

Parameters influencing deposit estimation when using water sensitive papers

Emanuele Cerruto, Claudia Aglieco, Sabina Failla, Giuseppe Manetto

Department DiGeSA, Section of Mechanics and Mechanisation, University of Catania, Italy

Abstract

The aim of the study was to assess the possibility of using water sensitive papers (WSP) to estimate the amount of deposit on the target when varying the spray characteristics. To identify the main quantities influencing the deposit, some simplifying hypotheses were applied to simulate WSP behaviour: log-normal distribution of the diameters of the drops and circular stains randomly placed on the images. A very large number (4704) of images of WSPs were produced by means of simulation. The images were obtained by simulating drops of different arithmetic mean diameter (40-300 μm), different coefficient of variation (0.1-1.5), and different percentage of covered surface (2-100%, not considering overlaps). These images were considered to be effective WSP images and then analysed using image processing software in order to measure the percentage of covered surface, the number of particles, and the area of each particle; the deposit was then calculated. These data were correlated with those used to produce the images, varying the spray characteristics. As far as the drop populations are concerned, a classification based on the volume median diameter only should be avoided, especially in case of high variability. This, in fact, results in classifying sprays with very low arithmetic mean diameter as extremely or ultra coarse. The WSP image analysis shows that the relation between simulated and computed percentage of covered surface is independent of the type of spray, whereas impact density and unitary deposit can be estimated from the computed percentage of covered surface only if the spray characteristics (arithmetic mean and coeffi-

cient of variation of the drop diameters) are known. These data can be estimated by analysing the particles on the WSP images. The results of a validation test show good agreement between simulated and computed deposits, testified by a high (0.93) coefficient of determination.

Introduction

Spray deposit and superficial coverage are among the main factors influencing the biological efficacy of applied pesticides, as well as the environmental hazards. The correct deposit ensures the lethal dose on the target, while for non-systemic products, coverage increases the probability of contact between pest and pesticide.

Both aspects are influenced by many other factors, among which the most important is the spray spectrum (Hewitt, 1997; Matthews, 2004; Nuyttens *et al.*, 2007). The ideal spectrum will maximise spray efficiency for depositing and transferring the required dose to the target, while minimising off-target losses due to drift and run-off, and reducing operator exposure (Hewitt *et al.*, 1998).

An efficient pesticide application should ensure uniform distribution of the droplets over the entire target, including the underside of the leaves. This can be better achieved with small droplets capable of drifting inside the canopy. In fact, since large droplets are heavier, they are not usually deflected by air movement, so their redistribution within the crop foliage is limited. Moreover, large droplets are more prone to roll off onto the ground, so increasing the environmental impact. Finally, large droplets are fewer in number, so reducing coverage and probability of reaching the pest target. On the other hand, if the droplets become too small, they are more subjected to drift and evaporation, and so do not reach the target.

Spray spectrum, therefore, plays a crucial role in reducing any negative impacts of pesticides on the environment and on public health. The European Directives 2009/127/CE and 2009/128/CE recognise the use of pesticides *as posing threats both to human health and the environment* and therefore *a sustainable use of pesticides should be established, taking account of precautionary and preventive approaches*. Moreover, *the design, construction and maintenance of machinery for pesticide application play a significant role in reducing the adverse effects of pesticides on human health and the environment* (European Commission, 2009a, 2009b).

Foliar deposit is currently assessed by adding suitable tracers to the mixture, then spraying and measuring the amount that reaches the target, while foliar coverage is assessed by analysing the impact of the drops on suitable artificial targets. Widely used tracers are water-soluble dye such as *Poinceau Red*, yellow tartrazine, fluorescent products (Pergher, 2004; Cerruto, 2007; Jamar *et al.*, 2010) or metal chelates such as copper, manganese, and zinc (Cross *et al.*, 2001; Ade and Pezzi, 2001; Solanelles *et al.*, 2006).

The most common artificial targets used to study superficial coverage are water sensitive papers (Salyani and Fox, 1999; Pezzi and Rondelli, 2000; Fox *et al.*, 2003) and polyvinyl chloride (PVC) targets

Correspondence: Emanuele Cerruto, Department DiGeSA, Section of Mechanics and Mechanisation, University of Catania, via S. Sofia 100, 95123 Catania, Italy.
Tel. +39.095.7147514 - Fax: +39.095.7147600.
E-mail: ecerruto@unict.it

Key words: pesticides, image analysis, drop pulverisation.

Contributions: the authors contributed equally.

Conflict of interests: the authors declare no potential conflict of interests.

Received for publication: 1 July 2013.

Accepted for publication: 31 August 2013.

©Copyright E. Cerruto *et al.*, 2013

Licensee PAGEPress, Italy

Journal of Agricultural Engineering 2013; XLIV:e9

doi:10.4081/jae.2013.e9

This article is distributed under the terms of the Creative Commons Attribution Noncommercial License (by-nc 3.0) which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

covered with silicon oil (Juste *et al.*, 1990; Cerruto, 2001). Water sensitive papers (WSPs) allow for a quick assessment of the superficial coverage, while PVC targets allow for a better study of the particles, as they can also be used with high volume rates. The particle size distributions in the two target types are strictly correlated (Cerruto *et al.*, 2009).

In the present study, the behaviour of water sensitive papers was simulated in order to estimate, in addition to the superficial coverage, the spray characteristics and the amount of deposit on the target.

Materials and methods

Sprays

Sprays can be classified according to the drop size spectra as established by the British Crop Protection Council (BCPC) classification scheme (Doble *et al.*, 1985; Southcombe *et al.*, 1997) or the ASAE S572.1 classification scheme (ASABE, 2009). Drop size can be described by means of a suitable probability density function (PDF) of the number of the drops. So, given a spray consisting of N_T drops and using $f_0(D)$ to indicate the PDF of the drop number, the quantity $N_T f_0(D)dD$ represents the number of drops whose diameter ranges from D to $(D + dD)$. Several PDFs have been proposed in literature to characterise the drop distribution, including the normal, the log-normal, the Rosin-Rammler and the gamma distributions (Ade and Fabbri, 2000; Babinsky and Sojka, 2002).

Beside the PDF, several mean diameters can be calculated to characterise the distribution (statistical moments) according to the formula:

$$D_{pq}^{p-q} = \frac{\int_0^{\infty} D^p f_0(D) dD}{\int_0^{\infty} D^q f_0(D) dD} \quad (1)$$

with p and q as typically positive integers. The mean diameters most commonly used are (Schick, 2008):

D_{10} : the arithmetic mean diameter (AMD);

D_{20} : the surface mean diameter;

D_{30} : the volume mean diameter;

D_{32} : the Sauter mean diameter, defined as the diameter of a drop having the same volume-to-surface area ratio as the total volume of all the drops to the total surface area of all the drops.

Other diameters referring to the volume of liquid sprayed or the number of drops can also be provided:

- D_{op} : a value so that the fraction p of the total volume of liquid sprayed consists of drops with diameters smaller or equal to this value. Commonly used fractions are 10% ($P=0.1$), 50% ($P=0.5$), and 90% ($P=0.9$). The $D_{v0.1}$ diameter is best suited to evaluate drift potential of individual drops, the $D_{v0.5}$ [volume mean diameter (VMD)] diameter is mainly used to compare the average drop size from various atomisers, and the $D_{v0.9}$ diameter is best suited when complete evaporation of the spray is required.

- D_{np} : a diameter so that the fraction p of the total number of drops consists of drops with diameters smaller or equal to this value. Commonly used fractions are 10% ($P=0.1$), 50% ($P=0.5$), and 90% ($P=0.9$). The $D_{n0.5}$ diameter is also known as numeric mean diameter (NMD).

Parameters indicative of the uniformity of the drop size distribution are the relative span factor (RSF), defined as:

$$RSF = \frac{D_{v0.9} - D_{v0.1}}{D_{v0.5}} \quad (2)$$

and the VMD-to-NMD ratio.

The experiments

Sprays with different AMD and different coefficient of variations (CV) were simulated. Reference AMD values (D_m^*) ranged from 40 up to 300 μm with 20 μm intervals (14 values), while reference CV values (CV^*) ranged from 0.1 to 1.5 with 0.2 intervals (8 values). Drop diameters (D) were log-normal distributed according to the PDF function:

$$f_0(D) = \frac{1}{\sqrt{2\pi} \sigma D} e^{-\frac{(\ln D - \mu)^2}{2\sigma^2}} \quad (3)$$

Expected mean E , variance Var and coefficient of variation CV are:

$$E = e^{\mu + \frac{1}{2}\sigma^2}; \quad Var = (e^{\sigma^2} - 1)e^{2\mu + \sigma^2}; \quad CV = \sqrt{e^{\sigma^2} - 1} \quad (4)$$

Fixing $E = D_m^*$ and $CV = CV^*$, Equations (4) allow the calculation of μ and σ :

$$\mu = \frac{1}{2} \ln \frac{D_m^*}{1 + CV^{*2}}; \quad \sigma = \sqrt{\ln(1 + CV^{*2})} \quad (5)$$

Images of WSPs 2×7 cm in size were produced, with reference values of superficial coverage S^* (not considering overlaps) ranging from 2% up to 10% with 2% intervals and from 10% up to 100% with 10% intervals (14 values). For each reference value of mean diameter, superficial coverage and CV, three replicates were carried out, so producing a total of 4704 images.

Simulation was developed according to the following procedure:

i) given the reference values of mean diameter D_m^* (μm) and coefficient of variation CV^* , calculate μ and σ according to the Equation (5) and then produce the drop diameter population (D) according to the Equation (3). The number of drops was calculated on the basis of the reference value of superficial coverage S^* (%). Due to the intrinsic variability of the simulation process, when the error between simulated and reference values was greater than 1%, other drop populations were produced;

ii) given the drop diameters D (μm), produce the corresponding stain diameters D_s (μm). Stain diameters were estimated using the equation:

$$D_s = 0.938 \cdot D^{1.143} \quad (6)$$

devised by the Authors by analysing the spread factor *i.e.* the ratio between stain diameter and drop diameter (QInstruments) (Figure 1);

iii) produce the WSP images by randomly allocating the stains, considered to be circular shaped. Images were produced with a resolution of 1200 dpi, sufficient to detect particles 24 μm in diameter;

iv) compute and store all the data used to produce each image: drop diameter population (D), simulated values of percentage of covered

surface S_s (not considering overlaps), arithmetic mean (D_{ms}), coefficient of variation (CV_s) and volume median diameter (VMD_s) of the drops, impact density ID_s (number of drop/cm²), and unitary deposit d_s (μL/cm²).

All the procedures were implemented using the open source software *R* (R Development Core Team, 2012).

Data analysis

The images produced via simulation were analysed using *ImageJ* software (Abramoff *et al.*, 2004) as real WSP images. The software detects the particles, without distinguishing between the overlapped ones, and provides some summary data for each image (percentage of covered surface S_c , particle density PD_c *i.e.* number of particles/cm²), as well as some data for each particle (area and shape descriptors). These data were correlated with the ones used to produce the images, and in particular the trends of S_s , ID_s and d_s versus S_c were studied varying the spray characteristics (D_m^* and CV^*).

Subsequently, studying the area of each particle detected by *ImageJ*, other quantities were computed, among which: i) the equivalent diameter D_{sc} of each particle (that of the circle with the same area); ii) the diameter D_c of the drop capable of producing a stain with diameter D_{sc} ; the calculation was carried out by inverting Equation (6); iii) the coefficient of variation CV_c and the arithmetic mean diameter D_{mc} of these drops; iv) the unitary deposit d_c (μL/cm²) due to these drops.

Again, these data were correlated with the theoretical data used to produce the images, and in particular the trends of d_s versus d_c , CV_c versus S_c and D_{mc} versus S_c varying the spray characteristics and image features were analysed. All statistical analyses and graphical representations were carried out using the same *R* software.

Results and discussion

Drop populations

Simulated sprays were classified according to the ASAE S572.1 standard (ASABE, 2009), considering, as classification criterion, only the VMD. The number of images produced for each class is reported in Table 1. Due to the variability introduced by the coefficient of variation (Figure 2), sprays even with low AMD were classified as extremely or ultra coarse. This implies that the VMD alone is not adequate for spray description, especially in case of high values of CV, RSF or VMD-to-NMD ratio. This last parameter grows very rapidly (up to 40) when the CV increases, especially in sprays with low AMD values. A more accurate classification should be carried out by considering the cumulative volumetric droplet size curves and taking into account other volume and number diameters.

The WSP images corresponding to the drop distributions of Figure 2 are reported in Figure 3. The reference percentage of covered surface is 50% for all the images.

Simulated and computed superficial coverage

When the simulated (not considering overlaps) percentage of covered surface S_s increases from 2% up to 100%, the one S_c computed from the images varies for each spray type (Figure 4). The regression equation of S_s on S_c is:

$$S_s = a + b \ln(100 - S_c) \tag{7}$$

The coefficients a and b are reported in Table 2. All the determina-

tion coefficients (range 0.995-1.000) are highly significant.

Considering that the regression coefficients a and b are almost equal for all the spray types (the biggest differences are due to the ultra coarse spray only), it is possible to conclude that the relation between S_s and S_c is independent of the type of spray. Including all the values in the same model, the regression equation becomes:

$$S_s = 471.0 - 102.3 \ln(100 - S_c) \tag{8}$$

with coefficient of determination R^2 equal to 0.997 highly significant. When the computed percentage of covered surface increases towards 100%, the simulated one tends to move asymptotically towards positive

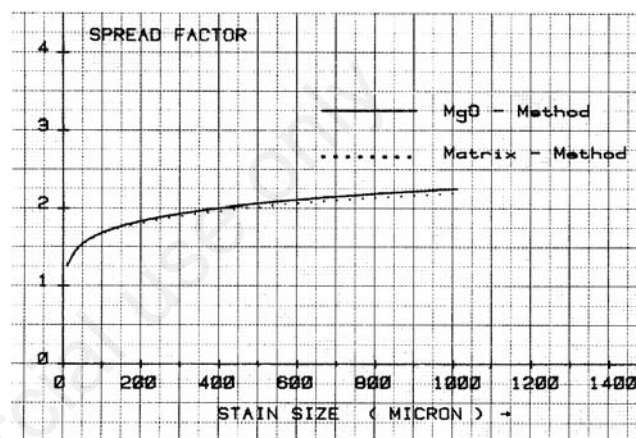


Figure 1. Spread factor versus spot diameter (QInstruments).

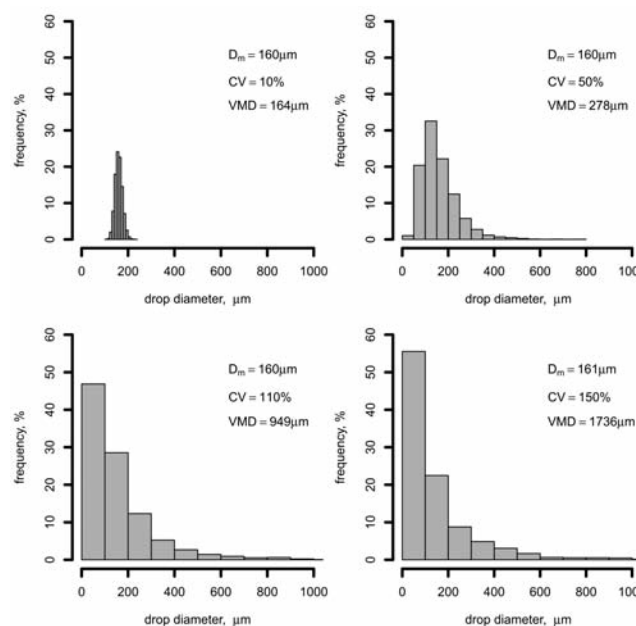


Figure 2. Examples of spray distributions. D_m , arithmetic mean diameter; CV, coefficient of variation; VMD, volume median diameter.

Table 1. Number of images simulated for each spray type.

Reference diameter (μm)	Spray type according to the ASAE S572.1 standard* (VMD, μm) (ASABE, 2009)							
	XF <50	VF 50–136	F 136–177	M 177–218	C 218–349	VC 349–428	XC 428–622	UC >622
40	84	84	29	13	43	12	36	35
60	0	126	42	0	44	25	36	63
80	0	85	41	29	42	13	45	81
100	0	84	40	2	42	16	43	109
120	0	42	42	41	41	4	44	122
140	0	0	84	0	44	40	38	130
160	0	0	42	42	42	19	33	158
180	0	0	0	43	83	3	44	163
200	0	0	0	42	69	15	44	166
220	0	0	0	0	84	42	42	168
240	0	0	0	0	84	40	17	195
260	0	0	0	0	85	2	45	204
280	0	0	0	0	78	6	49	203
300	0	0	0	0	43	41	43	209
Total	84	421	320	212	824	278	559	2006

VMD, volume median diameter; XF, extremely fine; VF, very fine; F, fine; M, medium; C, coarse; VC, very coarse; XC, extremely coarse; UC, ultra coarse.

Table 2. Regression parameters of S_s on S_c .

Spray type	a			b			R^2
	LL	E	UL	LL	E	UL	
XF	457.5	461.8	466.0	-101.3	-100.3	-99.3	1.0000
VF	460.5	462.4	464.3	-100.9	-100.4	-100.0	1.0000
F	461.1	463.3	465.5	-101.1	-100.6	-100.1	1.0000
M	461.6	464.3	466.9	-101.5	-100.8	-100.2	0.9999
C	464.0	465.4	466.8	-101.4	-101.1	-100.7	0.9999
VC	463.9	466.3	468.7	-101.8	-101.3	-100.7	0.9998
XC	466.3	468.0	469.7	-102.0	-101.6	-101.2	0.9997
UC	478.7	479.6	480.5	-104.3	-104.1	-103.9	0.9949

a, b , coefficients; LL, lower limit; E, estimated; UL, upper limit; XF, extremely fine; VF, very fine; F, fine; M, medium; C, coarse; VC, very coarse; XC, extremely coarse; UC, ultra coarse.

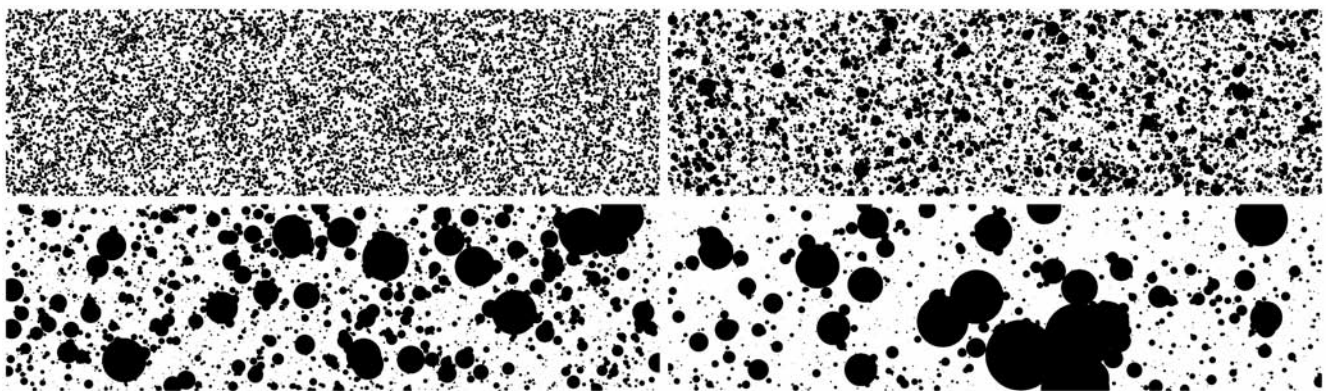


Figure 3. Water sensitive paper images corresponding to the drop distributions shown in Figure 2. The reference coverage is 50% for all the images.

infinity. According to Equation (8), when the simulated percentage of covered surface ranges from 10% up to 100%, the computed percentage ranges from 9.4% up to 62.4% and then the overlap ranges from 0.6% up to 37.6%.

Unitary deposit

Figure 5 reports the simulated unitary deposits d_s ($\mu\text{L}/\text{cm}^2$) in function of the computed percentage of covered surface S_C (%) for some AMD values. The trends are well described by quadratic relations of the form:

$$d_s = b_0 + b_1 S_C + b_2 S_C^2 \tag{9}$$

with coefficients b_0 , b_1 and b_2 ($\mu\text{L}/\text{cm}^2$) affected by mean and CV of the drop diameters (Figure 6). The coefficients of determination range from 0.933 up to 1.000, and are highly significant. This implies that the deposit can be estimated from the superficial coverage, but only if the spray characteristics are known. The estimation of arithmetic mean and CV of the drop diameters requires an analysis of the particles.

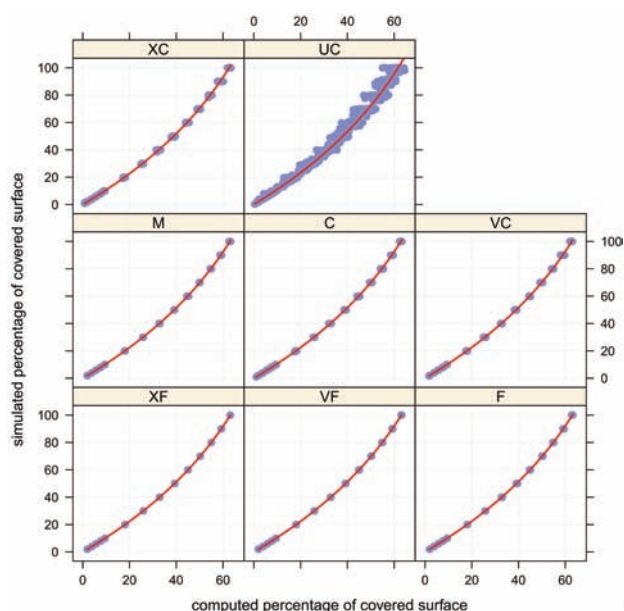


Figure 4. Correlations between simulated and computed percentage of covered surface at varying spray type. XF, extremely fine; VF, very fine; F, fine; M, medium; C, coarse; VC, very coarse; XC, extremely coarse; UC, ultra coarse.

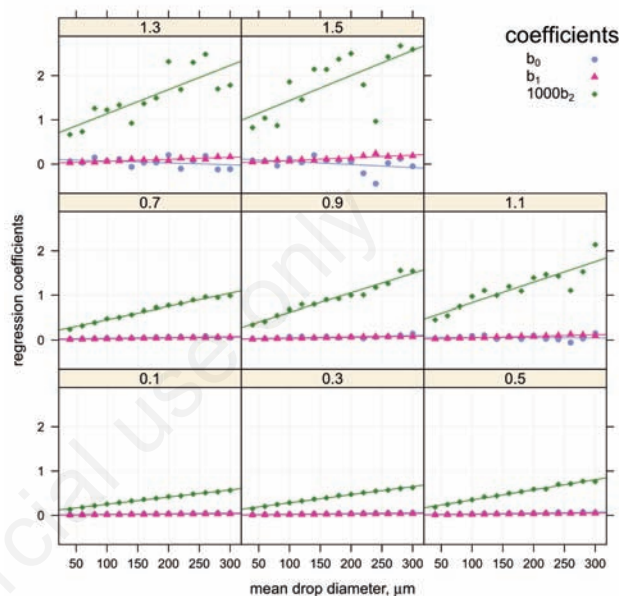


Figure 6. Coefficients b_0 , b_1 and b_2 ($\mu\text{L}/\text{cm}^2$) at varying mean and coefficient of variation of the drop diameters for the calculation of the deposit according to the Equation 9.

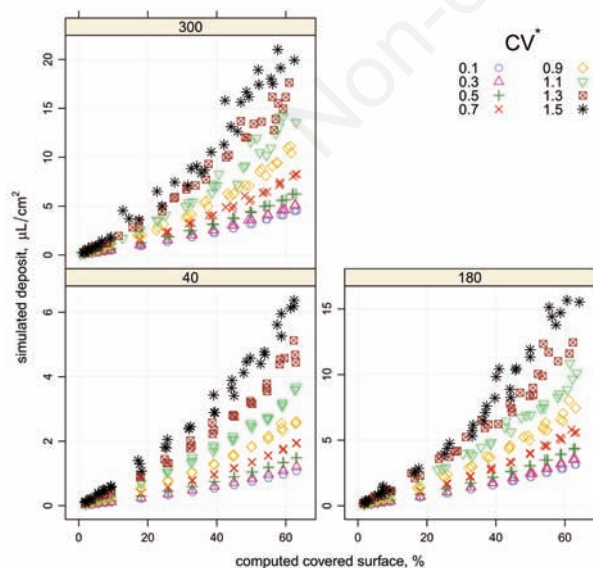


Figure 5. Examples of correlation between computed percentage of covered surface and simulated unitary deposit at varying mean and coefficient of variation (CV) of the drop diameters.

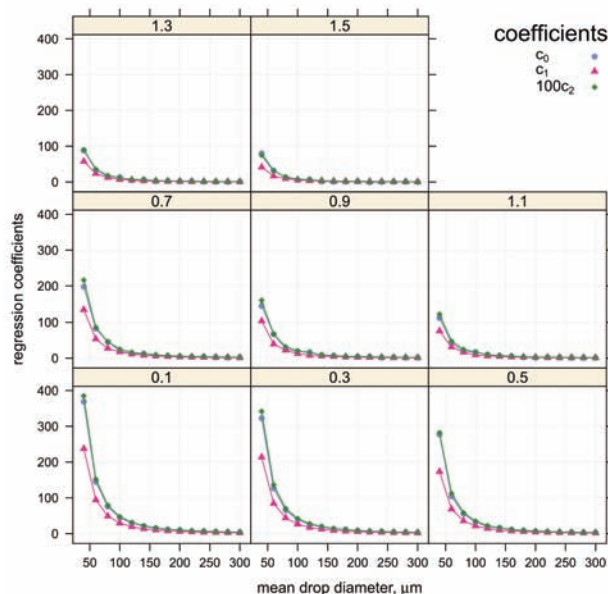


Figure 7. Coefficients c_0 , c_1 and c_2 (cm^{-2}) at varying mean and variation of the drop diameters for the calculation of the impact density according to the Equation 10.

Impact density

The impact density ID_S (cm^{-2}) (no. drops/ cm^2) increases in a quadratic manner *versus* the computed percentage of covered surface S_C (%):

$$ID_S = c_0 + c_1 S_C + c_2 S_C^2 \quad (10)$$

Again, the regression equation coefficients c_0 , c_1 and c_2 (cm^{-2}) depend on mean and CV of the drop diameters (Figure 7). The coefficients of determinations range from 0.987 up to 1.000.

Particle analysis

The analysis of the particles detected by *ImageJ* on the WSP images allows for the calculation of several quantities, among which spray characteristics, particle density and unitary deposit.

The first step was aimed at estimating the spray characteristics CV and AMD. To this end, the trends of D_{mC} and CV_C *versus* S_C , computed according to the procedure described in methodology, were analysed. As an example, Figure 8 reports the results from varying CV when $D_m^* = 140 \mu\text{m}$ or from varying AMD when $CV^* = 0.5$. Similar graphs were obtained for all the other test conditions.

An estimate of CV and AMD of the drop diameters can be obtained by extrapolating the trends of D_{mC} and CV_C to low S_C values (<5%). Figure 9 reports the relative errors, computed as:

$$RE_{D_m} = \frac{D_m^* - D_{mC}}{D_m^*}; \quad RE_{CV} = \frac{CV^* - CV_C}{CV^*} \quad (11)$$

In most cases, these are less than 10%: they are greater when estimating AMD less than $100 \mu\text{m}$ or CV less than 20% or higher than 100%.

The particle density *versus* S_C , in contrast to the impact density, due to the overlapping, reaches a maximum when the percentage of cov-

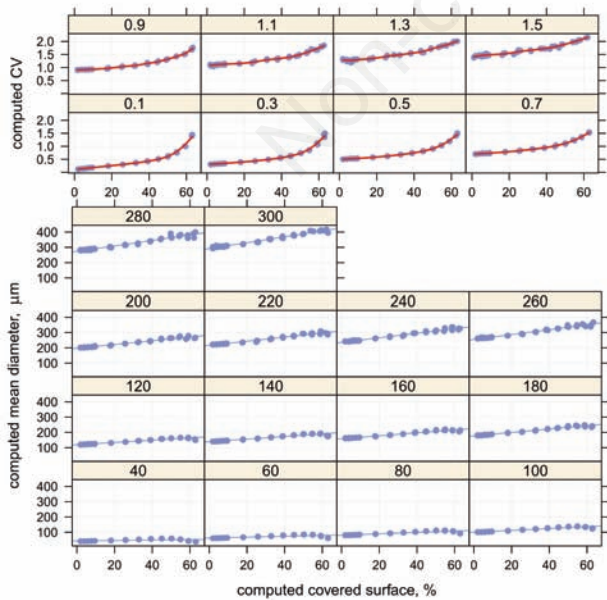


Figure 8. Examples of trends of computed coefficient of variation (CV) *versus* S_C at fixed arithmetic mean diameter (AMD) ($140 \mu\text{m}$) and of computed AMD *versus* S_C at fixed CV (0.5).

ered surface is approximately between 20% and 40% (Figure 10). Values can differ greatly, depending on the spray characteristics.

Finally, the particle analysis offers an alternative to Equation (9) to estimate the unitary deposit. As an example, the deposit d_C ($\mu\text{L}/\text{cm}^2$), computed by analysing the particles, was related to that simulated d_S ($\mu\text{L}/\text{cm}^2$) when the CV was 0.5 (Figure 11). The interpolating functions take the form:

$$d_S = a_0 + a_1 \cdot e^{-a_2 \cdot d_C} \quad (12)$$

where:

a_0 ($\mu\text{L}/\text{cm}^2$), a_1 ($\mu\text{L}/\text{cm}^2$) and a_2 ($\text{cm}^2/\mu\text{L}$) are coefficients depending on the spray characteristics. Figure 12 reports their trend *versus* the mean drop diameter when the CV is 0.5. Similar graphs were obtained at different CV values.

Altogether, the particle analysis on WSP images allows the main quantities of a spray application to be estimated: spray characteristics and unitary deposit.

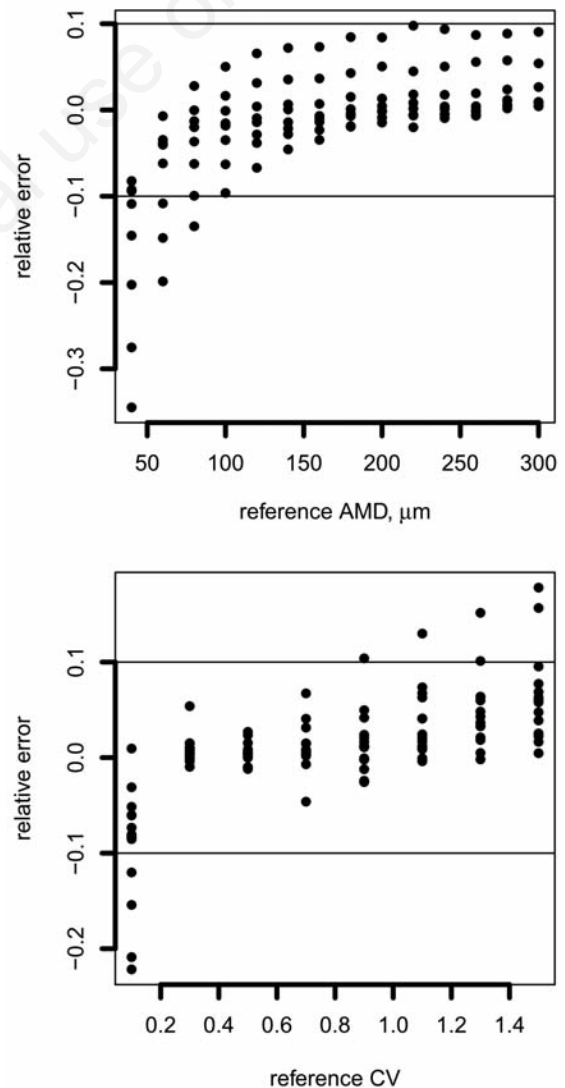


Figure 9. Relative error in estimating coefficient of variation (CV) and arithmetic mean diameter (AMD) of drop diameters.

Validation

The previous procedure was validated by applying it to a spray characterised by $D_m^* = 150 \mu\text{m}$ and $CV^* = 0.8$ (values not included in the experimental design). WSP images were simulated by considering impact densities increasing from 50 to 600 cm^{-2} with intervals of 50. No control was applied to the effective drop population simulated, as in a *real-life* spray application: the effective CV ranged from 0.76 to 0.98, the effective AMD ranged from 146 to 155 μm . Each test condition was

replicated three times for a total of 36 images.

The trends of D_{mc} (linear) and CV_C (local regression) *versus* S_C are reported in Figure 13; their extrapolation at $S_C = 0$ provides an estimation of 150 μm for the AMD and 0.82 for the CV. The relative error with respect to the reference quantities is approximately 2%.

Estimation of the unitary deposit using Equation (9) requires the coefficients b_0 , b_1 and b_2 to be known; these were computed on the basis of Figure 6, fixing $D_m = 150 \mu\text{m}$, $CV = 0.82$ and by using linear interpolations. The computed values were:

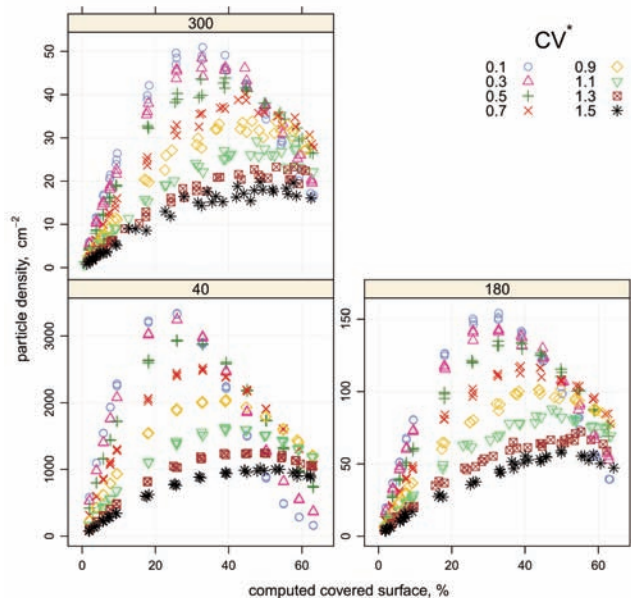


Figure 10. Example of correlation between particle density and computed percentage of covered surface at varying mean and coefficient of variation (CV) of the drop diameters.

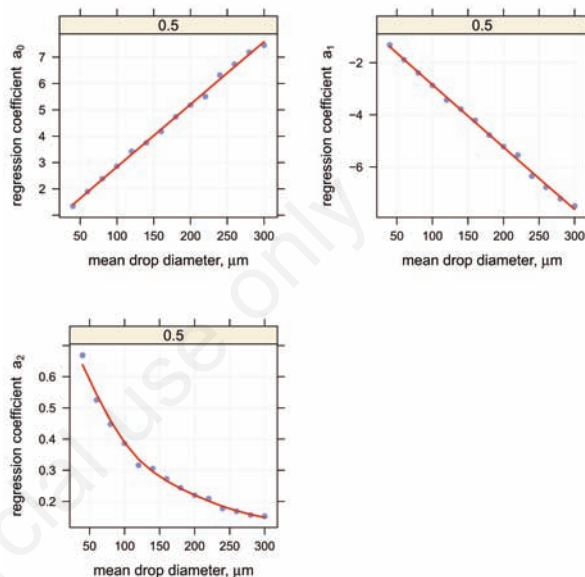


Figure 12. Coefficients a_0 ($\mu\text{L}/\text{cm}^2$), a_1 ($\mu\text{L}/\text{cm}^2$) and a_2 ($\text{cm}^2/\mu\text{L}$) at varying mean drop diameter when $CV=0.5$ for the calculation of the unitary deposit according to Equation 12.

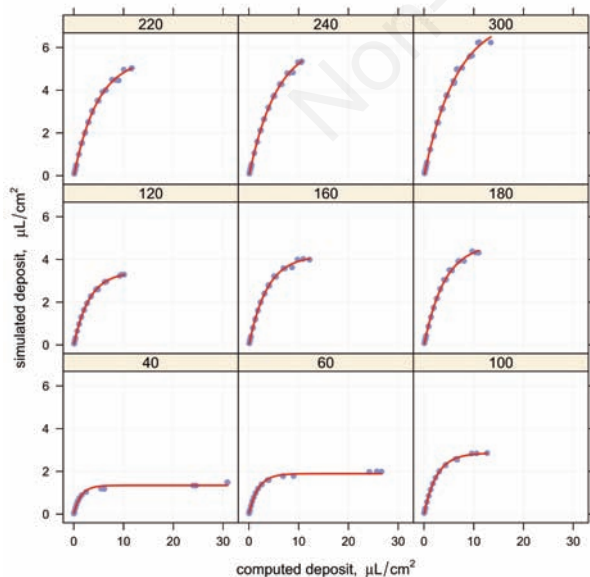


Figure 11. Simulated *versus* computed deposit for some arithmetic mean diameter values when $CV=0.5$.

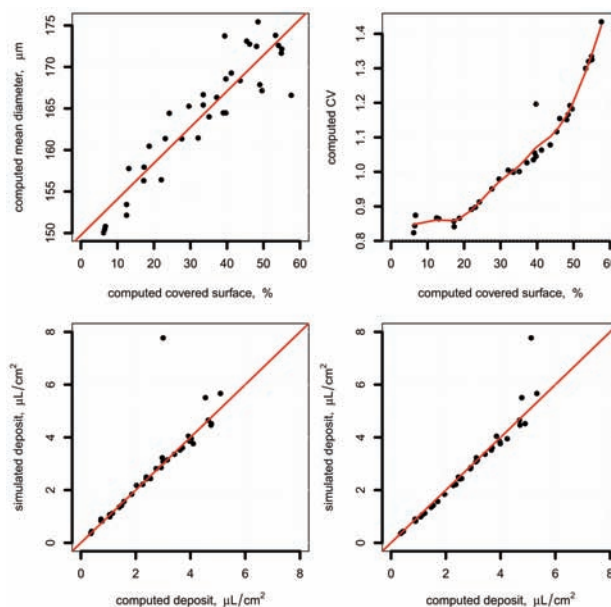


Figure 13. Results of the validation test: estimate of arithmetic mean diameter, coefficient of variation and unitary deposit using Equation 9 (left) and Equation 12 (right).

$$b_0 = 0.048 \mu\text{L}/\text{cm}^2; b_1 = 0.045 \mu\text{L}/\text{cm}^2; b_2 = 0.744/1000 \mu\text{L}/\text{cm}^2 \quad (13)$$

The comparison between computed and simulated deposit is reported in Figure 13. Only one deposit was heavily underestimated due to the presence of a very big drop on the image that masks other drops.

When using Equation 12, the coefficients a_0 , a_1 and a_2 , calculated on the basis of graphs (Figure 12) were:

$$a_0 = 7.375 \mu\text{L}/\text{cm}^2; a_1 = -7.435 \mu\text{L}/\text{cm}^2; a_2 = 0.163 \text{ cm}^2 / \mu\text{L} \quad (14)$$

The simulated deposits *versus* the computed ones are reported in Figure 13 and show a better agreement with respect to the previous approach, testified by a higher coefficient of determination (0.926 *vs* 0.786) and a lower residual sum of square (7.51 *vs* 23.50). The particle analysis is, therefore, more precise in estimating the unitary deposit, even if it requires a greater computational effort.

Conclusions

The results of this study show that, under the hypotheses of spherical drops, log-normal distribution of drop diameters and circular stains, the spray characteristics in terms of mean drop diameter, coefficient of variation, impact density and unitary deposit, besides the covered surface, can be assessed by using water sensitive papers.

This can be demonstrated by the following considerations.

- The relation between simulated superficial coverage and computed superficial coverage is highly significant and independent of the type of spray; this means it is easy to estimate the overlap between the particles.

- The relations between simulated unitary deposit and computed superficial coverage are highly significant, as are the relations between impact density and computed superficial coverage. However, these relations are affected by CV and AMD of the drop diameters.

- The particle analysis on the WSP images allows the spray characteristics CV and AMD and the unitary deposit to be estimated.

- The validation test shows a good agreement between simulated and computed values (AMD, CV, and unitary deposit).

It is also important to emphasise that, as far as the drop population is concerned, the classification criterion based on the VMD alone is not adequate to describe the spray because sprays with low arithmetic mean diameter, in the presence of high CV, would be classified as extremely or ultra coarse.

Therefore, the analysis of the water sensitive paper images provides a complete description of the treatment in terms of unitary deposit, drop diameter, particle and impact density. Further studies are necessary to cover other situations (*e.g.* different probability distribution functions of drop diameter in order to evaluate whether the results are distribution independent) and to verify the models under experimental conditions. Moreover, the results will be useful in calibrating the sprayers according to the recently introduced regulations in order to further reduce the environmental impact of chemical pest control.

Main symbol list

Drop distribution

D : drop diameter

$f_0(D)$: probability density function of drop diameter

D_{pq} : mean diameters (statistical moments of distribution f_0)

D_{vp} : diameters referring to the volume

D_{np} : diameters referring to the number

μ , σ parameters of the log-normal distribution

Reference values

D_m^* : reference arithmetic mean diameter

CV^* : reference coefficient of variation

S^* : reference percentage of covered surface (not considering overlaps)

Simulated values (for each water sensitive paper image)

D_s : stain diameter due to a drop of diameter D

S_s : simulated percentage of covered surface (not considering overlaps)

D_{ms} : simulated arithmetic median diameter

CV_s : simulated coefficient of variation

VMD_s : simulated volume mean diameter

ID_s : simulated impact density

d_s : simulated unitary deposit

Computed values (from each water sensitive paper image)

S_C : computed percentage of covered surface (considering overlaps)

D_{sC} : equivalent diameter of each particle

D_C : diameter of a drop capable of producing a stain with diameter D_{sC}

CV_C : computed coefficient of variation of the drops with diameter D_C

d_C : computed unitary deposit

Regression equations

a , b : coefficients in the regression equation of S_s on S_C

a_0 , a_1 , a_2 and b_0 , b_1 , b_2 : coefficients in the regression equations of d_s on d_C

c_0 , c_1 , c_2 : coefficients in the regression equation of ID_s on S_C

$RE_{D_m^*}$: relative error on the estimate of D_m^*

RE_{CV^*} : relative error on the estimate of CV^*

References

- Abramoff M.D., Magelhaes P.J., Ram S.J. 2004. Image processing with ImageJ. *Biophot. Int.* 11:36-42.
- Ade G., Fabbri C. 2000. Indagine teorica sul legame tra grado di copertura, numerosità e distribuzione della popolazione delle impronte sulle cartine idrosensibili. *Riv. Ing. Agr.* 2:104-8.
- Ade G., Pezzi F. 2001. Results of field tests on a recycling air-assisted tunnel sprayer in a peach orchard. *J. Agr. Eng. Res.* 80:147-52.
- ASABE (American Society of Agricultural and Biological Engineers) Standards. 2009. ANSI/ASAE S572.1: MAR2009. Spray nozzle classification by droplet spectra. ASAE, St. Joseph, MI, USA. Available from: <http://www.asabe.org/standards/images.aspx>
- Babinsky E., Sojka P.E. 2002. Modeling drop size distribution. *Progr. Ener. Combustion Sci.* 28:303-29.
- Cerruto E. 2001. Caratterizzazione mediante analisi d'immagine di bersagli in PVC per prove di irrorazione. *Riv. Ing. Agr.* 2:101-7.
- Cerruto E. 2007. Influence of airflow rate and forward speed on the spray deposit in vineyard. *Riv. Ing. Agr.* 1:7-14.
- Cerruto E., Balloni S., Conti A., Caruso L. 2009. Caratteristiche di bersagli artificiali per lo studio delle gocce in prove di irrorazione. *Proc. IX Natl. Congr. AIIA "Ricerca e innovazione nell'ingegneria*

- dei biosistemi agro-territoriali”, Ischia (NA), Italy, CD-ROM.
- Cross J.V., Walklate P.J., Murray R.A., Richardson G.M. 2001. Spray deposits and losses in different sized apple trees from an axial fan orchard sprayer: 1. Effects of spray liquid flow rate. *Crop Prot.* 20:13-30.
- Doble S.J., Matthews G.A., Rutherford I., Southcombe E.S.E. 1985. A system for classifying hydraulic and other atomizers into categories of spray quality. *Proc. Br. Crop Prot. Conf. Weeds* 3:1125-33.
- European Commission. 2009a. Directive 2009/127/EC of the European Parliament and of the Council of 21 October 2009 amending Directive 2006/42/EC with regard to machinery for pesticide application. In: *Official Journal*, L 310/29, 25/11/2009, available from: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:310:0029:0033:en:PDF>
- European Commission. 2009b. Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for Community action to achieve the sustainable use of pesticides. In: *Official Journal*, L 309/71, 24/11/2009, available from: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:309:0071:0086:en:PDF>
- Fox R.D., Derksen R.C., Cooper J.A., Krause C.R., Ozkan H.E. 2003. Visual and image system measurement of spray deposits using water-sensitive paper. *Appl. Eng. Agr.* 19:549-52.
- Hewitt A.J. 1997. The importance of droplet size in agricultural spraying. *Atomization Spray* 7:235-44.
- Hewitt A.J., Valcore D.L., Teske M.E., Schick R.J. 1998. Droplet size classification for agricultural sprays. *Proc. 11th Annual Conf. Liquid Atomization and Spray Systems*, Sacramento, CA, USA, pp 55-59.
- Jamar L., Mostade O., Huyghebaert B., Pigeon O., Lateur M. 2010. Comparative performance of recycling tunnel and conventional sprayers using standard and drift-mitigating nozzles in dwarf apple orchards. *Crop Prot.* 29:561-6.
- Juste F., Sanchez S., Ibanez R., Val L., Garcia C. 1990. Measurement of spray deposition and efficiency of pesticide application in citrus orchard. *J. Agr. Eng. Res.* 46:187-96.
- Matthews G.A. 2004. How was the pesticide applied? *Crop Prot.* 23:651-3.
- Nuyttens D., Baetens K., De Schampheleire M., Sonck B. 2007. Effect of nozzle type, size and pressure on spray droplet characteristics. *Biosyst. Eng.* 97:333-45.
- Pergher G. 2004. Field evaluation of a calibration method for air-assisted sprayers involving the use of a vertical patternator. *Crop Prot.* 23:437-46.
- Pezzi F., Rondelli V. 2000. The performance of an air-assisted sprayer operating in vines. *J. Agr. Eng. Res.* 76:331-40.
- QInstruments. 2013. Water sensitive papers. Available from: <http://www.qinstruments.com/en/service/downloads/downloads-wsp.html> Accessed: July 2013.
- R Development Core Team. 2012. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available from: <http://www.R-project.org>
- Salyani M., Fox R.D. 1999. Evaluation of spray quality by oil- and water sensitive papers. *Trans. ASABE* 42:37-43.
- Schick R.J. 2008. Spray technology reference guide: understanding drop size. *Spraying Systems Co., Bulletin No. 459C*. Available from: <http://de.spray.com/Portals/0/pdf/B459c.pdf>
- Solanelles F., Escolà A., Planas S., Rosell J.R., Camp F., Gràcia F. 2006. An electronic control system for pesticide application proportional to the canopy width of tree crops. *Biosyst. Eng.* 95:473-81.
- Southcombe E.S.E., Miller P.C.H., Ganzelmeier H., Van de Zande J.C., Miralles A., Hewitt A.J. 1997. The international (BCPC) spray classification system including a drift potential factor. *Proc. Br. Crop Prot. Conf. Weeds* 5A-1:371-80.