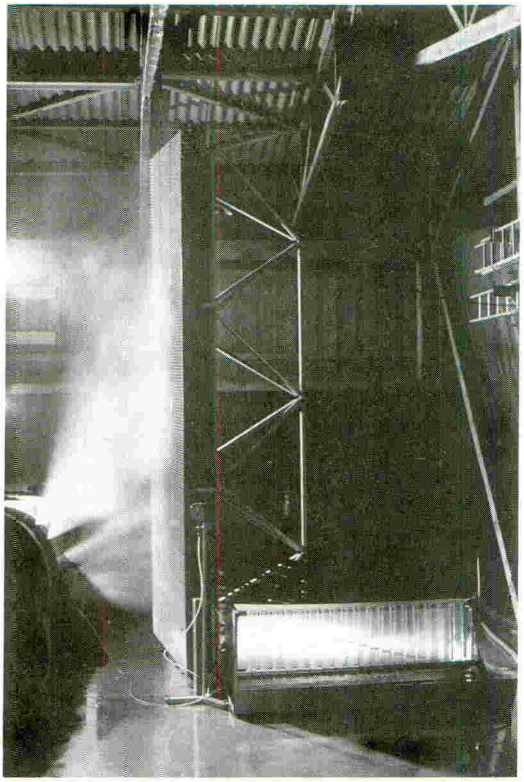


Fig. 1 The Lamellate Spray-Seperator

The lamellate spray-seperator offers the advantage that measurements can be taken in a hall without any disturbing weather factors. The effective seperation area is 1.6 m in width and 4.5 m in height. These dimensions guarantee that the whole two-phase-flow of normal sprayers passes through the drop-seperator. The relationship between the output volume and the eliminated volume is the seperation-rate. That value appears to be one simple way to criticize the operation mode of the spray seperator. The seperation-rate of our spray-seperator ranges from 80 % up to 90 %. The greater part of the volume loss occurs by evaporation during the transportation from the sprayer to the spray-seperator and the smaller part gets lost by evaporation inside the spray-seperator.

RELATIONSHIP BETWEEN THE VERTICAL DISTRIBUTION PATTERN AT THE LAMELLATE SPRAY-SEPERATOR AND THE DEPOSITION PATTERN IN ORCHARDS

By comparing the deposition pattern determined in the cultures with the vertical distribution pattern at the spray-seperator correction factors may be calculated. By means of these correction factors the sprayer adjustment can be managed in a way that the fluid's distribution pattern corresponded with the demands of the culture. Generally the fluid's distribution pattern in the two-phase-flow of sprayers is influenced by the following parameters:

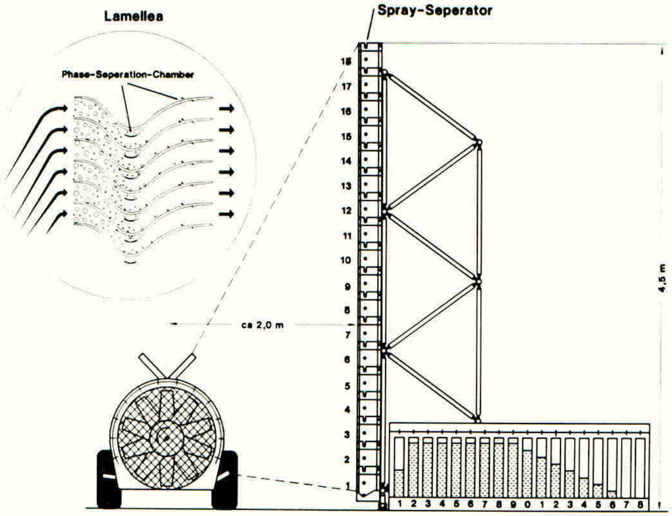


Fig. 2 Principle of the Distribution Pattern Measurement

fluid system
- nozzle arrangement
- nozzle orientation
- nozzle flow volume and v.m.d.
- effective area of a single nozzle

air-flow system
- blower kind and its size
- air volume quantity
- flow speed
- flow orientation
- turbulence

The deposition in the treated fruit culture also depends on:
- tree structure and its size
- row distance
- foliage (surface properties, structure, density)
- weather
- drift

By varying the nozzles and nozzle-angles on the air-assisted sprayers three specific distribution patterns were empirically set using the lamellate spray-seperator (Fig. 3). The distribution pattern at the spray seperator showing the best deposition pattern in the tree was called the 'nominal distribution pattern'. The desired harmonious deposit of the active agents on all parts of the plant could be obtained by such a vertical distribution pattern in which the fluid volume was kept constant in the middle section. This is valid although the wettable area decreases slightly with the height of the tree. The nominal distribution pattern of a fruit tree with weakly growing roots (type MM106 3.5 m in height) is shown in Fig.4.

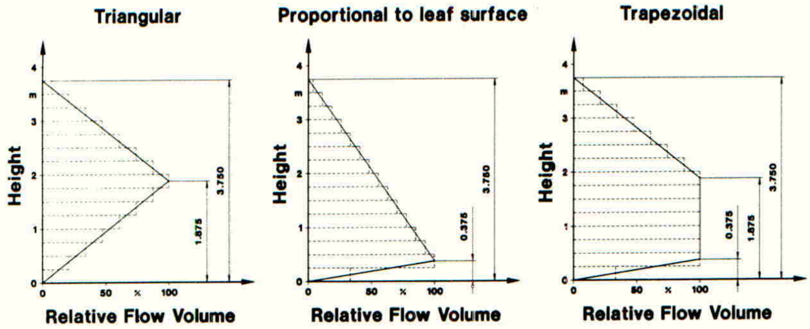


Fig. 3 Specific Distribution Patterns at the Lamellate Spray Seperator for emperically determined Sprayer Settings

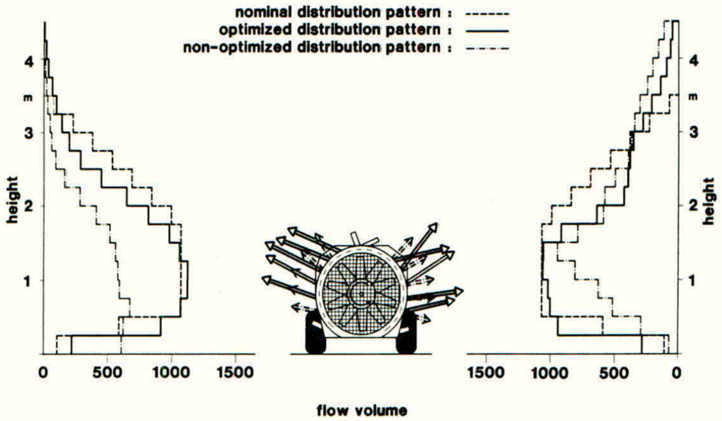


Fig. 4 Nominal Distribution Pattern at the Lamellate Spray-Seperator as soon as the Non-Optimized and Optimized Distribution Pattern of a Large Sized Axial-Sprayer

Measurements at the lamellate spray-seperator in a test room

Fig. 4 shows considerable changes in the measured vertical distribution pattern at both sides of the sprayer. Those differences only result from the specific choice of the nozzle size and the nozzle spray direction at each nozzle position. The dashdotted line shows the distribution pattern of an original sprayer. The interrupted line shows the desired distribution pattern and the continuous line represents the optimized distribution pattern. Especially the typical 'moment of momentum'-effect of an axial-sprayer could be eliminated successfully by the selection of the nozzle size and the nozzle spray

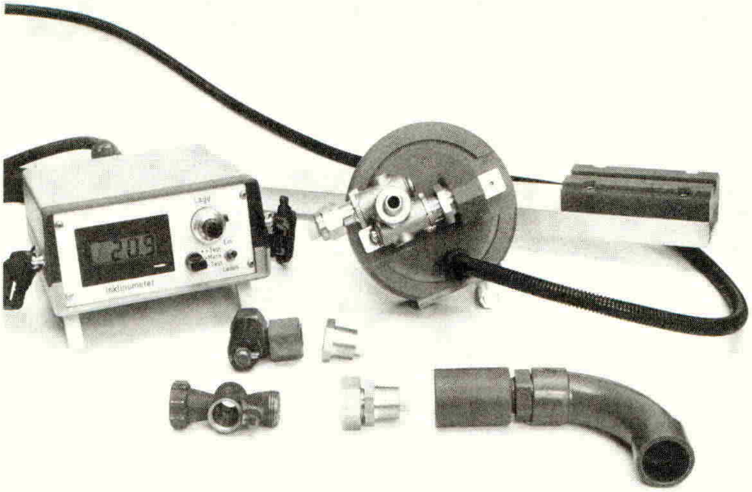


Fig. 5 Nozzle-Angle Meter (Pendulum Inclinometer) and Nozzle-Adapters

direction. That could be managed without influencing the air-flow; the total output volume was kept constant. The nozzle-angles were measured with a new-developed nozzle-angle-meter (pendulum inclinometer) (Fig. 5).

All tests were carried out at spray volumes of 200 and 500 l/ha respectively. The distance between the centreline of the sprayer and the spray-seperator was 2 m. This corresponds to the middle distance during the treatment of a typical orchard.

Orchard tests

The ascertained adjustments of the sprayers were transferred to the sprayers at the test farm which were used for field tests in the orchards. Their effects to the deposition pattern in natural fruit cultures were investigated.

Test trees

The deposition pattern measurements were conducted at apple trees (types M9 and MM106 3 m in height and 3.5 m in height). The test farm is located in the Elbmarschen, near Hamburg. Predominantly the test trees were treated only at one side allowing measurement of the penetrating effect and the filter effect of the canopy. All tests were executed at the same speed of 5.1 km/h in order to ensure repeatability.

Active agents and object carriers

For measuring the deposition pattern at the trees the fungicides ANTRACOL and DITHANE ULTRA were used at a concentration of 1.5 kg/ha.

All orchard tests could be made as often as necessary by using artificial targets. The filter papers have a dimension of 70 mm in diameter. They were hung up at equal positions in horizontal and vertical cross-sectional areas of the test trees. The filter papers were fixed to tightened wires inside the foliage. The wires were parallel to the direction of travel (Fig. 6). Altogether, 290 filter papers were positioned in the M9 tree and 500 filter papers in the MM106 tree. In each case 10 filter papers from one horizontal wire were added up for one deposition value.

With an Atomic-Absorption-Spectroscope the filter papers were analized for the concentration of Zinc (Zn) and Manganese (Mn). These substances were components of the applied fungicides. In addition, one probe of each sprayer charge was analized in order to check the active agent concentration.

Furthermore, qualitative statements could be given about the deposits at the upper side and the bottom side of the tree leaves. Fig. 7 shows the deposition pattern of a two-side treatment by a medium-sized

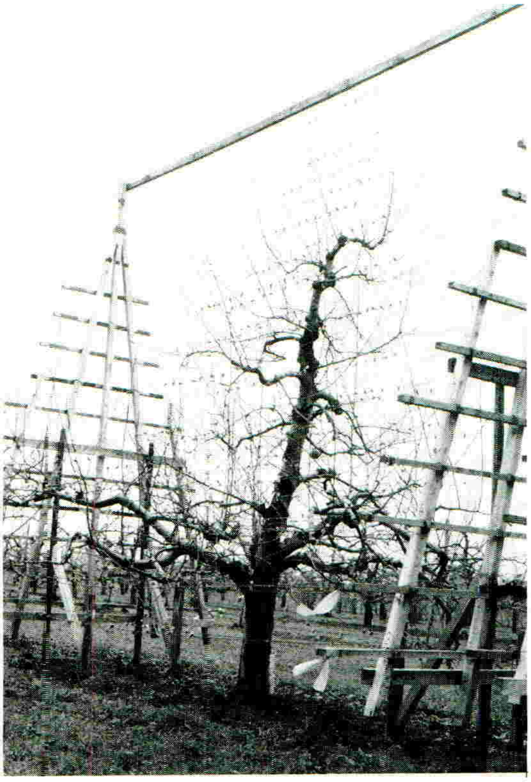
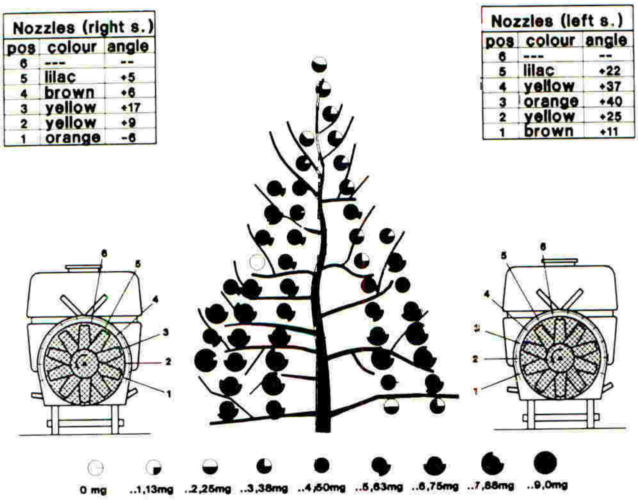


Fig. 6 Tree-Test-Arrangement at a MM106 Tree in



Nozzles (right s.)		
pos	colour	angle
6	---	--
5	lilac	+5
4	brown	+6
3	yellow	+17
2	yellow	+9
1	orange	-6

Nozzles (left s.)		
pos	colour	angle
6	---	--
5	lilac	+22
4	yellow	+37
3	orange	+40
2	yellow	+25
1	brown	+11

Fig. 7 Active Agent Deposit of a Medium-Sized Axial-Sprayer at the MM106 Tree

axial-sprayer e.g. at a MM106 tree. The used nozzle arrangement is shown in the tables of Fig 7. The nozzle angle was related to a horizontal plane (positive ≡ upwards). In the middle section the deposit is nearly constant and is intentionally decreased in the upper region of the tree in order to reduce the drift loss. That diminution produced a considerable reduction of the spray loss.

CONCLUSION

Experiments with the recently developed lamellate spray seperator demonstrate the possibility of significantly improving the performance of orchard sprayers.

Improvements have already been demonstrated by simply altering nozzle sizes.

Nozzle arrangement tables could be introduced so that farmers may set their own sprayers for optimum distribution.

METHODS OF CREATING AIR-ASSISTING FLOWS FOR USE IN CONJUNCTION WITH CROP SPRAYERS

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ABSTRACT

This paper examines the characteristics of fans commonly chosen to air-assist sprayers operating in both arable and bush and tree fruit crop canopies. The power requirements, efficiency and pressure characteristics of axial, centrifugal and cross flow fans are discussed in relation to applications on agricultural sprayers. The axial flow fan is commonly used because of its suitability to generate relatively high volume flow rates at medium to low pressures.

The design of ducting arrangements on boom sprayers is normally required to maintain an even air flow rate along the boom and on air-blast orchard sprayers to direct the flow into the canopy while imposing the minimum pressure at the fan. Methods of achieving these requirements are briefly considered.

Two methods of creating an air flow on laboratory scale boom sprayers driven from a compressed air supply are discussed and shown to be capable of producing maximum outlet air velocities of c 5.0 m/s measured 0.52 m below the boom.

INTRODUCTION

Air-assisted spraying techniques are used in applying treatments to both arable and bush and tree fruit crops with the potential advantages of improved spray distribution on the target including canopy penetration and, in the case of boom sprayers in arable crops, reducing spray drift. Most air-assisted sprayers use a single fan to create an air flow and three types of fan design, axial, centrifugal and cross-flow fans have been used in conjunction with agricultural sprayers.

Many designs of air-assisted sprayer do not specifically adjust the fan output to match crop canopy characteristics. Recent work and developments with both boom and air-assisted orchard sprayers has recognised the need to adjust fan volume output rates and flow directions to improve sprayer performance in different crop and weather conditions (Taylor, et al. 1989; Walklate, 1991). For a given machine, fan outputs have mainly been altered by changing rotational speed although in the case of axial flow fans, changes of blade angle have also been used to adjust volume output rates.

Relatively little published research work has examined the relationships between the characteristics of the air-assisting flows and spray deposition in different canopy conditions and hence many designs have been mainly empirical. Work by Randall (1971) showed that deposition in orchards was improved by using higher volumes of lower velocity air rather than lower volumes at higher velocities. This result then suggests that such air flows may best be provided from an axial flow fan.

Fan output characteristics are normally expressed as curves relating pressure, efficiency and power consumption to output air volume. When operating in a system providing a given pressure resistance/total flow characteristic, the operating condition will be where the fan characteristic and the system load characteristic intersect.

TYPICAL FAN CHARACTERISTICS

Axial flow fans

In this type of design, air enters and leaves the fan axially (i.e. a straight through flow) and the output air often has a high degree of swirl. In some more sophisticated designs, vanes or contra-rotating impellers are used to minimise this swirl but such designs are not commonly used in conjunction with agricultural crop sprayers. This type of fan has a characteristic useful in providing medium to high volume flow rates against a medium to low pressure resistance. The form of a typical characteristic for an axial flow fan is shown in Fig. 1(a). This type of fan is used with both orchard sprayers where guide vanes are often used to turn the output air through 90° and into the target area and on air-assisted boom sprayers using ducting with a large cross-sectional area. Both these arrangements impose relatively small back pressures on the fan. Measurements made with a particular design of air-assisted boom sprayer with an inflatable main duct indicated that back pressures on the fan were less than 14.7 mb (Miller, 1987).

Centrifugal fan

Centrifugal fans are normally capable of operating against higher pressures than axial flow fans and are commonly used for duties involving lower air flow rates. Air is drawn into the fan axially, accelerated by the blades and is discharged in a direction at right angles to the impeller shaft and the direction of entry. The detailed characteristics of this type of fan, although all similar, are dependent upon the form of the blades with backward curved, forward curved and radial bladed centrifugal fans developed for different applications. For agricultural sprayers, paddle bladed centrifugal fans which are a form of the radial bladed design are commonly used and have the advantage of being able to operate with air carrying dust and debris without clogging the fan. This type of design is also used on sprayers where air is ducted to individual nozzle outlets. Such a ducting arrangement can generate higher back pressures than guide vanes or single large cross-sectional area air ducts. A typical characteristic for a radial bladed centrifugal fan is shown in Fig.1(b).

Cross-flow fans

This type of fan design is used where the shape of the air outlet is required to generate particular air flow conditions into the crop canopy and has been used mainly on bush and tree fruit crop sprayers. The fan uses an impeller which is long in the axial direction and which has blades similar to those on a forward-curved centrifugal fan. Air enters all along one side of the cylindrical surface of the impeller and leaves on the other side. Cross-flow fans have a low efficiency (often in the order of 30%) and commonly operate at relatively low pressures. A typical characteristic for this fan design is shown in Fig. 1(c). One of the main uses of this type of fan is to generate an air curtain making use of the wide outlet. The outlet air flow from this fan type has little swirl. The rotational speed of a cross-flow fan may be limited because the long lengths of unsupported drive shaft will be prone to whirling and other out of balance effects at high speeds. Additional intermediate bearings along the shaft will reduce this problem.

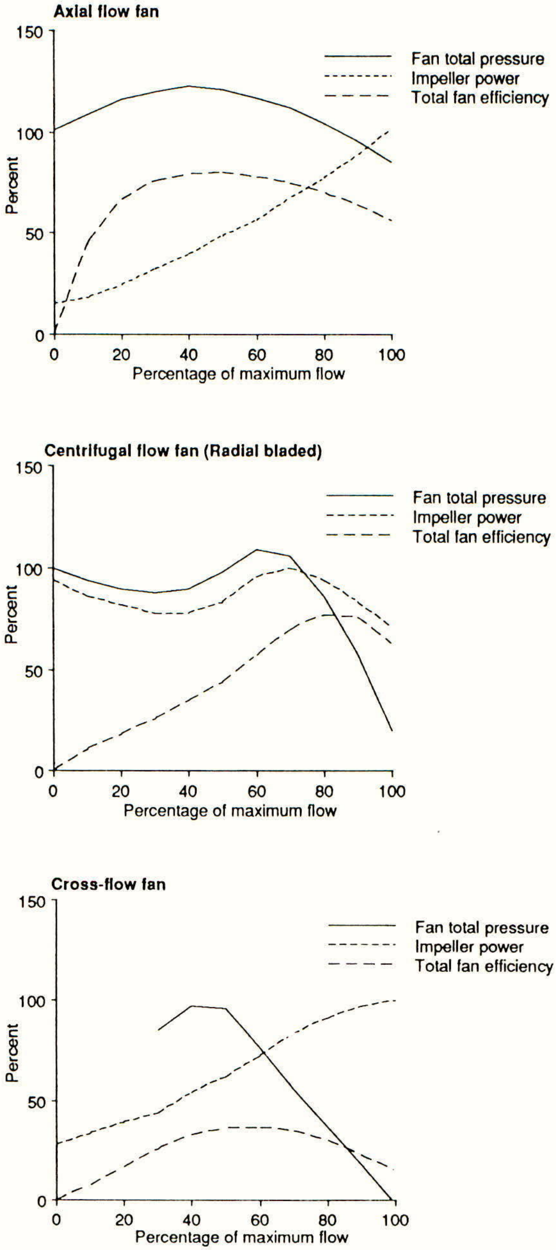

Fig.1. Typical fan characteristics normalised to maximum output volume flow rates and working pressures.
(Top) a. Axial flow fan
(Centre) b. Centrifugal flow fan (Radial bladed)
(Bottom) c. Cross-flow fan
(After Osborne)

The plotted characteristics show the changes in fan efficiency, pressure at the fan and total power consumption when the output air volume from the fan is reduced by the effects of the load system resistance.

Methods of regulating fan output

For a fan sized to be fitted to a sprayer based on maximum air volume flow rates, fan output can be reduced by changing speed, altering the conditions at either inlet or outlet (throttling) or in the case of an axial flow fan by changing blade angle.

Effect of fan speed

The effect of varying fan speed can be predicted over a limited range from the fan laws which can be expressed as:

$$Q = K_1 d^3 n \quad \ldots\ldots (1)$$

$$p = K_2 d^2 n^2 \eta \quad \ldots\ldots (2)$$

$$P = K_3 n^3 d^5 \eta \quad \ldots\ldots (3)$$

where Q is the volume flow rate, d fan diameter, n rotational speed, p pressure, P power consumption, η density of air and K_1 K_2 and K_3 are constants. Hence for a given size and design of fan (d = constant in equations 1-3), volume flow rate is directly proportional to rotational fan speed. Experiments with an axial flow fan on a sprayer driven via a mechanical gearbox reported by Miller (1987) showed a linear relationship between air output volume and p.t.o. speed as expected over a range from 300-600 rev/min (rated input speed = 540 rev/min). The fan laws can only reliably be applied over a limited range (± 50% max) without correcting for changes in Reynolds Number. It should also be noted that the relationship between fan power consumption and speed is cubic. Speed control is therefore an efficient method of controlling fan output.

Alternative methods of varying fan output

Methods of baffling either the inlet or outlet of fans as a means of controlling the delivery volume are relatively inefficient and rarely used on agricultural spraying machines. The effects on efficiency are minimised if, for example, vanes at the fan inlet impart a swirl to the air in the direction of the impeller rotation such that the fan blades then do less work on the incoming air.

Methods of adjusting the blade angle on an axial flow are difficult and expensive to effect and are therefore rarely used as a means of controlling air output volume rates on agricultural sprayers. The effect of changing fan blade angle can be seen diagrammatically on the characteristics plotted on Fig.2.

DUCT DESIGN

Minimising pressure losses

Ideally inlet air should enter a fan axially (except with a cross-flow design) and with no swirl. At the outlet, there should be a minimum of two impeller diameters before any bends; distances of less than this which are often necessary because of space limitations will reduce fan output particularly from axial flow fans. Pressure losses in bends are a function of air velocity, geometry and the position of the bend in relation to the fan and can be estimated from standard tables. For example, 90° elbow positioned less than two fan diameters downstream will increase pressure resistance by 4.9 mb when working with an air velocity of 20 m/s.

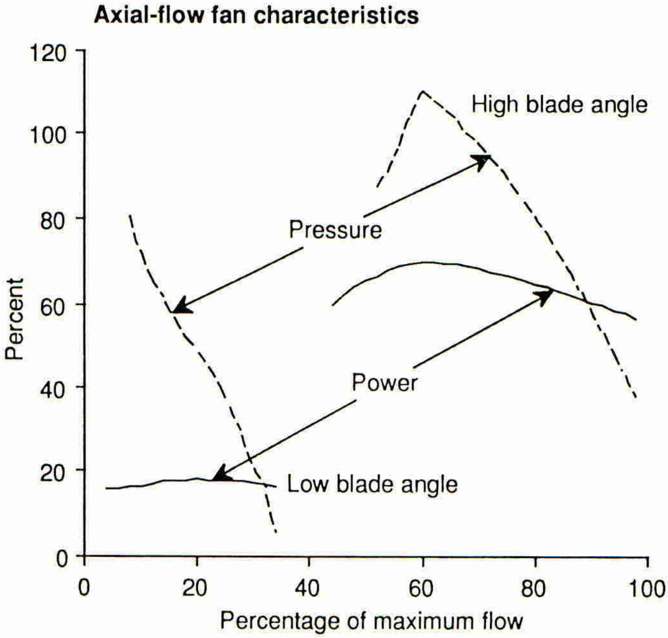

Fig.2 Diagrammatic fan characteristic showing the effect of changing fan blade angle on an axial flow fan.

The effects of bends and changes in duct section can be minimised by:

(i) Avoiding abrupt changes in section and streamlining duct sections in the direction of the flow, and

(ii) Using turning vanes across an inlet or outlet section that needs to use a bend close to the fan.

Producing a uniform flow from a perforated duct fed at one end.

This type of arrangement is now used to distribute air on air assisted boom sprayers. If air is fed into one end of a parallel sided perforated duct closed at the opposite end then at the inlet, air will have a high velocity which will then decrease along the length of the duct as air is lost from it. The total pressure at the inlet end of the duct will be slightly higher than that at the closed end because of small losses due to friction. The total pressure is made up of a velocity pressure component ($p_v = \frac{1}{2} \rho v^2$ where v = velocity) and a static pressure component. It is the static pressure component that determines the air flow rate through holes or slots in the duct. Close to the inlet where the air is travelling with high velocities much of the total pressure is as a velocity pressure, the static pressure is low and hence flow from the slot or holes in the duct will also be relatively low. Towards the closed end of the duct velocities will be much lower as will the velocity pressure component giving a higher static pressure component and high air flow volumes out of the duct.

To make the air flow from such a perforated duct uniform along its length, the duct is tapered such that the air velocity in the duct is approximately constant. To both minimise pressure losses in the duct and the effects due to not keeping air velocities in all parts of the duct exactly constant, mean air velocities in the duct should be as low as practical which means using ducts with relatively large cross-sectional areas.

The phenomena accounting for the variable flow from a closed duct fed at one end is termed 'static pressure regain' (Bruce, 1984) and computer programs have been written to aid the design of air ducts to minimise these effects.

ALTERNATIVES FOR CREATING AIR ASSISTING FLOWS ON LABORATORY SCALE SPRAYERS

Using "air-movers"

Four commercially designed "air-movers" (HMC Brauer Ltd) each 600 mm long were arranged to create an air flow either side of the spray generated from three flat fan nozzles mounted on a 1.2 m boom section. These units used compressed air which was forced through a fine slot (0.05 to 0.1 mm wide), turned through 90° by the coander effect and then entrained an additional air flow as both the spray and air stream developed. The arrangement used experimentally is shown in cross-section in Fig.3(a). Fed from a conventional laboratory air line (maximum pressure 7 bar) it was found that the maximum pressure that could be consistently maintained in the four "air movers" was less than 0.7 bar. The pressure in each "air mover" was limited due to pressure drops in the feed lines, control valves and filters. Good filtering of the input air was essential to remove moisture and oil which very readily blocked the small outlet slot in the "air movers". In some installations the main air line feed was not designed to handle significant air flow rates and large pressure drops resulted from the use of the apparatus. Estimates of the total input air volume were made by using a standard orifice plate on the input supply line fed with a 14.3 mm pipe and with an 11.1 mm orifice (Ower and Pankhurst, 1977). Pressure differences were measured with a micromanometer. For given pressures in the "air movers", input air volumes varied considerably in the range 0.3 to 1.0 kg/min/m at 0.34 bar up to 1.6 kg/min/m at pressures up to 1.03 bar when only sections of the apparatus were driven. Measurements of input and output air flow rates indicated a ratio of 1 : 18-20 due to entrainment when the duct was well set up. Operating with a pressure of 0.41 bar the "air movers" and a gap between elements of 30 mm gave mean centre line air velocities measured with a hot wire anemometer 250 mm below the skirt of 3.7 m/s. Experiments varying element spacing indicated that as spacing increased maximum centre line velocity decreased but the total mass of air moved remained approximately constant.

A major problem with the unit was setting the slot width in the "air mover" to give a uniform velocity along its length. Even when set for a given condition, the units were found to change in characteristics making repeatable experiments over a period of a number of weeks very difficult.

Using an air jet principle

An air jet unit was constructed again using the principle of establishing an air stream by entrainment. A 1.2 m experimental boom system was again used and compressed air fed into a 38.1 mm OD diameter pipe mounted along the length of the boom. An approximation to a linear air jet emitted vertically from the length of the tube was created by drilling 0.5 mm holes at 2 mm spacing along a flat surface machined on the outer wall of the tube. The tube had a nominal wall thickness of 0.78 mm. Alternative attempts using butting tangential plates to create an air slot of uniform width along the length of the tube from which a controlled jet could be directed had proved unsuccessful. The air jet was directed to flow between two profiled sections as shown in cross-section on Fig.3(b). The geometry of the profiled section was defined by Gilbert and Hill (1975)

Input air from a compressed air line was again monitored by using a standard orifice plate and micromanometer and the characteristics of the flow field below the skirt arrangement measured using a hot wire anemometer. Measured profiles for two different air flow rates are shown in Fig.4. By integrating the measured velocity field at a distance just below the jet exit, an estimate of the entrainment ratio achieved by the system could be obtained and typical results are presented in Table 1, obtained with the geometry shown in Fig. 3(b). Measurements were made across the centre of the boom section and do not account for observed convergence in the flow.

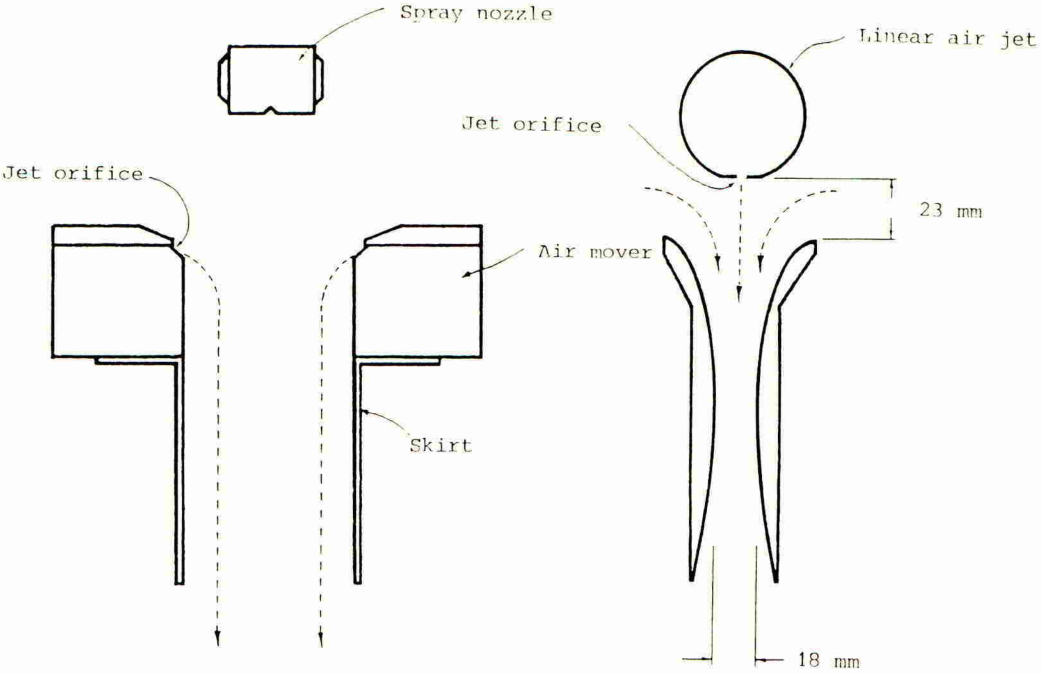

Fig.3 Laboratory air-assisted spraying systems based on the use of compressed air
(a) Left - using commercial "air movers"
(b) Right - using jet principle

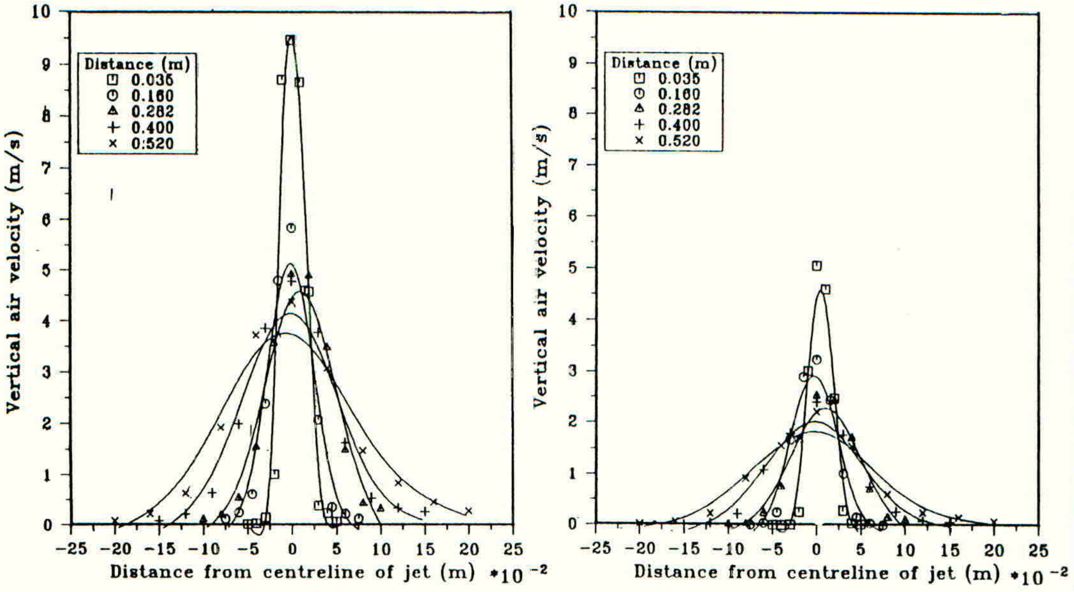

Fig.4. Measured velocity profiles from the laboratory air jet arrangement.
(a) Left - input flow of 1.49×10^{-2} kg/s/m.
(b) Right - input flow of 0.73×10^{-3} kg/s/m.

TABLE 1

Measured performance of air jet unit

Input mass flow rate, kg/s/m	Pressure at inlet, bar	Mass flow rate at base of skirt, kg/s/m	Entrainment ratio
1.49×10^{-2}	0.875	0.39	26
1.14×10^{-2}	0.569	0.29	25
$7.28\ \ 10^{-3}$	0.247	0.19	25

Results from computer simulation models suggest that the spacing between the profiled sections used and shown in Fig. 3(b) corresponded to the minimum setting at which viscous losses at these surfaces did not adversely affect the entrainment ratio. Further work is being conducted to both improve practical performance and the results from computer simulation studies with the system.

CONCLUSIONS

Axial flow fans have characteristics suitable for delivering high volume flow rates against low back pressures and are useful for many agricultural sprayer applications.

The design of ducting arrangements is important to ensure the required air volume distribution and turbulence characteristics while improving the minimum loading on the fan.

Systems using compressed air to generate higher volume flows for air assisting sprays have been useful in laboratory applications and may be useful on full-scale machinery if air volume demands are relatively low.

ACKNOWLEDGEMENTS

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REFERENCES

Bruce, D.M. (1984). Static pressure regain in bulk crop stores. *The Agricultural Engineer, Vol.39, No.4, 155-156.*

Miller, P.C.H. (1987). An air-assisted ground crop sprayer - measurements of the air flow distribution. *AFRC Institute of Agricultural Engineering Research, Divisional Note, DN 1417.*

Osborne, W.C. (1979). The selection and use of fans. *Oxford University Press for Design Council, British Standards Institution and Council of Engineering Institutions.*

Ower,E & Pankhurst,R.C. (1977). The measurement of airflow, Pergamon Press.

Randall, J.M. (1971). The relationships between air volume and pressure on spray distribution in fruit trees. *Journal of Agricultural Engineering Research, 16 (1), 1-31.*

Gilbert, G.B.; Hill, P.G. (1975). Analysis and testing of two-dimensional slot nozzle ejectors with variable area mixing sections. *2nd Symposium on Jet Pumps and Ejectors and Gas Lift Techniques, Cambridge, D3-45 to D3-64.*

Taylor, W.A.; Andersen, P.G.; Cooper, S. (1989). The use of air assistance in a field crop sprayer to reduce drift and modify drop trajectories. *Proceedings Brighton Crop Protection Conference, Weeds, 631-639.*

Walklate, P.J. (1991). Pesticide drift from air-assisted orchard sprayer - a numerical simulation. *Paper to this Symposium.*

PRACTICAL CONSIDERATIONS CONCERNING PESTICIDE APPLICATION IN INTENSIVE APPLE AND PEAR ORCHARDS

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ABSTRACT

This paper reports measurements of the spray distribution in hedgerow orchard crops from air-assisted sprayers operating at volume rates between 100 and 1600 l/ha, with different air output volumes and at forward speeds between 3.5 and 7.0 km/h.

Results from the work suggest that losses due to drift and evaporation are greatest at the low volume application rate. Losses to the soil are mainly due to direct application rather than as run-off. Run-off is most significant at the highest volume application rate but even then accounts for less than 2% of sprayer output.

Spray deposition within the canopy was not uniform with lower deposits consistently measured near the centre of the tree. This was little changed by increasing fan output.

Forward speed had little effect on the magnitude or distribution of spray deposits.

INTRODUCTION

In Spain, air-assisted sprayers are the only way technically available for pesticide application in intensive fruit orchards. Trailed sprayers are commonly used with tank capacities in the range 1000 l to 3000 l. The volume application rate to adult trees is in the range 600 to 1600 l/ha. The process of transport and penetration of the droplets is assisted by an axial fan placed at the rear of the sprayer. The inlet diameter of the fan is normally between 600 and 900 mm. Frequently the fan has fixed blades for conducting the air stream and avoiding any imbalance at the outlet due to the rotational movement of the air.

At the fan outlet, the air is deflected through 90° with respect to the fan axis and to the direction of forward travel. The air flow rate supplied by these fans ranges between 12,000 and 50,000 m^3/h and the power consumption between 15 and 35 kW.

Normally orchards are grown in a hedgerow arrangement with leaf densities defined at four levels. The maximum height of the adult trees is about 4.0 m or more and the distance between rows is 4.0 - 4.5 m. For these conditions we have undertaken different field tests during the period of 1985-86 to study the relationships of the volume application rate, fan output and forward speed on the quality of the spray application.

EXPERIMENTAL METHODS

Trials have been conducted to examine the effects of air output from the fan. In the field tests we have taken rectangular plots whose areas ranged between 64 and 96 m^2. The length of the plots ranged from 8.00 to 12.00 m and the width contained two adjacent rows of trees. Evaluation criteria aimed to quantify pesticide deposition on the leaf surface in different areas of the canopy and also to the soil surface. For deposition measurements on the soil we used rectangular plastic collectors, 255 x 180 mm. Spray deposits on both real leaf surfaces and the rectangular plastic collectors used to estimate soil contamination were quantified using atomic absorption spectrophotometry. Figure 1 shows the positions of the sampling sites within the tree and soil collectors used in this work.

Leaf area was measured at the different levels shown in Fig.1 by means of a linear regression analysis between the mass and the leaf area of a representative sample of leaves. After this, we weighed all the leaves in each level of a representative area of the orchard. Finally, from the regression equations, the leaf surface was estimated for each level together with the mean surface per leaf and the total number of leaves in the sampled zone.

EXPERIMENTAL RESULTS

The effect of volume application rate

Spray volume rates in the range 100 to 1600 l/ha were applied to an orchard of Spanish apples using a sprayer with an air output of 22,200 m^3/h and travelling at 4.0 km/h. The results of the leaf area estimation for this orchard are given in Table 1.

Table 1. Results of the estimation of leaf area index.

Level of canopy	Regression equation (n=50, p,0.05)	LAI (*)	Leaves /tree	Mean area/leaf
> 3.0 m	$s=2.42 + 27.99\ m$ (r=0.977)	0.37	1478	20.02 cm^2
2.0-3.0 m	$s=1.54 + 35.32\ m$ (r=0.975)	1.59	5778	22.01 cm^2
1.0-2.0 m	$s=3.60 + 40.32\ m$ (r=0.976)	2.03	6619	24.53 cm^2
0 - 1.0 m	$s=2.24 + 45.54\ m$ (r=0.959)	0.53	1700	24.94 cm^2
	Total	4.55	15575	23.37 cm^2

s: leaf area (cm^2)
m: leaf mass (g)
(*): leaf area/planted area

Calcium nitrate at 8 kg/ha was used as the tracer in this experiment. Spray applications were made in meteorological conditions of a temperature of 28°C, 68% relative humidity and a wind speed less than could be reliably measured (ie nominally still air conditions). The results of the distribution in the canopy are shown in Table 2.

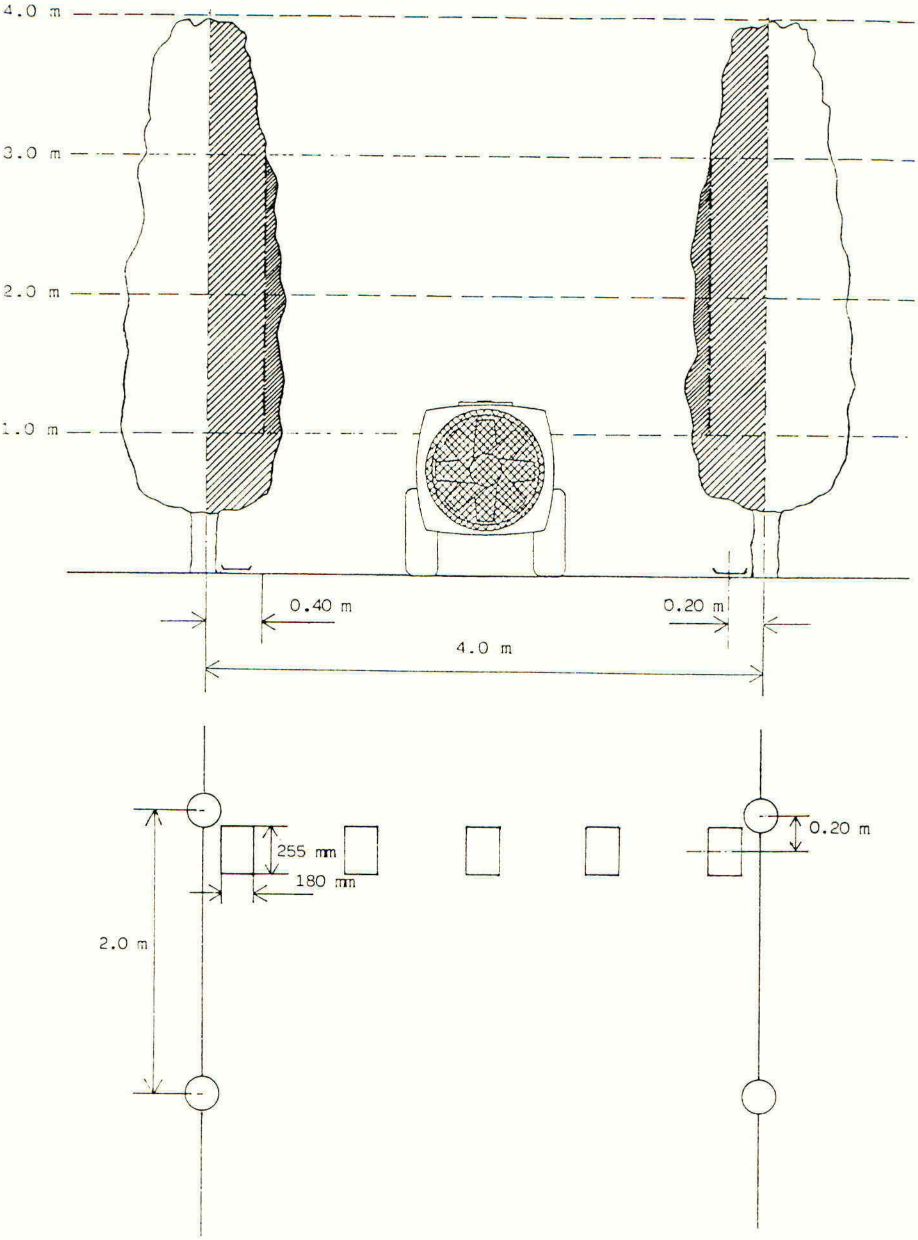

Fig.1 Diagram of experimental orchard including areas for determination of pesticide deposition on leaves and the positions of soil samplers.

TABLE 2. Deposit and losses as percent of total spray volume. Figures in parenthesis are the number of replicates, n. Figure followed by the same letter in the same column are not significantly different (Duncan's Multiple Range Test, $p<0.05$).

Volume rate l/ha	Total (T)	Recovery (n=16) from leaves	Losses to the soil (n=10)	Drift T-(R+S)
100 (*) VMD = 71-94 µm	100%	54.2% a	0.4% a	45.4%
400 VMD = 200-400 µm	100%	76.6% b	0.4% a	23.0%
1600 VMD = 200-400 µm	100%	74.5% b	1.6% b	23.9%

(*) spinning disc spray generator.

$$R = [Df\ .\ LAI\ .\ 100/\ t]\ .\ 100$$
$$S = [Ds\ .\ 100/t]\ .\ 100$$

where Df: mean deposition in leaves ($\mu g/cm^7$)
Ds: mean losses to the soil ($\mu g/cm^2$)
t : total pesticide sprayed (g/ha)

The losses of pesticide to the soil were further examined for the high volume treatment, 1600 l/ha, in a Spanish pear orchard (variety: Blanquille) using a copper oxichloride solution as a tracer applied at 3.2 kg/ha. Meteorological conditions at the time of spraying were a temperature of 22°C, 42% relative humidity and a wind speed that was too low to be reliably measured (ie nominally still air conditions).

Ground deposit collectors were all duplicated with one from each pair of collectors removed immediately after the sprayer had passed and the other remaining to collect any run-off from the tree. Results from this experiment are shown in Table 3. Measurements were made on both sides of the sprayer to examine any changes in air flow pattern and spray distribution due to the rotation of the fan.

TABLE 3. Mean and standard errors of the losses to the soil, µg Cu/cm. Figures in parenthesis and the number of replicates. Figures followed by the same letter in the same line are not significantly different (Duncan's Multiple Range Test, $p<0.05$).

	Mean	side (n=3)	
	(n = 6)	left	right
Direct deposition	5.13 ± 0.34 a	2.01 ± 0.34 a	8.26 ± 0.22 b
Run-off	0.92 ± 0.12	1.10 ± 0.12 a	0.74 ± 0.19 a

Effect of fan speed

Measurements were made in an apple orchard (variety: Golden Delicious) with a sprayer applying 1500 l/ha of a 50% solution of copper oxichloride tracer at 3.2 kg/ha. The sprayer was driven at a forward speed of 4.0 km/h and had an air output volume of 28,200 m^3/h when operating at 400 rev/min. Measurements were made in nominally still air conditions with a temperature of 22°C and a relative humidity of 42%. Two fan speeds were used, 400 and 540 rev/min and the mean results are given in the upper part of Table 4. The distribution of spray deposits within the crop canopy is shown in the lower part of Table 4.

TABLE 4. Mean and standard error of the deposition on leaves, μg Cu/cm^2. Figures in parenthesis and the number of replicates. Figures followed by the same letter in the same column are not significantly different. Figures followed by the same letter in parenthesis in the same line are not significantly different (Duncan's Multiple Range Test, $p<0.05$).

Rotation speed	Mean (n=36)	CV	Side	
			left	right
400 rev/min	2.62 ± 0.23 a	51%	2.50 ± 0.34 a(a)	2.73 ± 0.33 a(a)
540 rev/min	2.37 ± 0.17 a	42%	2.28 ± 0.24 a(a)	2.45 ± 0.25 a (a)

Rotation speed	Canopy area (n=6)					
	0 - 1m	1 - 2m outside	1 - 2m inside	2 - 3m inside	2 - 3m inside	3 -4m
400 rev/min	2.07 ± 0.55 a(b)	4.22 ± 0.28 a(c)	1.34 ± 0.28 a(a)	4.15 ± 0.22 b(c)	1.28 ± 0.14 a(a)	2.85 ± 0.21 a(b)
540 rev/min	2.15 ± 0.24 a(b)	3.73 ± 0.26 a(c)	1.36 ± 0.17 a(a)	3.20 ± 0.14 a(c)	1.33 ± 0.26 a(a)	2.45 ± 0.21 a(b)

Effect of forward speed

The effect of forward speed was examined in an apple orchard (variety: Golden Delicious) again using a solution of copper oxichloride as a tracer applied at 3.2 kg/ha in 8,900 l/ha. The sprayer was arranged to deliver an air flow rate of 32,600 m^3/h. Meteorological conditions at the time of spraying were a temperature of 20°C, 85% relative humidity and nominally still air conditions. The results from this experiment are given in Table 5.

TABLE 5. Mean and standard error of deposition in leaves, $\mu gCu/cm^2$. Figures in parenthesis and the number of replicates. Figures followed by the same letter in the same column are not significantly different. Figures followed by the same letter in parenthesis in the same line are not significantly different (Duncan's Multiple Range Test, p<=.05).

Forward speed	Mean (n=24)	CV	Side (n=12)	
			left	right
3.5 km/h	2.97 ± 0.34 a	54%	2.60 ± 0.41 a(a)	3.33 ± 0.57 a(b)
7.0 km/h	3.32 ± 0.38 a	54%	3.36 ± 0.52 b(a)	3.29 ± 0.59 a(a)

Forward speed	Canopy area (n=4)					
	0 - 1 m	1 -2 m outside	1 -2 m inside	2 - 3 m outside	2 - 3 inside	3 -4 m
3.5 km/h	1.21 ± 0.11 a(a)	3.88 ± 0.51 a(b)	1.88 ± 0.20 a(c)	5.79 ± 0.55 a(c)	1.94 ± 0.28 a(a)	3.11 ± 0.26 a(b)
7.0 km/h	1.31 ± 0.16 a(a)	5.19 ± 0.65 b(d)	2.35 ± 0.34 a(b)	5.84 ± 0.58 a(d)	2.02 ± 0.12 a(ab)	3.21 ± 0.37 a(c)

DISCUSSION AND CONCLUSIONS

The main part of spray losses are apparently caused by evaporation and drift processes, related to the size of droplets sprayed. The low volume application rate, 100 l/ha, provided by the spinning discs, shows a trend to produce a higher contamination.

The losses to the soil surface are more important at the high volume application, 1600 l/ha. In spite of this, at this volume rate, mean losses in our test were only 1.6% of the total product sprayed (Figure 2). Losses to the soil have their main source in the direct action of sprayer fan. The effect of dripping has a low influence on the total losses (TABLE 2). It would be expected to be more efficient using an improved design of the fan to reduce the direct losses.

The spray distribution in the canopy has always been irregular and the outside and upper areas of the canopy receive the highest dose rates. Because of their density, the middle part of the canopy is the most difficult to penetrate by droplets (TABLES 4 and 5).

The effect of the fan is directly responsible for the higher deposition on the right side of the sprayer observed. In the same way, in our working conditions, it was shown that the air flow from the fan at 540 rev/min and forward speed up to 4.0 km/h was too high for the structure of the trees. These results confirm the large losses as drift and evaporation observed.

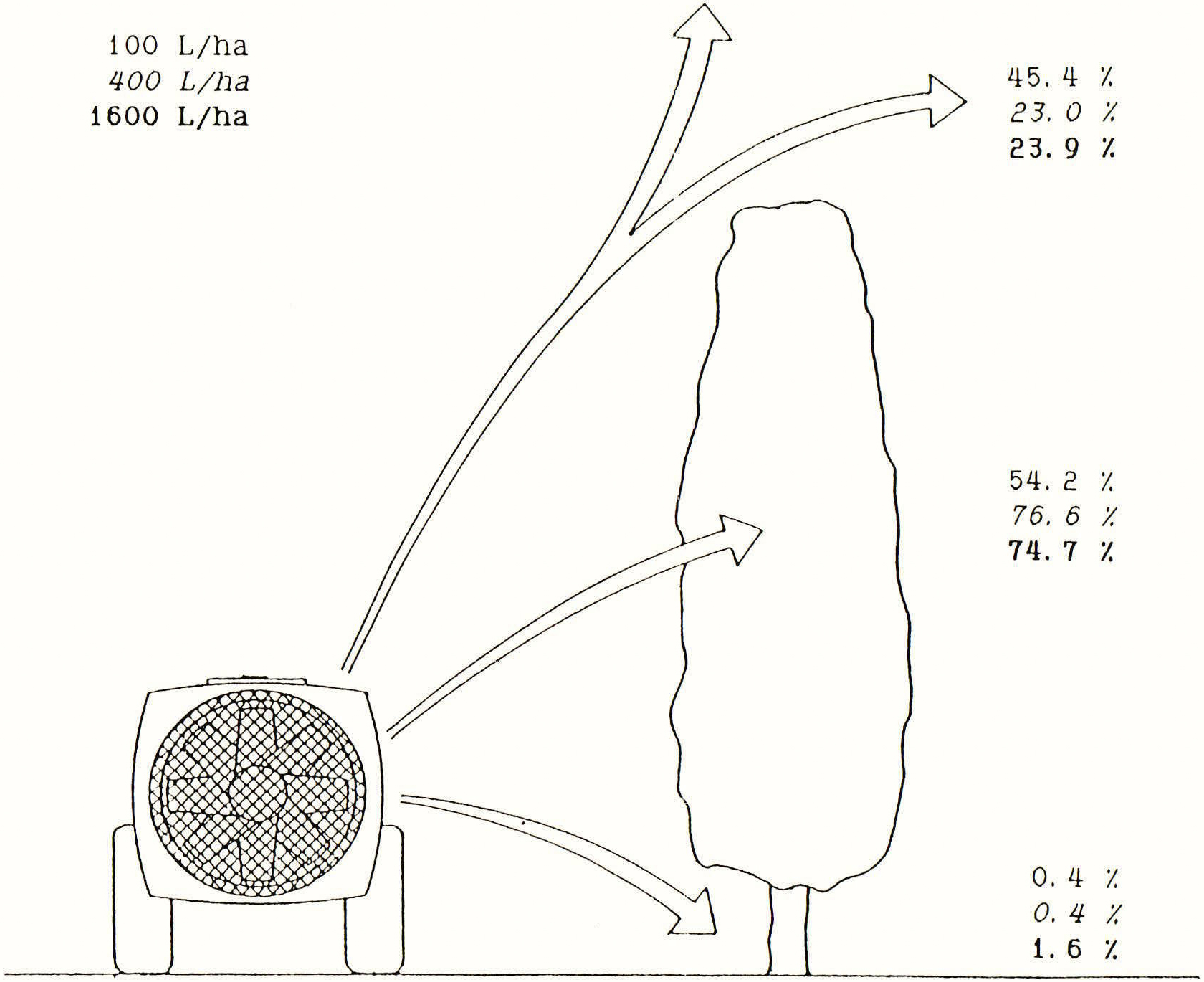

Fig.2 Results of deposition and losses both as run-off and drift at the different volume application rates.

In the determination of the air flow rate necessary for the orchard applications, different authors assume that the air at the outlet of the fan is expanded 2 or 3 times in volume. As a result of our tests, it could be possible to adopt a value near to 3. However, in view of the fact that in hedgerow orchards there are few results against which to compare our work, we recommend that further experiments are undertaken to validate our findings.

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References

Ade, G. (1986. Prestazioni dei ventilatori assiali per le irroretrici. Atti Giornate Fitopatologiche 1986, 2: 499-508. Bologna.

Fox, R.D. et al. (1984). Penetration of an apple tree canopy by orchard-sprayer air jets. OARDC, Fruit Crops-1985: A summary of Pes., .

Giles, D.K. et al. (1989) Spatial distribution of spray deposition from an air-carrier sprayer. Trans. ASAE. Vol 32 (3): 807-811.

Planas, S. (1988). Caracterizacion en campo de ventiladores de pulverizadores hidroneumaticos. FIMA. 20 Conf. Int. Mec. Agr. Zaragoza. pp 189-198.

Travis, J.W. et al (1987). Effects of travel speed, application volume and nozzle arrangement on deposition and distribution of pesticides in apple trees. Plant Disease Vol. 71 (7): 606-612.