

The use of narrow-angle cone nozzles to spray cocoa pods and other slender biological targets

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Received in revised form 3 December 2003; accepted 22 February 2004

Abstract

Cone nozzles were investigated to maximise deposition of fungicides on cocoa pods to control diseases such as black and frosty pod rots. Currently most farmers use variable cone nozzles, but efficiency and work rate need to be improved. Droplet size spectra and spray angles were compared at different pressures (100–300 kPa). Narrow cones and fine droplet spectra achieved with smaller orifice plates appear to improve dose transfer efficiency to small targets, but they are subject to a greater risk of blockage. Disc (> D1.5) combinations should minimise the risk of blockage, but flow rates and cone angles are increased for a given swirl plate. The outputs produced by discs and swirl plates from different manufacturers may vary, so an international coding standard is needed.

In a field study, fluorescein tracer residues were assessed on cocoa pods in two trials as deposit (ml m^{-2} of cocoa pod surface) per unit emitted (ml s^{-1} equivalent to spraying approximately 1 m of branch). In each trial, a “standard” configuration (D2-45 at 300 kPa) that gave a 40° Cone of spray, as used in other field trials was compared with narrower cone angles and low flow rates. The combinations DC31-25 and D1.5-25 (both at 200 kPa) that produce spray angles of approximately 25° and 35°, respectively, achieved substantially better (approximately $\times 3$) deposits on pods per volume emitted than the D2-45. Such descriptive information on nozzle outputs should be helpful for a number of applications where efficient spray deposition is required on smaller biological targets, such as narrow branches and individual fruit.

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Keywords: Manual sprayers; Application efficiency; Cone nozzle; Fungicide; Droplet size spectra; Cone angle; Pesticide deposition; Cocoa; *Theobroma cacao*

1. Introduction

In terms of dose-transfer to the biological target, most pesticide application is highly inefficient (Graham-Bryce, 1977). However, relating ‘ideal’ deposits with biological effect is fraught with difficulty (e.g. Hislop, 1987). In spite of Hislop’s misgivings, it is relatively easy to demonstrate that massive amounts of pesticides are wasted by run-off from the crop and into the soil, in a process that Himel (1974) called *endo*-drift. Minimising *endo*-drift and maximising dose transfer efficiency to the biological target will be of greatest interest to farmers, when reduced pesticide costs can be demonstrated. Since larger (> 200 μm) droplets are especially prone to bouncing off plant surfaces (e.g. Brunskill, 1956) *endo*-

drift is usually volumetrically more significant than *exo*-drift, caused by down-wind movements of smaller (< 100 μm) droplets, beyond the crop boundary. In many countries down-wind *exo*-drift has become a major issue for research and regulation (e.g. the LERAP scheme in the UK), but reducing run-off should reduce contamination of soils and pollution of ground water with pesticides.

Most cocoa farmers are small holders, who usually minimise inputs for pest and disease management, and may do nothing when cocoa prices are low. However, pod diseases such as *Phytophthora megakarya* (black pod in W. Africa) and *Crinipellis* (*Moniliophthora roreri*) (frosty pod rot in Latin America) have the capacity to reduce yields by up to 80%. Farmers spray for *Phytophthora* spp. on a regular basis, since copper compounds and other fungicides are efficacious (Evans and Prior, 1987); this study forms part of a current effort to mitigate losses caused by *Crinipellis* spp.

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Current research into improved cocoa disease control includes work on better application methods in order to: (a) provide practical and economic techniques to reduce the use of chemical fungicides and (b) to improve the effectiveness of experimental microbial and chemical control agents.

Application of large volumes of carrier water is inefficient in terms of dose transfer, and makes spraying tedious and labour intensive. In commercial operations, the cost of labour can be reduced substantially by reducing volume application rate, and thus increasing work rate (effectively by reducing the number of tank-loads per hectare). Although low-volume spraying with motorised mistblowers was specifically developed for cocoa (Clayphon, 1971), much pesticide application takes place using low-cost, manual (hydraulic) knapsack sprayers. Hislop (1963) compared knapsack mistblower application with a pressurised hydraulic sprayer and a tractor-mounted mistblower for black pod control in Nigeria. He concluded that the tractor-mounted machine was expensive to use and gave inferior disease control compared with portable sprayers, and suggested that even knapsack mistblowers may only be economic where labour is expensive or scarce. Some authors (e.g. Pereira, 1985) believe that mistblowers are now unsuitable for small-holder farmers, due to their capital cost and the maintenance required for 2 stroke engines. If necessary, treatment of tall trees can be achieved by the use of extended booms fitted to manual sprayers, but their pumps must be adequate to achieve sufficient pressure (>200 kPa) at the nozzle. Many locally available sprayers are fitted with variable cone nozzles that produce an infinitely variable range of droplet sizes and flow rates, and are arguably (e.g. Bateman, 2003) a contributory factor to reported poor or variable fungicide efficacy.

Cone nozzles are most appropriate for applying insecticides and fungicides to complex surfaces such as dicotyledonous foliage (Matthews, 1974). High pressures can be used to create small droplet sprays, sometimes reaching 1–2 MPa (150–300 p.s.i.), but manual equipment is more typically operated at 100–300 kPa (15–45 p.s.i.). Atomisation is achieved by swirling the pesticide mixture in the nozzle, then forcing it through a narrow circular hole. Spray droplet formation often occurs at the periphery of a cone-shaped liquid sheet (Fraser, 1956). Early droplet spectrum analysis, using a laser particle size analyser, was carried out by Combellack and Matthews (1981), and manufacturers such as Spraying Systems give data on flow rates and cone angles for nozzle configurations that are likely to be used in their principal markets (e.g. on tractor booms at pressures up to 2 MPa).

Jollands and Jollands (1984) appreciated that more targeted application on cocoa trunks and pods could be achieved with careful selection of cone nozzles. They

investigated the efficacy of a metalaxyl (a systemic phenylamide fungicide) and cuprous oxide mixture for control of black pod (*P. palmivora*). Reducing volume application rates (VAR) to as little as 65 l/ha, using a TX2 ‘Conejet’ giving a 67° Cone angle, had no effect on yield and significantly reduced the spread of black pod lesions. However, Matthews (1974) pointed out that low flow rate nozzle tips with narrow orifice sizes are prone to blockage, especially with tank mixtures containing particulate suspensions. In recent field trials, a directional spray was simulated in a reproducible way with a D2-45 fitted to a 300 kPa pressure regulating valve to give a VAR of 200 l/ha at a flow rate of 760 ml/min (Hidalgo et al., 2003). Even though this hydraulic nozzle combination had not been optimised, it achieved better cocoa pod disease control than a motorised mistblower fitted with a rotary atomiser. It appeared that a greater proportion of the spray cone had hit the biological target (flowers, pods, etc.) with less wastage of fungicide (copper hydroxide in water).

Cone nozzles are available in a number of forms:

1. Standard (integral) hollow cone tips (Spraying Systems: ‘ConeJet’ and ‘VisiFlo’ TX range; or Hypro Lurmark ‘HollowTip’: HCX series); these are cylindrical in form and protrude from the nozzle holder. The original Spraying Systems ‘Conejet TX’ nozzle was designed to produce an 80° spray at 689 kPa (100 p.s.i.), and ‘TY’ nozzles a narrower 65° Cone. Narrow cone TY-3 nozzles were found to be optimal on tail-booms for cotton spraying since smaller sizes were prone to blockage and larger sizes would result in unacceptably high VAR^s (Matthews, 1974).
2. Full (or solid) cone tips: are more rarely encountered and are manufactured for spot applications: e.g. the Hypro Lurmark ‘FulcoTip’. Applications include pest colonies and post emergence contact herbicide spraying of plant suckers, with manually operated sprayers. They typically produce an 80° angle of larger spray droplets than the two types above, under equivalent operating conditions.
3. Disc and swirl plate types: give a similar hollow cone of spray and as its name suggests come in two parts. These were originally labelled by Spraying Systems Dx-yz where D describes the disc (e.g. D2-25). Hypro Lurmark have a similar coding system, starting with the 1 mm DC02 disc (although smaller sizes are available) and similar swirl plates: thus the equivalent of the D2-25 is DC02/CR25. Commonly used orifice discs range from the D1 to the D10 (3.97 mm), the numbers from D3 upward originally signifying 64th^s of an inch, but this is not the case with D1, D1.5 and D2 (see Table 1). Discs are usually made from stainless steel (numbered) or engineering plastic such as polyacetal, which may be colour coded, although unfortunately not according to any international

Table 1
Disc dimensions

Disc	Orifice size (mm) (inches)	Colour	
		Spraying systems	Hypro Lurmark
D1 (DC-31)	0.79 (0.031")	White	Black (non-standard)
D1.5	0.91 (0.036")	White	—
D2, DC02	1.0 (0.039")	Orange	Brown
D3, DC03	1.19 (3/64")	Green	Orange
D4...	1.59 (1/16")...	Yellow	Red

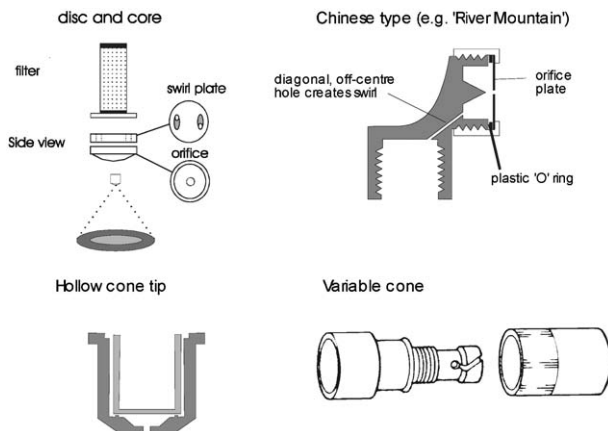


Fig. 1. Some hollow cone nozzle types.

standard. Swirl plates (often called ‘cores’ in the USA) are made in engineering plastic, stainless steel or brass and are numbered, most commonly: 13, 23, 25 and 45. For hollow cone nozzles, the first digit signifies the numbers of slot-shaped diagonal holes; the second digit indicates their size relative to other swirl plates. A hole drilled in the centre of the plate, creates a full cone spray, but the numbering system here is arcane (M.G. Baxter, Spraying Systems, pers. comm.). If a liquid jet is required, a disc can be used alone—with the swirl plate removed. In combination, discs and plates can give a range of spray angles (from 15° to 115°), depending on the combination of disc, swirl plate and pressure used.

- Proprietary cone nozzle designs are fitted as standard to certain manual sprayers. These include a Chinese design (shown in Fig. 1) fitted to low cost sprayers, which are also exported to adjacent Asian countries. Although they are not widely known in the west, the Chinese Academy of Agricultural Sciences estimates that 80 million of these nozzles are in service at any given time.
- Variable cone nozzles are often fitted to cheaper lever-operated knapsack and garden sprayers and can be set from a fine hollow cone to a jet of spray by adjusting the depth of the swirl chamber by a screw

thread. Because they are infinitely variable, the spray pattern cannot be duplicated and they are not recommended for professional use (see below).

Bateman (2003) measured droplet size spectra produced from a variable cone nozzle. When screwed down to its minimum setting it produced spray sizes that gave a comparably good-quality spray relative to certain fixed cone nozzles: such as the D2-25 or a Chinese design (commonly encountered in Asia). However, even unscrewing the sleeve slightly, to produce a narrow spray jet (as frequently done when attempting to treat high branches of tree crops) resulted in a dramatic increase in droplet size, and thus potential endo-drift. Suitably fine droplet size spectra are often achieved at normal, low (<300 kPa) pressures with cone nozzles, fitted as standard by manufacturers of manual sprayers (e.g. Bateman et al., 1999). However their angles of spray (normally >70°) are visibly too wide for target cocoa pods, hence much fungicide is wasted.

This paper provides a survey of the spray output from a number of potentially useful, lower-range cone nozzles. I have focused on disc and swirl plate nozzle combinations since these appear to be the most widely and easily available means of achieving narrow cone sprays in cocoa producing countries. The objective was to identify nozzle combinations that achieve <40° (ideally <30°) spray angle with a relatively fine droplet size spectra, followed by field studies on spray recovery with cocoa pods.

2. Materials and methods

2.1. Assessment of nozzle outputs

Tests were carried out on various cone nozzles obtained from Spraying Systems Co. (Wheaton, IL, USA), Hypro Lurmark Ltd. (Longstanton, Cambridge, UK) and a single standard nozzle fitted to Aspee sprayers (ASPEE Pvt. Ltd., Malad, Mumbai, India). All spray output measurements were with tap water with 0.1% Agral (a standard surfactant used for spray nozzle evaluation, e.g. Arnold, 1983), which was placed in a tank and propelled to the nozzle with a pressure-regulated air line. Nozzle pressures were 100–300 kPa (1–3 bar) at 50 kPa intervals, and checked with a meter (Bundenberg: accurate to 10 kPa) connected with a ‘T-piece’ adjacent to the nozzle body. Just before measuring droplet spectra, the cone angle was estimated using a large (150 mm radius) protractor, with a back light to aid observation of the spray.

Droplet spectra were measured with a Malvern 2600 PSA (Malvern Instruments Ltd., Spring Lane South, Malvern, Worcestershire, UK), fitted with an 800 mm lens. Each reading comprised of 1000 scans (equivalent

to sub-samples). Measurements were repeated at least once on a separate occasion to check for consistency and are presented here as means. The experimental design was similar to that used by Arnold (1983), with the cone nozzle directed horizontally and positioned approximately 200 mm in front of the beam. A 150 mm flexible pipe, connected to a centrifugal fan and situated at the rear of the apparatus, withdrew spray away from the sampling area, in order to minimise operator exposure to spray and prevent small droplets re-circulating in the beam. Numbers were exported electronically into a database in the form of cumulative volume distributions over 32 size classes.

2.2. Indicative field tests of spray deposits on pods

The use of tracers to assess spray residues is discussed by Cooke and Hislop (1993) and a detailed description of the technique, using fluorescein, is described by Thornhill et al. (1995). Applications took place on two occasions in the cocoa breeding farm at CATIE, Turrialba, Costa Rica, with a mixed population (varieties) of mature cocoa trees spaced at 4×4 m.

A stock solution of 0.25 g l^{-1} fluorescein sodium technical dye (BDH: now available from VWR International, Lutterworth, Leicestershire, UK) was prepared and applied using a side-lever knapsack sprayer (Carpi, Agrosuperior SA, San Jose, Costa Rica), fitted with 'CFValve' pressure regulating valves (G.A.T.E. Llc, Deerfield Beach, FL, USA). The cone nozzles and settings used are given in Table 2: the Hypro Lurmark DC31 (black) disc used in trial 1, with an orifice diameter 0.031" (0.79 mm), is not normally sold for agricultural purposes, but is approximately equivalent to a D1. Table 2 gives measured nozzle outputs, and for illustration, estimates of VAR have been calculated accordingly. Cocoa pod-laden branches were labelled with marker tape and sprayed with an even stroke of approximately 1 m s^{-1} along the branch. After allowing treatments to dry (and drip in some cases) pods from

each treatment were individually collected in strong, 300×400 mm polyethylene bags. In order to standardise recovery of tracer, further samples of unsprayed pods were collected in bags and then treated with a standard volume of $200 \mu\text{l}$ stock solution. All pods were individually washed, by pouring 0.5 l tap water into the bags, then shaking vigorously for approximately 20 s. The concentrations of fluorescein in the washings were assessed with a fluorimeter (Sequoia-Turner, Model 450), which was calibrated with diluted stock solution.

After washing, the dimensions and volume (displacement in a large beaker of water) of each pod were recorded. From these measurements, pod surface area was estimated using a pod model based on a hemisphere (pedicel end = $2\pi r^2$), cylinder and cone of equal heights ($2h = \text{length} - \text{radius}$): $2\pi r h$ and $\pi r \sqrt{(r^2 + h^2)}$. Statistical analysis was carried out using a spreadsheet, on calculated surface residues (ml m^{-2}) for each pod.

3. Results

The droplet size spectra and cone angles of a number of standard cone tips are given in Fig. 2. Data have been presented as diagrams that consist of a line with bars (left hand scale) that represent the volume median diameter (VMD) or $D_{[v,0.5]}$ with the 10% and 90 percentiles ($D_{[v,0.1]}$ and $D_{[v,0.9]}$) of the droplet size spectra (i.e. representing the relative span).² The lines marked with triangles (right hand scale) represent the measured angle of cone. The very small orifice TX1 and TY1 (Spraying Systems) nozzles produce relatively narrow, and similar, cone angles at the pressures tested, but atomisation is visibly unstable in the ranges. However, the cone angles of both this and the TY4 widened to near the specified 65° at pressures of $> 200 \text{ kPa}$. The Aspee 60–250 similarly widens to its specified 60° at relatively low pressures, and although possibly more suitable than other common cone nozzles, it is still too wide for optimal deposition on narrow targets such as pods. Should nozzle blockage not be a problem, the HCX2 at 200 kPa produces a relatively fine droplet spectrum in 35° of spray. The cone angles of the larger HCX3 and HCX4 are too wide for this purpose though.

Combinations of lower-range discs (DC31/D1.5, D2 and D3) and standard swirl plates, from Hypro-Lurmark and Spraying systems, are illustrated in Figs. 3–5, respectively. The small aperture disc combinations (Fig. 3) appear to give suitably narrow angles of spray at a range of pressures, especially with the no. 25 swirl plate. In order to produce $< 40^\circ$ sprays, D2 discs must be used with the high flow rate, no. 45 swirl plate

Table 2
Spray parameters

Nozzle	Pressure (kPa)	Measured flow rates		Nominal VAR ^a	
		ml/min	ml/s	ml/tree	l/ha
<i>Trial 1 (Hypro Lurmark nozzles)</i>					
DC2-45	300	758	12.6	316	197
DC2-25	300	575	9.6	240	150
DC31-25	200	448	7.5	186	117
<i>Trial 2 (Spraying Systems)</i>					
D2-45	300	768	12.8	320	200
D3-25	300	718	12.0	299	187
D1.5-25	200	439	7.3	183	114

^aBased on flow rate—taking 25 s to treat 1 tree at 625 trees/ha.

²Relative span = $(D_{[v,0.9]} - D_{[v,0.1]}) / D_{[v,0.5]}$.

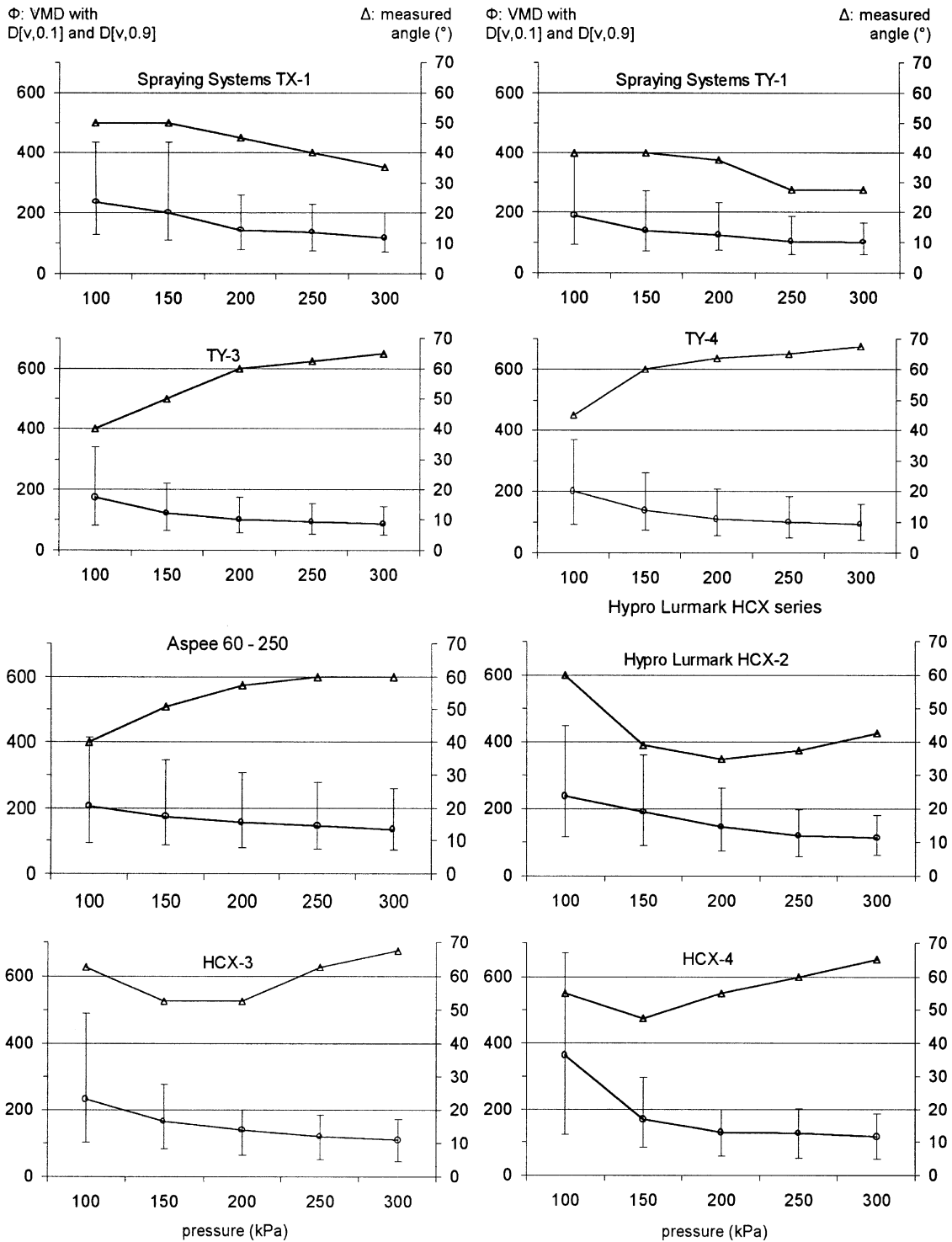


Fig. 2. Various cone nozzles showing droplet size spectra (left-hand side scale) and cone angle (right-hand side scale). (NB: the bars represent the relative span of the spray droplet size spectra (bounded by the 10% and 90% volume fractions) and are *not* error bars.)

(Fig. 4), but the VMD and relative spans are appreciably higher than with smaller disc sizes. D3-type discs (Fig. 5) show a similar pattern, but spray angles are even larger, and thus unsuitable for small targets.

Table 3 gives mean readings and calculated residues from the two field tests for spray deposits on cocoa

Pods. Data are expressed as mean volume of tank mixture (μl) recovered from pods and estimates per unit surface area (ml/m²), in order to assess the efficiency of spray application. In trial 2, mean pod furrow depths were also estimated, and pod volumes were calculated using equivalent formulae to the surface areas. The

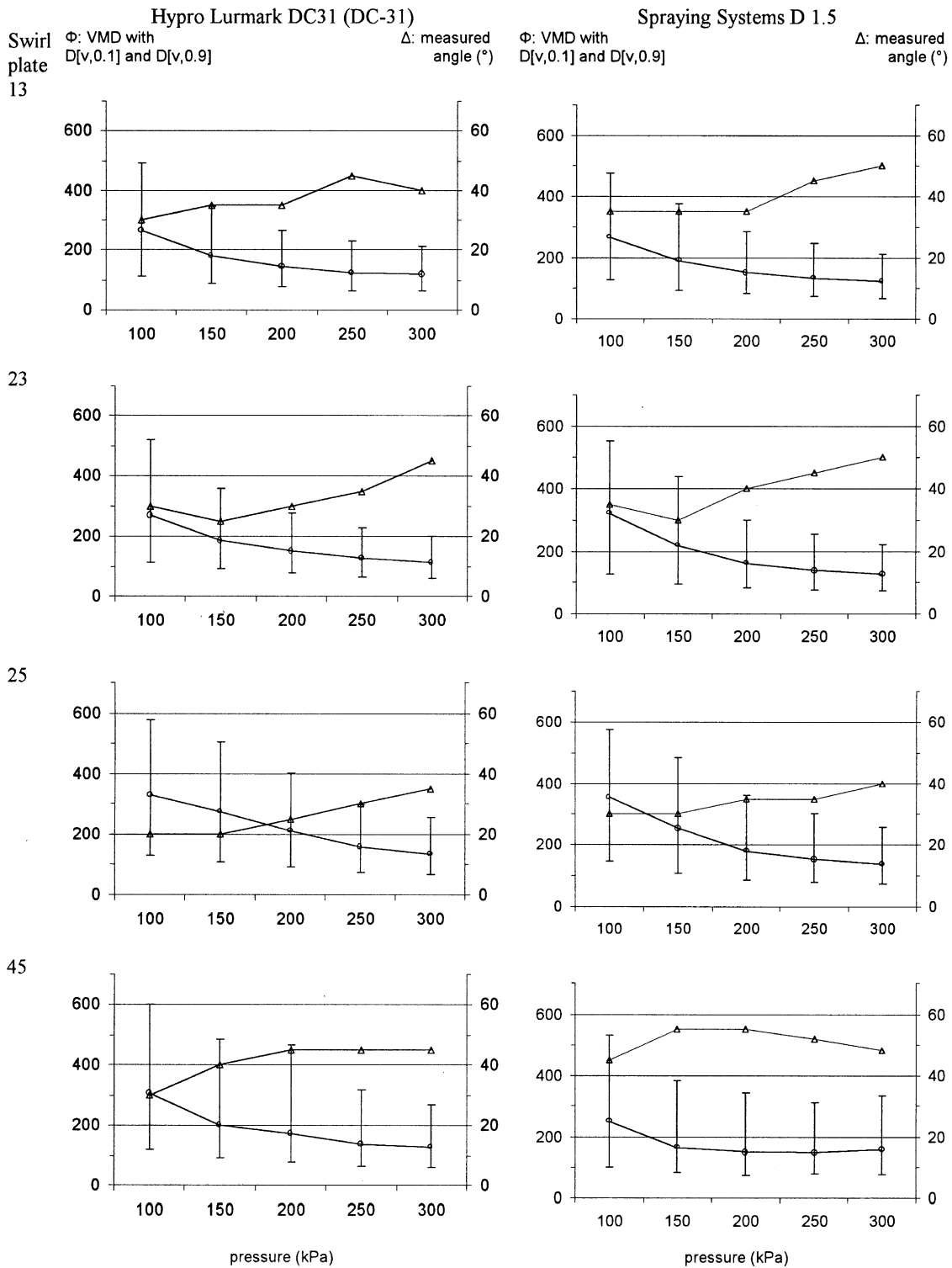


Fig. 3. Small aperture disc-swirl plate combinations. (NB: the bars represent the relative span of the spray droplet size spectra (bounded by the 10% and 90% volume fractions) and are *not* error bars.)

grand-mean volume estimate was only 1% greater than the measured mean volume, but 17 out of the 121 sampled pods were more than $\pm 10\%$ different. A similar check showed that a “Zeppelin” model (using a

second hemisphere instead of a cone) was inferior, with a 14% difference between mean calculated and measured volumes. Attempts to compensate for the furrows did not improve the volume estimates.

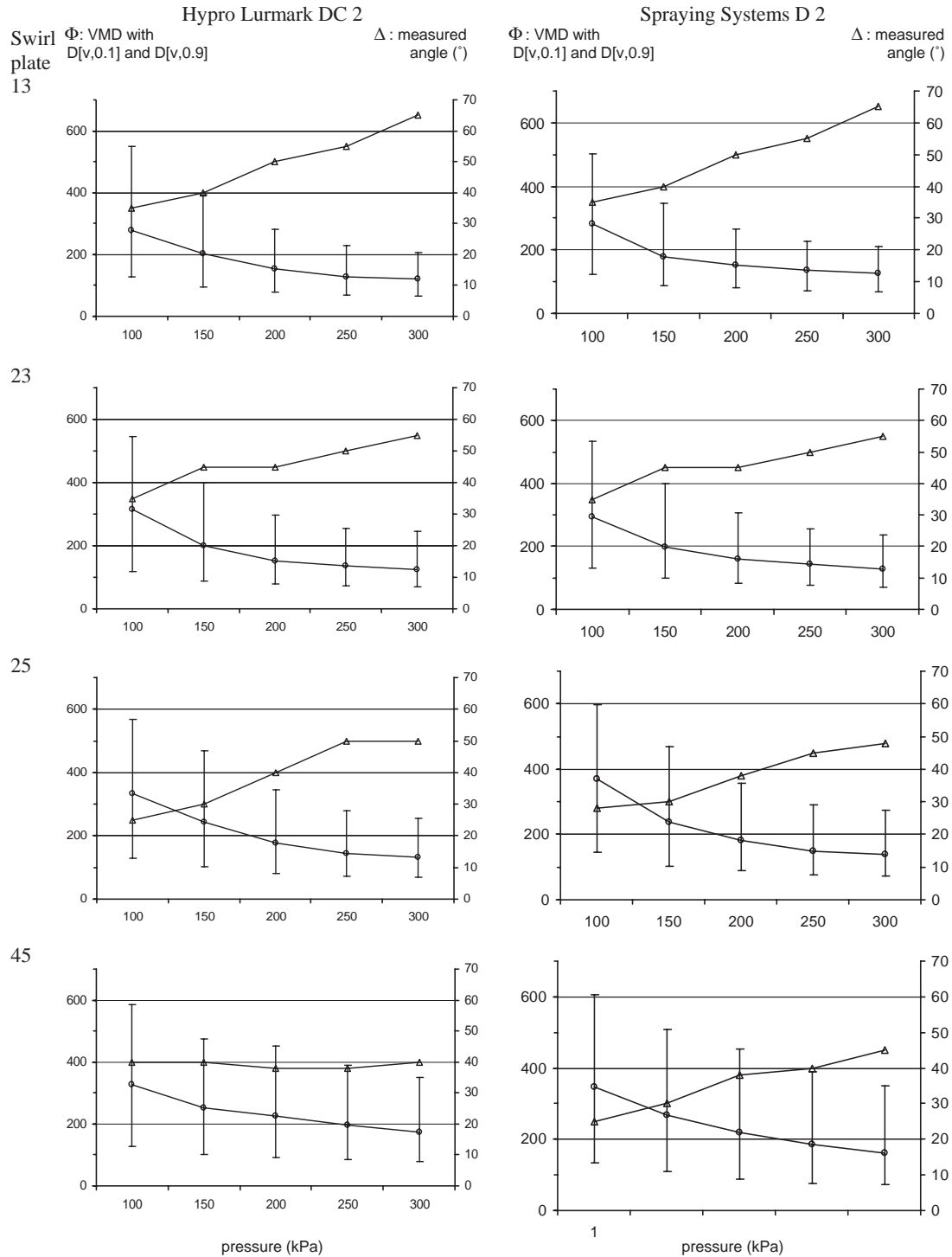


Fig. 4. D2-type disc–swirl plate combinations (NB: the bars represent the relative span of the spray droplet size spectra (bounded by the 10% and 90% volume fractions) and are *not* error bars.)

On both occasions, one-way analysis of variance indicated that residues per m² of pod surface were significantly higher with the low flow rate, narrow-cone sprays in contrast to the other two nozzles. In trial 1 this was DC31-25 ($F = 8.12$; d.f. = 2,54; $p < 0.001$) and in

trial 2 this was the D1.5-25 ($F = 17.1$; d.f. = 2,88; $p < 0.001$). In both trials, deposits from the other two nozzles were not significantly different from one another: as indicated by the least significant difference (l.s.d.) values at $p = 0.05$.

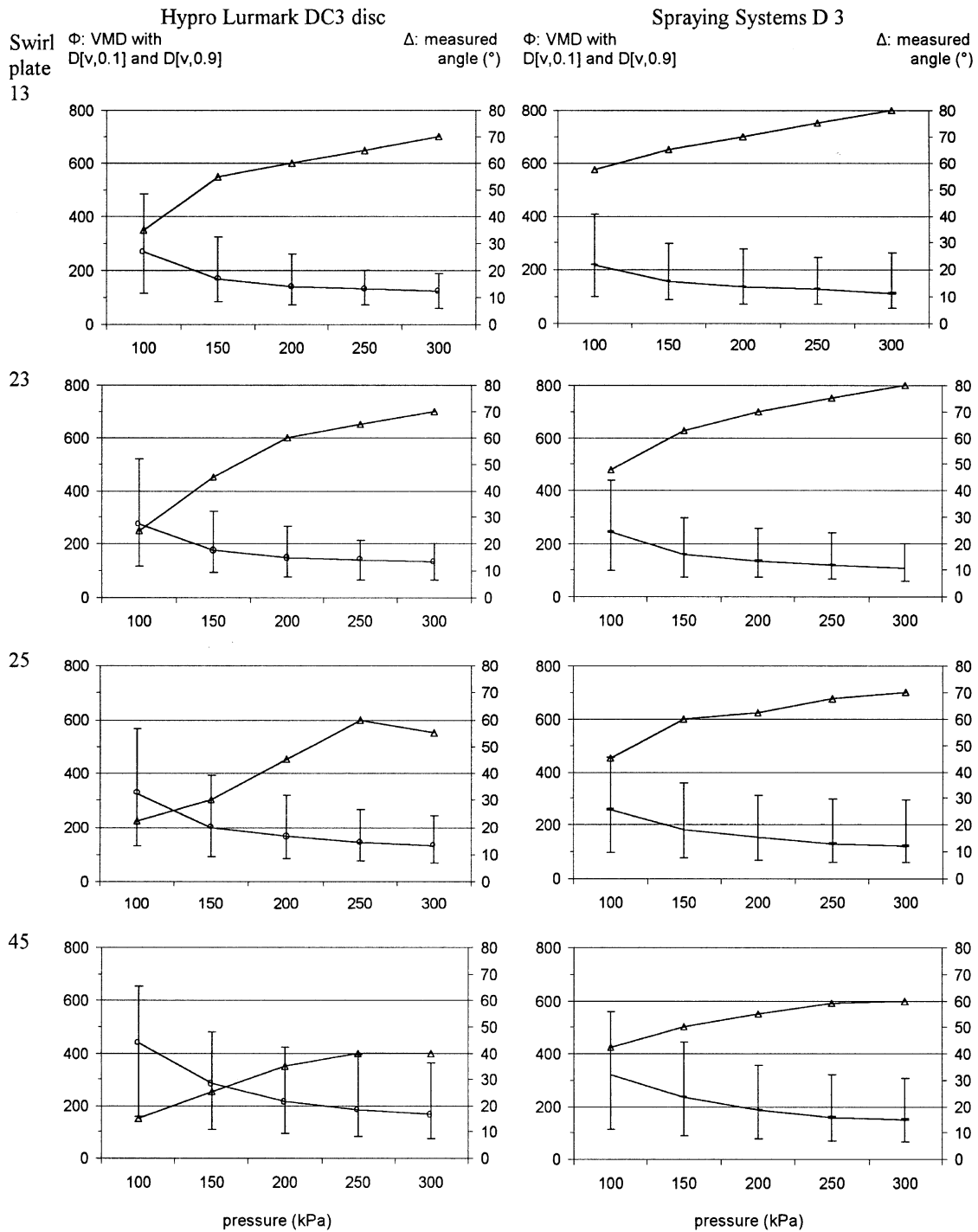


Fig. 5. D3-type disc–swirl plate combinations (NB: the bars represent the relative span of the spray droplet size spectra (bounded by the 10% and 90% volume fractions) and are *not* error bars.)

4. Discussion

4.1. Cone nozzles for narrow targets

It is unusual to use many of the disc and swirl plate settings tested here: application technologists often prefer higher pressures and flow rates that achieve more

stable atomisation. For example, [Combella and Matthews \(1981\)](#) carried out measurements on D4, D6 and D8 with 25 and 45 swirl plates at pressures exceeding 500 kPa. The range of pressures tested here (100–300 kPa) are those most likely to be generated by manual sprayers. Narrower cones and finer droplet spectra are achieved with smaller orifice plates, but these

Table 3
Readings and calculations

Nozzle	No. pods examined	Mean volume: ml (\pm s.e.)	Measured deposit μ l spray/pod (\pm s.e.)	Estimated mean pod surface area (m^2)	Calculated surface residue ($ml\ m^{-2}$)
<i>Trial 1</i>					
DC2-45	20	702 (50)	247 (29)	0.0382	6.7
DC2-25	18	637 (48)	289 (25)	0.0364	8.3
DC31-25	19	465 (34)	330 (37)	0.0287	11.6
Standard	20	554 (30)	200 (applied dose)	0.0333	
					<i>l.s.d.</i> : $p = 0.05$: 2.5 $p = 0.001$: 4.5
<i>Trial 2</i>					
D2-45	29	772 (110)	426 (45)	0.0395	11.1
D3-25	31	689 (49)	452 (49)	0.0387	11.3
D1.5-25	31	701 (65)	728 (61)	0.0384	19.1
Standard	30	747 (64)	200	0.0394	
					<i>l.s.d.</i> : $p = 0.05$: 3.2 $p = 0.001$: 5.5

results demonstrate that some combinations are unstable, with small alterations to pressure resulting in large changes in spray characteristics. Another practical factor is that very narrow ($<D3$) discs are subject to blockage with poor formulations and water quality. $D3$ (or larger) discs should minimise the risk of blockage, but lower rated swirl plates (no. 25 or less) are accompanied with wider-cone sprays and high flow rates. The use of high quality formulations and fine, in-line strainers is essential for discs and standard tips with small apertures (i.e. $D2/HCX2$ or less).

Narrow ($<45^\circ$) spray angles can be achieved by using a number of disc and swirl plate combinations, and generally, reducing disc hole size or increasing swirl plate rating reduces the angle (for a given pressure). Cone angles can often be reduced by lowering the pressure, but there is a “pay off” with an accompanying increase in droplet size. For a given nozzle combination, the VMD always decreases at higher pressures, but narrower discs can often achieve spectra that are similar in size and quality to larger discs at lower pressures (e.g. VMD $DC31-45$ at $200\ kPa = 172\ \mu m$; $DC2-45$ at $300\ kPa = 173\ \mu m$). Amongst the widely available cone nozzles, small-orifice discs and swirl plates are generally more versatile for generating narrow-angle sprays than standard nozzles, although the $HCX2$ produced $<45^\circ$ sprays over the $150\text{--}300\ kPa$ range. Narrow angle (40°) flat fan nozzles are manufactured and might have been considered, but they are practically never available in cocoa growing areas.

The outputs produced by discs and swirl plates from different manufacturers may vary, but are broadly similar. This study was complicated by the arcane coding system for disc and cone nozzles—using the products of just two companies. Representatives of these companies were very helpful to the author and pointed

out that a more rational system would have been developed had they “started from scratch” with internationally recognised coding in place. The system developed for flat fan nozzles (ISO 10625, 1996) is based on flow rate and can only be applied to standard cone tips, but a uniform, agreed colour coding for discs and swirl plates would be helpful, as manufacturers convert from nozzles made of metal to engineering plastics.

The issues surrounding inconsistencies between droplet sampling techniques have been discussed by several authors including: Combella and Matthews (1981), Arnold (1990), Parkin (1993), Chapple et al. (1995). Chapple et al. in particular express concerns about using spatial sampling techniques such as the ‘Malvern’ for hydraulic sprays with varying droplet velocities: especially for label recommendations and (exo)drift studies. However their data, which were based on a temporal sampling of flat fan nozzles, indicated relatively small ($\approx 10\ \mu m$) differences between temporal and spatially transformed volumetric statistics, when measurements were taken of a nozzle that was $200\ mm$ or less from the laser beam. Most conveniently, the ‘Malvern’ takes a transverse scan through the complete spray cone to produce reproducible, comparative data that is useful for selecting sprays of a desired droplet size range. For comparison of nozzles, 0.1% Agral surfactant was added according to standard British Crop Protection Council protocols (http://www.dropdata.net/bcpc_ewg/). Butler Ellis et al. (2001) describe how various surfactant solutions can reduce the VMD of sprays produced by hydraulic sheet break up (with flat fan and cone nozzles) in comparison with water alone. However variations with hollow cone nozzles, produced by different adjuvant mixtures, are unlikely to exceed 10% .

4.2. Spray recovery on cocoa pods

The purpose of the trials was to investigate improvements in dose transfer efficiency of selected nozzle combinations, especially if they are capable of applying fungicides at reduced volumes (ideally, from >200 l/ha to approximately 100 l/ha). Courshee (1960), in his review of insecticide application at that time, was one of the first authors to stress the importance of ‘recovery’: the percentage of pesticide emitted from a machine that can be located on the (biological) target after spraying. As a practical measure, he had previously coined the term Deposit per Unit Emission (DUE) to describe the amount of pesticide recovered down-wind in the target zone, relative to the volume emitted from the spray nozzle (originally in locust control operations). Hislop (1987) also urged researchers to obtain and express results in terms of DUE, as an overall measure of efficiency, permitting valid comparisons of spray recovery. It is usually expressed in units such as ml m^{-2} (mean quantity recovered in a unit area) per ml m^{-1} (liquid emitted over a unit of spray track), but in foliar canopies leaf area index also must be estimated and taken into account.

In this case, DUE estimates required an assessment of pod surface area, but in absence of sophisticated scanning techniques, true measurements of surface area are much more difficult to obtain than volumes. The question being posed here is similar to a well-known fractal conundrum: “What is the length of the British coastline”? Estimates can vary vastly, depending on the detail with which the cocoa pod (or coast-line) is traced. Hislop (1963) carried out deposition studies using paper covered, smooth wooden pod models: similarly based on a cone and cylinder, but with a truncated cone at the pedicel end. In this study I have used real pods and a relatively large number of samples, but the assumptions made here probably constitute one of the greatest sources of experimental error.

In Table 4, I attempt to estimate the relative dose transfer efficiencies for the nozzle combinations tested in Costa Rica. Table 2 gave the measured flow rates and

settings for the three nozzle combinations under test. In practice, operators are unlikely to adjust their pace of application to flow rates. From these figures I have estimated a “concentration factor”: the amount that tank mixtures would be adjusted (relative to a VAR of 200 l/ha) to achieve equivalent area doses. By multiplying this factor with the calculated residue (from Table 3), estimates of ‘adjusted’ deposit indicate the relative efficiency of nozzle configurations.

In both trials, very acute (<35°) angled sprays (DC31-25 and D1.5-25) achieved some 3-fold better dose transfer than the other nozzles tested. With a lower operating pressure and plate orifice size these nozzles operated at substantially lower flow rates, but somewhat larger droplet size spectra than the other nozzle settings. Smaller droplets should achieve better coverage than larger ones, which is known to be important with contact fungicides, although there are important interactions with concentration and total dosage (e.g. Frick, 1970). Although the ratios between adjusted deposits were consistent in the two trials, there were quite large differences in the absolute residue values. The mean pod sizes were slightly larger in trial 2, but this does not account for the variability. Trials are often variable in nature—and this may be due to operator technique—the ultimate test will be improved levels of disease control when farmers do the spraying. Much fungicide application research on cocoa has been with copper fungicides and it appears that (a) with heavy rainfall, much redistribution of deposits occurs and (b) delivering and maintaining total copper deposits on the target is crucial for disease control (e.g. Rudgard et al., 1990). Improving the efficiency of spray application could be especially useful for applying relatively expensive chemicals or slow acting biopesticides.

Extensive field testing would of course be required to show whether better disease control (or reductions in dosage) could be achieved with narrow angles of spray. However, studies of this nature, guided by the nozzle output data given in this paper, should assist researchers to “fast-track promising candidates” before carrying out expensive and time consuming field trials on cocoa and

Table 4
Summary of trials with nozzle characteristics

Nozzle	Pressure (kPa)	Cone angle (°)	VMD	$D_{[v,0.9]}$	“Concentration factor” (from flow rate)	Estimated residue (ml m^{-2})	Deposit adjusted for concentration
<i>Trial 1</i>							
DC2-45	300	40	173	351	1.01	6.7	6.7
DC2-25	300	50	132	257	1.34	8.3	10.9
DC31-25	200	25	211	404	1.72	11.6	19.6
<i>Trial 2</i>							
D2-45	300	45	163	350	1.00	11.1	11.1
D3-25	300	55	129	244	1.07	11.3	12.1
D1.5-25	200	35	179	362	1.75	19.1	33.4

similar crop targets. Reproducibility can be achieved by using hydraulic pressure control valves together with nozzle combinations. Pressure management valves are available rated at 100, 150, 200 and 300 kPa and have proved especially useful in field trials; they may also substantially lower farmers' pesticide costs.

Training of cocoa farmers in spraying techniques will be essential in order to achieve better application, lower pesticide usage and improved disease control. In the indicative study described here, the spray nozzle was passed at an even speed along cocoa branches. However, if operators continue to apply fungicides with "spray to run off" methods, this work regrettably will have little impact.

Acknowledgements

I am most grateful to John Clayton, Graham Matthews and two anonymous referees for their suggestions in the preparation of this paper. I would also like to acknowledge the assistance and advice of a number of colleagues including: Julie Flood, Mark Holderness, Keith Holmes, Belinda Luke and Sarah Thomas at Ascot, together with Johnny García, Eduardo Hidalgo, Martijn ten Hoopen and Ulrike Krauss at CATIE. This work was funded by the USDA-ARS, ACP, and I thank Eric Rosenquist for his continued support.

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