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The Transformation of Spatially Determined Drop Sizes to their Temporal Equivalents for Agricultural Sprays

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A statement of formulation effects on atomization by agricultural nozzles is already a requirement for the registration of a new chemical or formulation in the USA and parts of Europe. The laser-based instruments used for obtaining such data can be divided into two types: those that analyse the sample signal either spatially or temporally. It is known that for agricultural nozzles operating from ground rigs without air assistance, spatial measurements of the spray cloud overestimate the small drop component. Consequently, spatially determined data can be used to separate different atomization methods and formulations on a qualitative, but not a quantitative, basis.

Data acquired from temporal analyses of the drop spectra produced by agricultural nozzles using an Aerometrics PDPA 100-1D particle analyser are presented. The results show that for a given nozzle, there is a "coefficient" for each of the common spray descriptors (e.g. arithmetic mean, volume median diameter, etc.) whereby the *spatially* derived descriptor can be converted to its temporal equivalent, for a wide range of atomization pressures and formulations. Such "coefficients" would render spatially determined data more applicable to solving the problems involved in applying agrochemicals. However, these "coefficients" would have to be obtained in a manner applicable to spatial sampling methodology.

1. Introduction

Currently, three laser-based systems are commonly used to obtain information about spray clouds produced by agricultural nozzles. These are the Malvern (Malvern Instrument Ltd, Worcs. UK), the PMS (Particle Measuring Systems Inc., Boulder, CO, USA), and the PDPA (Phase/Doppler Particle Analyser: Aerometrics Inc., Sunnyvale, CA. USA). The performance of the three instruments has been compared,[1] and the theory behind their operation reviewed by LeFebvre.[2] In short, the Malvern samples spatially ("measurement of drops contained within a volume under conditions such that the contents of volume do not change during any single measurement")[2] using composite diffraction; the PMS and the PDPA measure temporally ("measurement of drops that pass through a fixed area during a specific time interval")[2] using direct shadowing and laser velocimetry/phase/Doppler interferometry respectively—i.e. the latter systems measure both particle size and velocity. For agricultural nozzles, spraying under normal conditions, spatial sampling results in an overestimate of the small drop component,[1] the magnitude of error dependent upon the spread of drop size velocities within a given drop size class. In contrast, temporal sampling provides a more accurate measure of actual numbers and volume in given drop size classes.

For any purpose where the velocity component of the spray cloud is important (e.g. modelling spray cloud dynamics), drop size data collected spatially will have less value than the same data collected temporally. This is especially relevant for drift studies, where it is important to have a reliable estimate of the volumes of atomized liquid contained in drop sizes below critical values. It is also becoming accepted that "small drops drift" is an over-simplification of the drift problem. Drops having relatively low kinetic

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energy are more likely to drift than drops having a relatively high kinetic energy: velocity measurements are indispensable for such considerations. Researchers investigating the biological interactions between deposit and target require accurate extrapolations from atomization to deposit and dose, which spatially collected data does not supply.

Spatially derived data may separate formulations on the basis of small (or driftable) drops, but even the relative proportions can be questioned. A critical assumption is that the drop spectra measurements of the formulation/nozzle combinations were made at the same distance from the nozzle under the same conditions. When comparing different nozzles, a second assumption is that the velocity profiles for the two nozzles do not differ substantially at the point or plane of measurement.

Temporally collected data can be transformed to its spatial equivalent by removing the velocity component from the measurements. The PDPA-100 is supplied with a spatial/temporal transformation module [Eqn (1)]. Provided the sample size is large, spatial reduction gives a respectable emulation of spatial sampling.[3]

$$\text{Spatial bin count}_{(d)} = \frac{\text{PVC bin count}_{(d)}}{\text{Vmean}_{(d)}} \quad (1)$$

In Eqn (1) "Spatial bin count" can be considered as "number concentration". "PVC bin count" (or number flux) is the Probe Volume Corrected Count sample size for a given drop diameter class "d" (μm), and "Vmean" is the mean velocity (m/s) for that drop size class. The probe volume is that region where the two in-phase lasers cross. "PVC bin count" is calculated by the PDPA software. The light intensity across the probe volume has a nominally Gaussian intensity cross-section, so small particles must pass through the probe volume at regions of high intensity in order to produce a detectable signal. Large particles can be detected further out. Hence, when sampling a heterogeneous spray cloud, the raw (or uncorrected) data is weighted towards the larger droplets. The PDPA software then "fills in" the small droplets that were not observed in the probe volume (Aerometrics PDPA-100 1D manual).

For most laboratory purposes, the choice of laser system falls between the PMS, the PDPA, and the Malvern (or their equivalents). In terms of ease of use, personnel training required, initial and ancillary costs, and the speed at which results can be obtained, the Malvern is an obvious choice. Of especial advantage is the relatively small volumes of sometimes hazardous liquid needed for an analysis by the Malvern, and the ease of "global" measurements of whole spray clouds. The main advantage of the temporal measurement systems is the quantitative comparisons that can be drawn between different nozzles, formulations, etc. Therefore, it would be an advantage if the ease of use of the Malvern could be combined with the wider usefulness and relevance of measurements made with the PMS or PDPA.

The objectives of this study were:

(1) to determine if the translation of temporal spray cloud measurements to their spatial equivalents could be accurately and reliably reversed, such that within the narrow confines of the atomization characteristics of a particular nozzle, spatially collected data could be back-converted to a reasonable approximation of data obtained using a temporal measurement system;
(2) to investigate the magnitude of error caused by altering nozzle to measurement point distances on the difference between the temporally and spatially derived spray descriptors; and
(3) establish whether or not the differences between the two measuring methods are larger than the nozzle-to-nozzle variability inherent in nozzle production methods.

2. Materials and methods

2.1. *Atomization and nozzles*

The spray spectra produced by atomizing a variety of liquids were determined using an Aerometrics PDPA 100-1D particle analyser.[4,5] The PDPA 100-1D measures drop size and vertical component of velocity at a point where two in-phase lasers cross, that is, the probe volume. With two exceptions, the lens combinations remained the same throughout the work (1000 mm transmission lens, 160 mm collimation lens, and 495 mm receiver lens, giving a nominal probe volume waist diameter of 748 μm); photomultiplier tube voltage was set at 325 volts; velocity offset 20 m/s; auto-HV and intensity validations off. Measurement range was 20–700 μm, unless otherwise stated.

Nozzle position was controlled using an XYZ positioner ("Unislide", Velmex Inc. Bloomfield, NY, USA). For traversing the spray cloud, nozzles were moved at $\leqslant$0·25 cm/s ($\pm$0·1 mm/s), and positioned at a vertical distance of 30 cm above the probe volume. Pressure was supplied to the nozzle using a ProCon (ProCon Products, Murfeesboro, TN, USA) rotary vane pump (max. output 7 l/min) with recirculation, or a pressurized container. The spray cloud was analysed along the long axis of the elliptical spray pattern produced by the flat fan (*Fig. 1*), a reasonable approximation of a "global" analysis.[6] The percentage of droplets rejected for measurement by the PDPA (i.e. due to asphericity, out of size and velocity measurement range, etc.) was never >20%, and in almost all cases, was <10%.

2.2. *Analysis*

The drop spectra parameters used in this study were volume median diameter (VMD or $D_{0 \cdot 5}$), 10% point ($D_{0 \cdot 1}$), and 90% point ($D_{0 \cdot 9}$), that is the drop diameters such that 50%, 10%, and 90% of the volume is in drops of smaller diameter, respectively;[2] the D10, D30, and D32 (length, volume, and Sauter [i.e. area] mean diameters respectively (see Ref. 2, 90–99); and the number median diameter (NMD: the drop diameter such that 50% of the drops by number are of smaller diameter).[2] The PDPA "spatial reduction" module was used to transform the temporal measurements to their spatial equivalents [Eqn (1)].

Agricultural engineers and crop protection biologists are particularly interested in certain fractions of the spray cloud. For drift studies (i.e. off-target losses of the applied material), researchers are typically interested in the numbers of drops and volume of liquid below critical values, e.g. <150 μm diameter, as these drops are considered most prone to drift. From a biological viewpoint, it has been demonstrated repeatedly for insecticides[4] that efficiency of utilization of active ingredient (ai) is inversely proportional to drop size, particularly as drop size approaches approximately 100 μm. (The data for fungicides[7] is more scarce.) Hence, for this study, the % volume and % number of various fractions of the spray cloud were calculated.

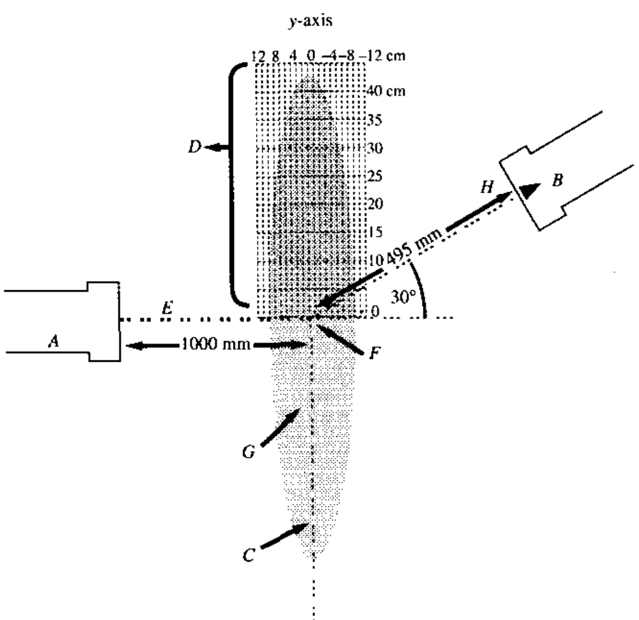

Fig. 1. Orientation, from above, of PDPA-100 transmitter (A) and receiver (B); traverse direction for experiments 1, 3, and 4 (C); and measurement matrix for experiment 2 (D). The lasers (E) cross to form the probe volume (F) through which the spray cloud (G) is traversed, giving rise to the signal (H).

2.3. *Experimental design*

Four data sets were obtained as follows.

2.3.1. *Effect of nozzle to probe volume distance on temporal and spatial measurements*

An XR8004VS nozzle (BCPC nozzle code F80/1·58/3, medium;[8] all TeeJet nozzles supplied by courtesy of Spraying Systems, Wheaton, IL, USA) was used throughout. The drop spectra produced by spraying tap water were assessed for a single traverse of the long axis of the elliptical swath produced by the flat fan nozzle, taken at 2 cm height increments from 6 to 30 cm below the nozzle, pressure 276 kPa. PDPA transmission lens was 2000 mm.

2.3.2. *Effect of sample size of varying velocity profile*

The drop spectra were determined for a matrix of discrete points (see *Fig. 1*) across the whole swath pattern using tap water at 207 kPa and an XR8003VS flat fan (F80/1·18/3, medium), probe volume 30 cm below nozzle. The data were collected for 180 s at 5 cm intervals on the x-axis and 1 cm intervals on the y-axis.[6] The number of drops measured at each point ranged from <200 to >30 000, with a wide range of drop velocities for different drop sizes, and number and volume frequency distributions varying from skewed log-normal to bi-modal. Velocity offset was 7·0 m/s.

2.3.3. *Effect of pressure, formulations, and adjuvants*

Droplet spectra were determined for an XR8003VS flat fan (F80/1·58/3, medium), single traverse of the long axis, probe volume 20 cm below nozzle, spraying various liquids: water; two polymer-based drift retardants; a UV tracer; two 2,4-D experimental EC formulations; the 2,4-D formulation blanks (i.e. placebos: the formulation minus the active ingredient); and various two- and three-way combinations. The majority were sprayed at 276 kPa, but some at 138 and 414 kPa. Sample size was not less than 10 000 drops. Measurement range was 20–700 μm, or 25·7–900 μm, depending on formulation.

2.3.4. *Variability of nozzles relative to differences due to temporal/spatial measurements*

Three examples of three all-plastic construction flat fans, Hardi 2080-10, 2080-20, and 2080-30 (F80/0·46/3, F80/1·47/3, and F80/2·94/3: fine, medium, and coarse, respectively; all Hardi nozzles supplied by courtesy of Hardi International, Taastrup, Denmark) were assessed for drop spectra parameters using a single x-traverse, probe volume 20 cm below nozzle, at 276 kPa. The nine nozzles were sampled three times each, using a complete randomized block design: means separation was based on Tukey's Honestly Significant Difference test.[9]

3. Results

The effect of vertical distance between nozzle orifice and point of measurement on the difference between the original temporal measurement of various drop spectra parameters and their spatial transformations is given in Table 1 and *Fig. 2*. From Table 1, the spray parameters decrease with increasing distance of the measuring point from the nozzle: this effect is more pronounced for the spatially transformed data. Proportions contained in various size classes also change with measurement distance, and again, greater differences are observed for the spatial transformation. The data are presented in *Fig. 2* as the percentage by which the spatial transformation under- or overestimates the temporal values, and ranges from overestimates by 2·5% for measurements close to the orifice (<10 cm) to underestimates by as much as 75%.

Table 1

Spray cloud descriptors for XR8004VS, water at 276 kPa, for three distances below the nozzle, temporal and spatial equivalents

Descriptor	*Temp.*	*Spat.*	*Temp.*	*Spat.*	*Temp.*	*Spat.*
Distance below nozzle, cm	10	10	20	20	30	30
Corrected count	20838		21309		25419	
% Validations	91.4		96.0		98.1	
Avg velocity m/s	14.14		11.49		8.39	
Arithmetic mean (D_{10}) μm	160·9	148·6	147·4	123·2	144·7	118·8
Volume mean (D_{30}) μm	213·0	203·6	203·0	178·4	198·3	165·3
Sauter mean (D_{32}) μm	276·6	272·5	272·9	253·3	266·3	229·1
10% Point ($D_{0\cdot1}$) μm	165·9	161·7	162·6	143·0	157·1	122·1
90% Point ($D_{0\cdot9}$) μm	497·8	493·6	501·4	489·2	500·6	470·3
VMD($D_{0\cdot5}$) μm	311·6	313·0	315·5	305·1	305·9	275·7
NMD μm	127·7	114·2	112·5	84·8	110·0	86·9
% Volume < 100 μm	1·88	2·4	2·39	4·1	2·75	5·9
% Volume < 150 μm	7·45	8·2	8·08	11·1	8·91	15·9
% Number < 100 μm	35·2	42·7	43·9	58·1	45·0	58·3
% Volume < 150 μm	58·8	64·5	65·0	75·9	66·3	79·0
% Volume > 300 μm	46·3	55·0	45·3	55·7	48·0	59·6
% Number > 300 μm	91·6	93·3	92·6	93·0	93·4	94·3

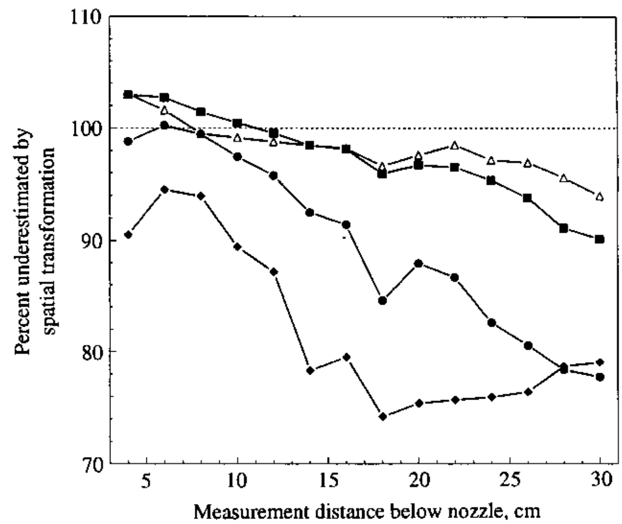

Fig. 2. The effect of vertical distance between nozzle orifice and point of measurement on the discrepancy between the original temporal measurement of $D_{0\cdot1}$ ●—●, $D_{0\cdot9}$ △—△, VMD ■—■, and NMD ◆—◆, and their spatial transformations. XR8003VS nozzle, 276 kPa, tap water

The effect of sample size on the relationship between the temporal measurement and its spatial conversion is given in *Fig. 3* for D_{10}, D_{20}, D_{30}, and D_{32}. For a given spray parameter (e.g. D_{10}), each data point is derived from a wide range of sample sizes. Although there is no clear linear relationship, there is an indication of a correlation for some of the data, and a suggestion of two or three distinct groups within each data set (e.g. D_{10} and D_{30}). An arbitrary breakdown of size classes for the D_{10} data set is given in *Fig. 4*, indicating that the majority of data points which do not adhere to a linear correlation have less than 5000 counts. At the extremities of the range of measurements, sample size appears to be unrelated to a correspondence with a linear fit.

The linear relationships between the temporal measurements of NMD, VMD, D_{10}, D_{20}, D_{30}, and D_{32} and their spatial transformations are given in *Fig. 5*. Each data point is derived from a minimum of 10 000 counts from a wide range of formulations and pressures (see above). Figures in the legends are slopes followed (in brackets) by the Pearson's multiple r^2 for the correlation. All regressions have been forced through zero. *Fig. 5* shows a clear linear relationship between spatial and temporal measurements, with good multiple r^2 values for the correlation analysis, ranging from 0·892 to 0·996.

An analysis of the differences between the three

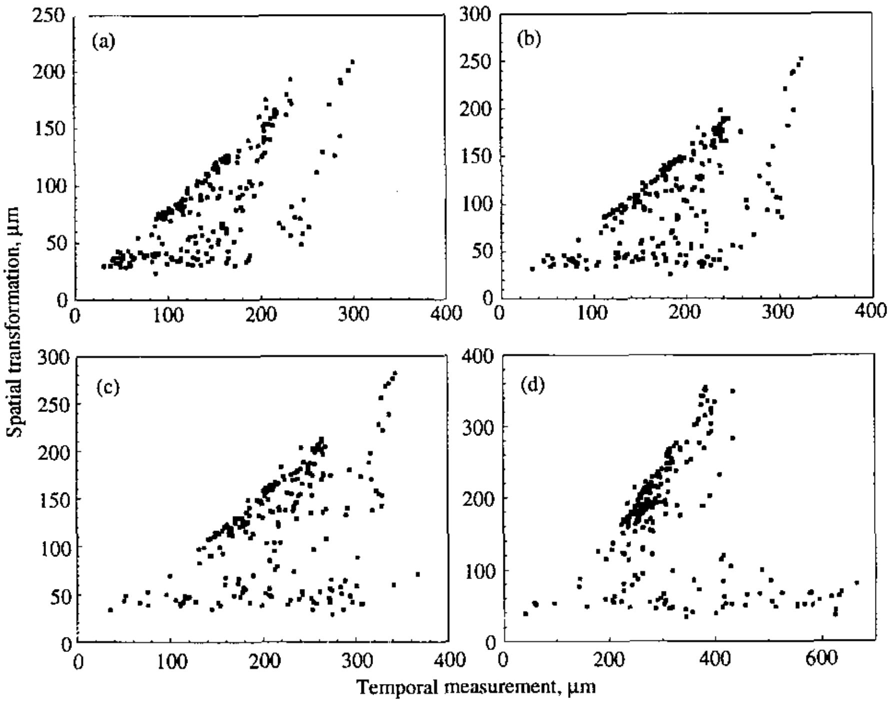

Fig. 3. Correlation of temporal measurement (x-axis) with spatial transformation (y-axis) for (a) D_{10}; (b) D_{20}; (c) D_{30}; and (d) D_{32}. Each data point constitutes the spray parameter derived from a wide range of counts (<0 to >800 000). XR8003VS nozzle, 207 kPa; 30 cm spray height, tap water

individual nozzles measured as representative of a range of orifice sizes is given in Table 2. The 95% confidence interval for each measurement is given (e.g. for the 4110-16 nozzle, measured temporally, VMD is 171 to 185 μm). The level of statistically significant difference is given for each spray parameter for each nozzle type (measured temporally or converted to its spatial equivalent), indicating the level of variability between nozzles of the same type. The nozzles gave significantly different VMDs for each individual nozzle, but not for NMD. VMD is a more variable measurement than NMD, but is also more sensitive to sizing errors. Statistical differences were observed for all nozzle types when considering volume <100 μm or <150 μm for temporal data, but not necessarily for spatial transformed data. The confidence intervals (ranges) for the measurements allow for comparisons between the drop size parameters derived from temporal or transformed data.

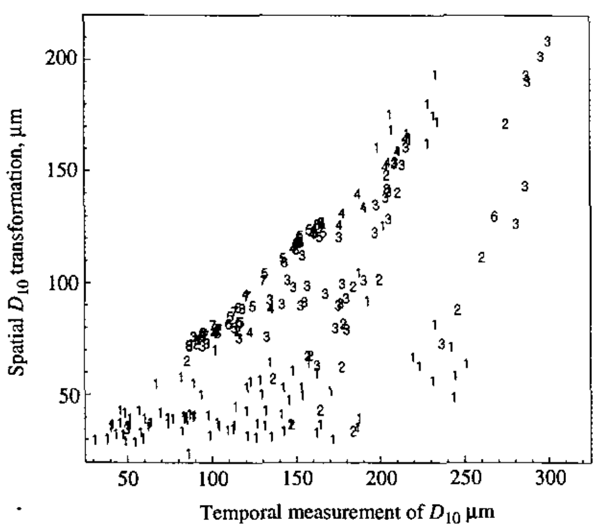

Fig. 4. Breakdown of size classes constituting the data points for the D_{10} data set [see Fig. 3(a)]. Classes are: 1: n = <500; 2: n = 500–1000; 3: n = 1000–5000; 4: n = 5000–10 000; 5: n = 10 000–15 000; 6: n = 15 000–20 000; 7: n = 20 000–40 000; 8: n = >40 000

4. Discussion

It is clear from Table 1 that increasing the distance from the orifice to the measurement point affects the eventual result derived using the PDPA. This is most likely a function of the method of measurement, namely a traverse of the spray cloud centre line and using the instrument with the "auto-high voltage" parameter off, which sets the optimum detection voltage for a given number-density/drop size distribu-

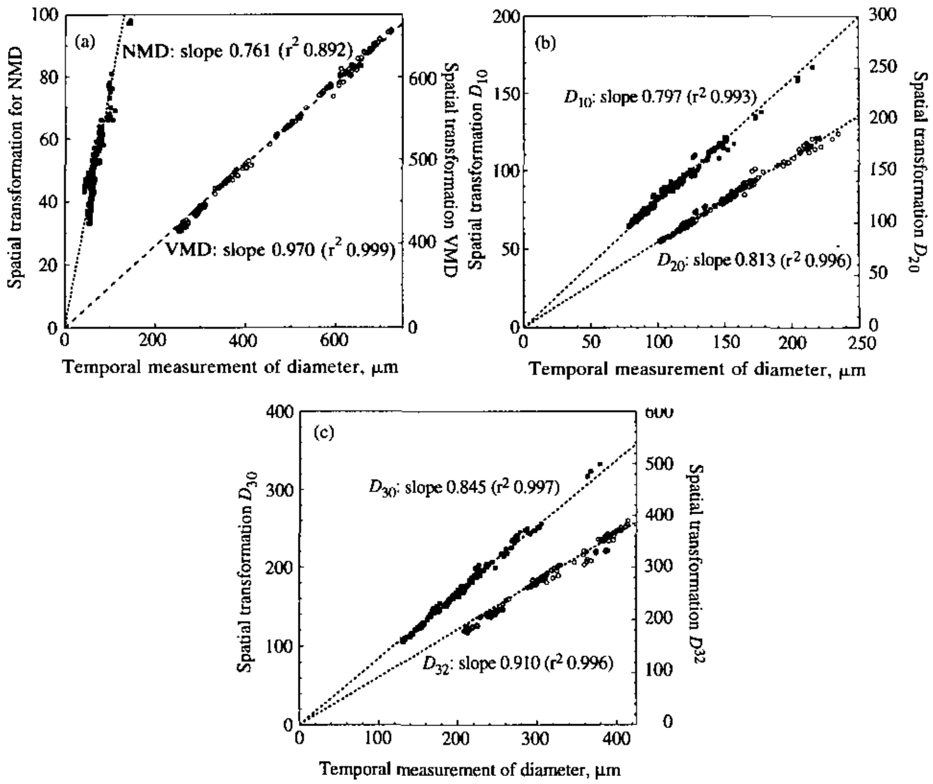

Fig. 5. The linear relationships between the temporal measurements of: (a) NMD ■—■, VMD ○—○; (b) D_{10} ■—■, D_{20} ○—○; (c) D_{30} ■—■, D_{32} ○—○; and their spatial transformations. Each data point is derived from a minimum of 10 000 counts; for the various line fits, slopes followed in brackets by the Pearson's multiple r^2 for the equation (spatial measurement = temporal measurement × coefficient). All slopes forced through intercept. XR8003VS nozzle, 138, 276, or 414 kPa, 20 cm spray height, various formulations

tion. The optimum voltage will change for different number-densities and as a traverse of a spray cloud contains a wide range of drop flux densities and sizes,[6] no optimal setting can be pre-set for the entire cloud. In this work, a compromise has been made at 325 V, determined for the centre of the flat fan spray cloud at 20 cm from the orifice. Hence, it is important that comparisons between nozzles and/or formulations be made using data sets collected in exactly the same manner. Of interest is the overestimate of the spatially transformed VMD and $D_{0\cdot9}$ (*Fig. 2*), which suggests that at positions close to the nozzle, small drops have a higher velocity than large drops.

The spatially transformed data is affected by increasing the distance from the orifice (Table 1 and *Fig. 2*) to a far greater extent than the original temporal measurements (Table 1), a function of change in velocity profile for the spray cloud. Not surprisingly, the drop size parameters describing the small component of the spray cloud are most affected. However, it should be noted that close to the nozzle, the larger drops are more likely to be distorted from spherical, and, as the PDPA will reject drops that are non-spherical, will tend to an overestimate of the small drop component. This may explain the small *over*-estimate of $D_{0\cdot9}$ and VMD close to the nozzle (*Fig. 2*).

The premise that spatial measurements can be converted to their temporal equivalents rests on the assumption that the spatial conversion performed by the Aerometrics software does emulate a spatial measurement system,[3] and that for a spray cloud of particles having the same velocity, the temporal measurement and spatial measurements give the same result.[1] For a heterogeneous spray cloud, containing not only a wide range of drop sizes but a wide range of velocities within each drop size class, the conversion from spatial to temporal measurements also relies on a narrow variance around the mean velocity for each drop size class. *Figs 4* and *5* suggest that a sample size >10 000 drops is required before the relationship between temporal and spatial measurements approaches linear, as shown in *Fig. 5*. However, of especial interest is the range of formulations and pressures for which the linear relationship holds true (water, two formulations of 2,4-D and their placebos, polymeric drift retardants, tracer, and various com-

Table 2

Various spray cloud parameters for a factory fresh batch of 80° flat fan nozzles (manufacturer unspecified), showing measured ranges for VMD, NMD, volume <100 µm and 150 µm. Nozzles spraying water at 276 kPa, probe volume 30 cm below nozzle

Nozzle	*4110-10§*	*4110-20*	*4110-30*
	Temporal	Temporal	Temporal
VMD µm	171–185**	291–321*	449–480*
NMD µm	57·3–58·3^{ns}	57·1–58·5^{ns}	60·7–64·6^{ns}
% Volume < 100 µm	11·8–14·2**	3·8–4·6*	1·8–2·2**
% Volume < 150 µm	31·3–37·3**	10·2–12·3*	4·3–5·1*
	Spatial	Spatial	Spatial
VMD µm	153–167**	270–298*	434–470*
NMD µm	48·3–49^{ns}	44·4–46·9^{ns}	49·4–51·3^{ns}
% Volume < 100 µm	20·1–23·5^{ns}	7·0–8·3^{ns}	3·2–4**
% Volume < 150 µm	41·5–48·3*	15·0–17·8^{ns}	6·3–7·8*

§ Indicates level of statistical difference between individual nozzles for the parameter measured: not significant^{ns}; significant at $P = 0{\cdot}05$*; and $P = 0{\cdot}01$**. Tukey's Honestly Significant Difference Test used throughout

binations, at 138, 276, and 414 kPa). Hence, for the nozzle tested (TeeJet XR8003VS) and for the measurement methodology employed, it is possible to transform spatially measured data to its temporal equivalent, provided the spatial data is collected under the same conditions and measures the same part of the spray cloud.

Reproducing the temporal measurement method using, for example, the Malvern system, poses technical problems. Although the methodology employed in this work has been shown to approximate reasonably a "global" analysis,[6] it should be noted that the conversion constants described here are themselves approximations. The accumulation of errors due to measurement technique must be borne in mind when considering the translation of data obtained by one method to that obtained using a second. "Global" measurements are possible, although laborious, using the PDPA (pers. comm. T. M. Wolf, Application Technology Group, Agriculture Canada, Regina, Saskatchewan, Canada), and much work using both instruments—the PDPA and Malvern—would be required to obtain the relevant data.

In this work, we used what we consider to be some of the best designed and manufactured nozzles available for spraying agrochemicals. Agricultural nozzles have been credited with wide tolerances of manufacture which obviate the need for accurate measurements of spray clouds. Table 2 indicates that nozzle variability is sufficiently large to be detected using the measurement techniques currently available. Whether these differences constitute a biological difference in a field situation has yet to be resolved. The spatial transformations overlap the temporal measurements for VMD only (Table 2). For all other parameters, the spatial estimates are statistically different from the temporal measurements, by as much as a factor of two. If spatially collected data were to be presented documenting the likelihood of drift from a given nozzle/formulation, the estimates of possible drift hazard could be incorrect to a degree that can only be considered unacceptable.

The analysis and interpretation of spatial and temporal measurements of the same phenomenon is a problem common to a number of disciplines. In agriculture and ecology, for example, we are frequently required to assess the size of an animal or plant population. We may wish to assess the size of a population at a particular instant, but total enumeration being impossible, sampling is required which takes time. The longer the period necessary to acquire a sample large enough for analysis, the larger the bias in our estimates: the population size is continually changing as a result of births, deaths, migration, or behaviour. The less instantaneous our sample, the less precise our estimate. Ideally, taking photographs of a population provides an instantaneous picture of the population state in space (spatial sampling), but we lose information on rates of change, necessary for predicting population size at a future time. Sampling over time provides information on rates of change, but we lose precision on position, so our projection of population change in time becomes less precise. *Fig. 4* clearly shows the effect that increasing sample size has on our ability to overcome uncertainty in such measurements.

Thus, the implications of this work go well beyond the practical issue of relating spatial and temporal drop sizing techniques, but may have value in other areas such as population ecology and agricultural pest management by providing further insights into the way sample size impacts the measured property. Examination of insect sample data at the very large (country) scale suggests that population estimates are dependent on size of the sampler. This phenomenon has been called fractal.[10]

5. Conclusions

The analysis of the spray clouds produced by agricultural nozzles using laser-based devices is a complex subject. No single device offers a comprehensive source of results in answer to the varied requirements of researchers in the field of spray application. However, we would argue that assessing drop spectra of agricultural flat fans using spatial measurement systems cannot be justified when the results are for purposes such as label recommendations, formulation registration, or extrapolating to potential drift: spatial measurements can overestimate the proportion of drops <100 μm by more than 100%. This research has demonstrated that within the confines of agricultural applications using conventional hydraulic nozzles, spatial measurements made under specific conditions can be converted to their temporal equivalents with little loss of information, provided the conversion coefficients are available. More importantly, the coefficients are independent of formulation and pressure, within wide tolerances. At present, these coefficients exist only for the TeeJet stainless steel-insert XR8004VS nozzle, and for a specific set of measurement circumstances.

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