biosystems engineering 111 (2012) 11–23

Available online at www.sciencedirect.com
SciVerse ScienceDirect
journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Assessing the ability of image processing software to analyse spray quality on water-sensitive papers used as artificial targets

*Mario Cunha**, *Claudia Carvalho, Andre R.S. Marcal*

Faculdade de Ciências da Universidade do Porto and Centro de Investigação em Ciências Geoespaciais, Rua do Campo Alegre s/n, 4169-007 Porto, Portugal

ARTICLE INFO

Article history:
Received 11 June 2011
Received in revised form
3 October 2011
Accepted 6 October 2011
Published online 21 November 2011

The performance of several commercial and experimental software packages (Gotas, StainMaster, ImageTool, StainAnalysis, AgroScan, DropletScan and Spray_imageI and II) that produce indicators of crop spraying quality based on the image processing of water-sensitive papers used as artificial targets were compared against known coverage, droplet size spectra and class size distribution verified through manual counting. A number of artificial targets used to test the software were obtained by controlled spray applications and given droplet density between 14 and 108 drops cm^{-2} and a wide range of droplet size spectra. The results showed that artificial targets coupled with an appropriate image system can be an accurate technique to compute spray parameters. The between-methods differences were 6.7% for droplet density, 11.5% for volume median diameter, <3% for coverage (%) and <3% coverage density. For the 16 droplet class size distribution tested the between-methods differences were all <15%. However, most of the image analysis systems were not effective in accurately measuring coverage density when coverage rate is greater than about 17%. The Spray_imageII software estimated the coverage density with a mean absolute error of 2% and the absolute error is below 10%, even with about 43% of coverage rate. This software, when compared to the other programmes tested, provided the best accuracy for coverage and droplet size spectrum as well as for droplet class size distribution.

1. Introduction

Spraying is the most common process of applying pesticides to crops because it is a low cost, effective and rapid method. Efforts to developed non-chemical or biological pest-management are well documented, however, pesticides are still the most powerful tool for crop pest-control (Giles, Akesson, & Yates, 2008; Matthews, 2000). Nevertheless, it is generally accepted that crop-pesticide application by spraying is an inefficient process (Salyani, Farooq, & Sweeb, 2007) and the quantity of the chemical that reaches the target is significantly less than that released from sprayer. Several studies (Balsari & Marucco, 2009; Panneton, Theriault, & Lacasse, 2001) have estimated that the amount of pesticide deposited on the target is not more than 55% of the volume sprayed and that the other 45% goes to the ground (~25%) or is lost as small airborne droplets (~20%). Any pesticide which is released from a sprayer but does not eventually have the desired

* Corresponding author.
E-mail address: mcunha@mail.icav.up.pt (M. Cunha).

1537-5110/$ – see front matter © 2011 IAgrE. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.biosystemseng.2011.10.002

Nomenclature

Symbols

σ_B^2	between-methods variance
σ_w^2	between-WSP variance
A	spot area (m)
D	spot diameter (m)
$D_{V0.1}$	diameter 10% cumulative by volume
$D_{V0.5}$	diameter 50% cumulative by volume
$D_{V0.9}$	diameter 90% cumulative by volume
ICC	intra class correlation coefficient
MAD	mean absolute difference
R^2	coefficient of determination
SD	standard deviation
VMD	volume median diameter

Abbreviation

WSP	water-sensitive paper

biological effect on the target, can induce off-target pesticide resistance, increase costs for the grower, and increase chemical contamination in the environment (De Moor, Vereeckle, Jaeken, Lootens, & Vandecasteele, 2000; Giles & Downey, 2003).

Despite the criticisms of chemical pest-control it is expected that farmers will continue to rely on pesticides use by spraying (Panneton, Lacasse, & Piché, 2005). Correct adjustment of sprayers improves their accuracy and efficiency resulting in more targeted and uniform sprays which helps to prevent inadequate pest-control. Optimisation of spray application parameters has been the focus of many studies dating back more than 30 years (Fisher & Menzies, 1976; Matthews, 2000) and research in this area has been reviewed by several authors (Giles et al., 2008; Prokop & Veverka, 2003; Zhu, Salyani, & Fox, 2011). Most of these studies have focused on biological, economic and environmental regulation aspects of crop pest-control and they have consistently determined that an intricate relationship exists between spray coverage of the target, droplet size spectra and the efficacy of spraying applications. However, controlling these spray parameters remains a challenging and complex research topic in agricultural spray technology.

Nowadays, many pesticides and sprayers require specific information related to the crop spray quality such as the amount of spray deposited on the target, droplet size spectra and target coverage uniformity. The deposit and distribution of spray on foliage, or artificial targets, can be assessed by adding a fluorescent or metallic tracer to the spray and examining by chemical, fluorimetric, colorimetric or optical analyses. Reviews of the merits and limitations of these techniques used in different combinations under various applications (Furness, 2006; Matthews, 2000; Salyani, 2000; Salyani & Fox, 1999) have shown that none of the existing measurement methodologies is appropriate for all conditions. Furthermore, the choice of an appropriate technique may also be affected by the availability of labour, degree of automation and cost. Moreover it is important for researcher and applicators to understand quantitative parameters related with the spraying quality as described by ASAE-Standards (1997).

Water-sensitive papers (WSP) have been used for more than 40 years, being the most popular artificial targets for evaluation of agricultural spray parameters. WSPs are coated papers with a yellow surface which turns dark blue in contact with aqueous droplets. This colour change is due to the reaction of the water with the bromophenol-blue indicator contained in the coating which changes blue with pH from 2.8 to 4.6 (Turner & Huntington, 1970). Since water in the spray stains the WSP the spot size on the paper can be observed or measured, permitting the use of WSP to evaluate spray deposits. Droplet sizing is also possible when a proper spread factor or calibration equation has been developed to convert the size of the WSP stains into droplet size (Giles & Downey, 2003; Hoffmann & Hewitt, 2005; Syngenta, 2002).

The WSPs can be useful to quickly produce indicators related to crop spray quality provided that their limitations are taken into account. These limitations are:

- The colour of the unstained areas on WSPs changes as the distance between stain decreases (Panneton, 2002).
- Droplets that are less than 50 μm in diameter do not generally contain enough water to create a detectable stain on WSPs (Hoffmann & Hewitt, 2005).
- WSPs can be operator sensitive because they can turn blue under high humidity conditions (i.e. >85%) which makes them unreadable, therefore, it is recommended that they are not used under high humidity conditions (Syngenta, 2002). Moreover stain size can continue to increase even after two months of the application.
- Droplet spread varies with the physical properties of the spray liquid such as surface tension, direction (angle) of impact and energy of impact. By dividing the measured spot diameter by a spread factor, it is possible to determine both the diameter and volume of the original droplet that formed the stain on the WSP. This process assumes that all droplets have the same physical proprieties and impact on the WSP under similar conditions; this may not be the case within a canopy (De Moor et al., 2000). However, this problem is more pronounced with larger droplets and it may not produce large errors with fine and medium quality sprays (Hoffmann & Hewitt, 2005).
- For an accurate assessment of the coverage and droplet spectra on WSPs, specialised image equipment and automatic image processing system must be used.

Digital image processing techniques for scanning WSP have been developed over many years (Last, Parkin, & Beresford, 1987; Salyani & Fox, 1994; Sistler, Smith, & Rester, 1982). The advances in image processing technology have led to the development of different experimental or commercial software applications that produce indicators related to the spray quality based on the image processing of scanned WSP. Reviews of some of these programmes have been published, and their limiting factors investigated (Fox, Derksen, Cooper, Krause, & Ozkan, 2003; Franz, 1993; Giles & Crowe, 2007; Hoffmann & Hewitt, 2005; Leiva & Araujo, 2009;

Salyani & Fox, 1999, 1994; Wolf, 2003). This literature has revealed that there are still difficulties for these software tools in situations of high spray coverage with overlapping stains. Image processing techniques based on mathematical morphology have been used for granulometry studies (Dougherty & Sand, 1995) and these have been adapted to develop a software application with low sensitivity to high coverage and overlapping stains (Marcal & Cunha, 2008).

One of the difficulties in evaluating of the performance of software applications based on image processing of scanned WSPs is the lack of standard images that can be used to obtain absolute accurate measurements of the stain characteristics and number. The most common processes to test the accuracy of the image system results are the comparison with reference card with known coverage and droplet size (Zhu et al., 2011), microscopic measurements (ex. Chaim, Pessoa, Neto, & Hermes, 2002; Salyani & Fox, 1994) and manual measurements on enlarged images of the artificial target (ex. Marcal & Cunha, 2008; Salyani & Fox, 1994).

Many spray technology researchers, growers, sprayer dealers, agro-chemical companies and regulatory agencies are interested in the performance of the available software applications to produce indicators related to the spray quality based on image processing of scanned WSP. Nevertheless, even with considerable studies already documented to evaluate the performances of available image systems, agricultural spray technology suffers from a lack of consistent evaluation of the accuracy and operability of these automatic systems under different conditions.

The main goal of this study was to compare the ability of commercial and experimental programmes for image processing of WSPs used as artificial target to assess agricultural spray quality parameters. The accuracy of each image system was tested by a process, which included comparisons against know sizes spectra and coverage verified by manual counting of WSPs obtained under controlled applications. The patterns of these WSPs were selected to cover the requirements of coverage and droplet size spectrum characteristics of typical crop spray applications.

2. Material and methods

2.1. *Sampling artificial targets*

Syngenta Water-Sensitive Papers (76 × 26 mm) (Spraying Systems Inc., Wheaton, IL, USA) were used as spray targets for the between-methods (manual and automatic) comparison of the spray parameters. Various distribution patterns of spray coverage and droplet size spectra were simulated using a handheld sprayer. Nine of these sets of WSPs were selected as representing the most common patterns of stain coverage and droplet size spectra using in crop spraying (Fig. 1). These preliminary selections were done using visual inspection. The WSP were sorted by perceived coverage and spot size (visually rated) and compared with a standard WSPs with known values of coverage and droplet size spectra provided by Syngenta (2002). These reference cards contained stains related to droplet densities ranging from 16 to 258 drops cm^{-2}.

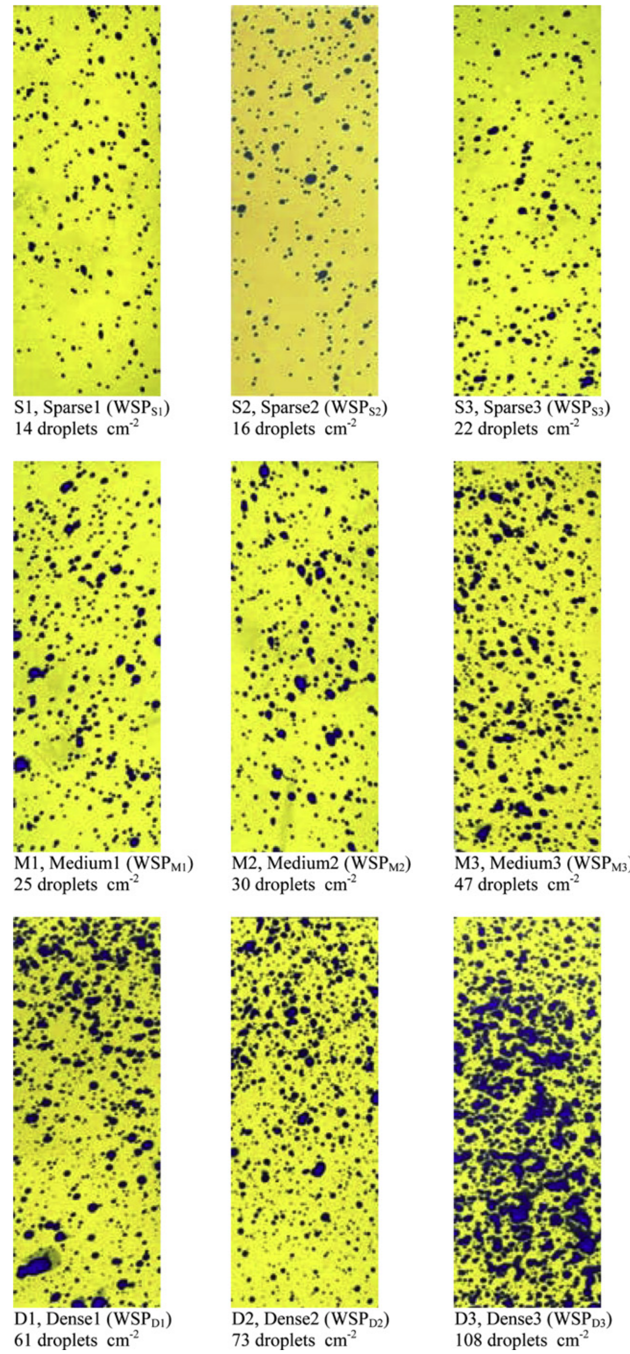

Fig. 1 – Images of water-sensitive papers (WSP) scanned with resolution 1200 dpi and manually counted droplet density (droplets cm^{-2}). The WSP were grouped according the coverage (droplets cm^{-2}): Sparse (WSP$_{E1}$, WSP$_{E2}$, WSP$_{E3}$) < 25; Medium 25 to 50 (WSP$_{M1}$, WSP$_{M2}$ and WSP$_{M3}$) and Dense > 50 droplets cm^{-2} (WSP$_{D1}$, WSP$_{D2}$ and WSP$_{D3}$).

After being sprayed and allowed to dry, the WSPs were placed in a sealable plastic bag and stored. The nine WSP test samples were digitised using a photographic scanner (EPSON Perfection 4990 Photo). Two different scanning resolutions were used, resulting in 24-bit colour images of 1770 × 1189 pixels (600 dpi) for automatic analysis of the WSPs, and 3541 × 2379 pixels (1200 dpi) for manual inspection. Grey scale 8-bit images were created from the original RGB images, as well as binary images, obtained using the Otsu threshold method (Otsu, 1979).

An evaluation of the effects of scanning resolution on the measurement of the stain size range and distribution was carried out by Marcal and Cunha (2008). It was concluded that the 600 dpi resolution appeared to be the most suitable choice, as the stain profiles were very similar to the 1200 dpi profiles but the computational load was much lower. Furthermore, very high scanning resolution rates tend to introduce unwanted artefacts. Thus a resolution of 600 dpi was selected for the automatic image processing used here.

2.2. *Quantitative spray parameters analysis*

In this work the following quantitative parameters of spray coverage and droplet size spectra, as described by ASAE-Standards (1997) and Schick (2008) were used:

- Parameters related to droplet size spectra:
  - i) Volume Median Diameter (VMD but also known as $Dv_{0.5}$), is the most common single measure used to describe spray droplet size spectra. The VMD represents the droplet diameter (μm) where 50% of the spray volume (or mass) is contained in droplets smaller (or larger) than this value. With small samples a few large droplets can account for a large proportion of the spray volume and thus significantly increase the value of VMD.
  - ii) Two additional droplet size parameters that are commonly used to describe more of the distribution than the median alone are the $D_{V0.1}$ and $D_{V0.9}$. These describe the 10 and 90 percentiles of the spray volume contained in droplets of the specified diameter size or less. The $D_{V0.1}$ is often used to estimate the relative portion of sprays that are prone to drift (Schick, 2008).
- Parameters related with coverage:
  - i) Area coverage (%), is the percentage of target area covered with spots
  - ii) Droplet density (drops cm^{-2}), is the number of droplet per target area.
- Class size distributions analysis was performed in 16 class sizes ranging from <100 μm to >800 μm, with constant increment of 50 μm between class sizes.

The blue stains created on WSPs by droplets are larger than projected area of the spray droplets due to spreading. A spread factor must be used to calculate the droplet diameter that created a particular stain size on the WSP. In this work, the droplet size spectra for the automatic and manual methods were computed from the stain size spectra using the spread factors presented in Table 1. These spread factors were determined using by the magnesium oxide and silicon-oil methods and referring to water at 20 °C, about 40% relative humidity and the droplets reaching the WSP at sedimentation velocity (Syngenta, 2002).

2.3. *Targets preparation and manual image measurements*

A manual counting of the number and size of stains was performed for the nine WSPs by visual inspection. The images

Table 1 – Spread factor values used to convert stain spectra to droplet sizes.

Stain diameter of drops, μm	Spread factor	Drop diameter, μm
100	1.7	58.8
200	1.8	111.1
300	1.9	157.9
400	2.0	200.0
500	2.1	238.1
600	2.1	285.7

Source (Syngenta, 2002)

obtained at 1200 dpi were printed in a plotter and magnified by a factor of 10, resulting in image sizes of 51.22 × 74.95 cm.

The length and the width of each stain were measured with a ruler. One operator counted all manual measurements. The spots that touched each other were counted as individual spots. The minimum diameter considered in the printed image was 1 mm, corresponding to a stain radius of 0.05 mm in the original WSP. It was assumed that droplets that are <100 μm diameter do not generally contain enough water to create a detectable stain-contrast on the WSP. It should be emphasised that the lower limit of WSP sensitivity is a physical rather than an image detection limit.

Stain length was defined as the greatest dimension (major axis) and with was the dimension perpendicular to the length. Calculated spot diameters (D) were based on the assumption that the measured area was circular. The spot diameters were determined by averaging the length and width of each spot and spot area (A) was calculated by:

$$A = \pi\left(\frac{D}{4}\right)^2 \quad (1)$$

Next, the coverage and droplet size spectra were calculated for each target. The percentage of the image area covered with spots was calculated by dividing the area sum for all spots (A) by the total area of the card.

Fig. 1 shows the pattern of the nine WSPs grouped according the droplet density: *Sparse* (<25 drops cm^{-2}); *Medium* (25–50 drops cm^{-2}); *Dense* (>50 drops cm^{-2});

2.4. *Automatic image measurements*

Seven automatic image processing software tools for scanning WSPs were tested. From these seven tools, six were commercially available systems (Gotas, StainMaster, ImageTool, StainAnalysis, AgroScan and DropletScan™) and one tool, with two versions (Spray_imageI and Spray_imageII) was a prototype for spray analysis, developed by the Faculdade de Ciências, Universidade do Porto (Marcal & Cunha, 2008). The Spray_imageII is based on work by Marcal and Cunha (2008), but using alternative morphological operators as described in Marcal (2008).

The main process of automatic analysis involves the acquiring of images from the WSPs that has been placed on the scan bed. Generally spray parameters estimated by this type of programmes include coverage and droplet size spectra; however each software tool produces different reports. Table 2 summarises the main features of each of the software tested as well as the quantitative spray parameters included in the report produced after the image was analysed. This table also contains appropriate references for full explanations of the abilities of each of the software tools.

Each of the software tools can analyse spots of various sizes and shapes and some of them have the ability to accommodate stains that hit the card and produce teardrop-shaped stains that touch each other. The tools DropletScan, StainMaster and Spray_imageII had the highest specifications in terms of their ability to handle overlapping stains.

StainMaster and DropletScan could be used to analyse a WSP-area in the user-defined areas or throughout the entire image. However, in this work for consistency only the entire image option was used. With Spray_imageI and II it was also possible to evaluate the spatial uniformity of the WSP pattern (Marcal & Cunha, 2008), but this feature was not used here. The resolution used by each software tools was 600 dpi for consistency with the resolution used for scanning the WSP.

2.5. Statistics analysis

Several statistical procedures were used to analyse the data extracted from each WSP and make comparisons between methods (i.e. manual vs. automatic) and measurements of spray parameters. A paired *t*-test analysis, considering each WSP as a replicate, was performed to test the hypothesis of no between-methods differences on the spray parameters of the same set of images. This statistical test checks only whether the mean results are the same whilst the (random) differences between measurements can be large even for equal means. In order to avoid this misinterpretation, other complementary statistics tests were used to assess the agreement of between-methods measurements.

The agreement between the two types of methods (manual vs. automatic) was quantified using the intra class coefficient correlation (ICC). The ICC is a general evaluation of agreement or consensus, where the measurements used are assumed to be parametric (continuous and with a normal distribution). The ICC provides a scalar measure of agreement or concordance measures between manual and each automatic programme result. Initially, an analysis of variance was carried out to derive two variance components: the between-methods variance (σ_B^2) and the within WSPs variance (σ_w^2).

The ICC for each software tool expresses the between-methods variance as the proportion of the sum of the two variance components, as described by:

$$ICC = \frac{\sigma_B^2}{\sigma_B^2 + \sigma_w^2} \quad (2)$$

As a sample attribute, the ICC contains both measurement of accuracy (how far the best-fit line deviates from the concordance line) and a measure of precision (how far each observation deviates from the best-fit line). A ICC = 1 represents perfect agreement, and ICC = 0 no agreement at all.

In this work, the level of between methods agreement was classified as (Landis & Koch, 1977): *Excellent* (ICC 0.81–1.00), *Substantial* (ICC 0.61–0.80), *Moderate* (ICC 0.41–0.60), *Fair* (ICC 0.21–0.40), *Slight* (ICC 0.00–0.20), and *Poor* (ICC < 0.00). The null hypothesis of ICC = 0 was also tested.

Table 2 – Main characteristics and features for each image analysis system tested.

Characteristics features	Image analysis system						
	Gotas	StainMaster[b]	Image tool	Stain Alysis	Agro Scan	Droplet Scan	Spr@y _Image
References	Pessoa and Chaim, 1999	www.stainmaster.com.ar	UTHSCSA, 1997	REMSpC, 2002	Araujo and Araujo, 2001	Whitney and Gardisser, 2003	Marcal & Cunha, 2008
Water-sensitive paper (WSP)							
Optical resolution (dpi)	≥300	≥600	≥300	≥600	600≤	≥600	≥300
Overlap features	No	Yes	No	No	No	Yes	Yes
Spread Factor:							
Table based[a]	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Equation based	No	No	No	Yes	No	Yes	No
Spray parameters							
Area Coverage (%)	Yes	No	No	No	No	Yes	Yes
Droplet density (droplets cm^{-2})	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of droplets	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Class size distribution	No	Yes	Yes	Yes	Yes	Yes	Yes
$D_{V0.5}$ (VMD)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
$D_{V0.1}$	No	Yes	Yes	Yes	Yes	Yes	Yes
$D_{V0.9}$	No	Yes	Yes	Yes	Yes	Yes	Yes

$D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$: droplet size spectra factors corresponding respectively to 10%, 50% and 90% of the cumulative spray liquid volume contained in droplets up to the indicated diameter.

a see Table 1.

b Version 1.09.

The agreement was also quantified by the identity regression line between manual and automatic measurements.

3. Results and discussion

3.1. *Manual measurements of the target*

The results of manual WSP measurements were assumed to be more accurate than the results measured by automatic image analysis. A visual assessment of the coverage and droplet size spectra of the WSPs is shown in Fig. 1. As expected, the WSPs turned blue where the spray impinged. In the WSPs with a high coverage density the stains became light blue or produced a mixture of dark blue stains on light blue background (WSP_{D1} and $WSP_{D3,}$ see Fig. 1). Visual evaluation of the WSPs showed clear differences among distribution patterns of various droplets sizes. Fine spray generated more uniform deposit distributions than larger droplets.

Table 3 presents the general parameters of droplet density, area coverage and droplet size spectra measured manually in each WSP grouped according to the coverage density. The set of WSPs tested gave droplet densities between 14 and 108 drops cm^{-2}, area coverage between 5% and 36% and a wide range of droplet size spectra (Table 3). Therefore the different patterns produced on these WSPs were suitable for an evaluation of automatic image system for use in a wide range of situations.

The droplet density, area coverage and droplet size spectra selected for this study cover largely the most commonly spraying patterns recommended by Syngenta (2002) to provide satisfactory results of crop-protection: 20 to 30 drops cm^{-2} for insecticide or pre-emergence herbicide applications, 30 to 40 drops cm^{-2} for contact post-emergence herbicides, and 50 to 70 drops cm^{-2} for fungicide applications. Because both automatic and manual measurements of WSP proved to be normally distributed (data not shown), the ICC and *t*-tests could be used to compare between-methods spraying parameters.

Table 3 – Statistics of coverage and droplet size spectra obtained by manual counting for the WSPs grouped according the coverage density.

Spray parameters	Sparse		Medium		Dense	
	Min	Max	Min	Max	Min	Max
No. of droplets	272	425	501	924	1206	2137
$D_{v0.5}$ (μm)	357	405	500	524	643	589
$D_{v0.1}$ (μm)	226	226	250	238	310	333
$D_{v0.9}$ (μm)	575	667	1060	862	1145	1024
Coverage:						
Area Coverage (%)	3.9	5.4	8.8	13.9	18.2	35.6
Drop Density (droplets cm^{-2})	13.8	21.5	25.4	46.8	61.1	108.2

Coverage density (drops cm^{-2}): *Sparse*: <25; *Medium* 25 to 50 and *Dense*: >50 drops cm^{-2}

$D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$: droplet size spectra factors corresponding respectively to 10%, 50% and 90% of the cumulative spray liquid volume contained in droplets up to the indicated diameter.

3.2. *Between-methods comparison of droplet size spectra parameters*

A summary of between-methods comparison for the spray parameters related with for droplets size spectra is presented in Table 4. Large between-methods differences of coverage (drops cm^{-2}) were reported by the image systems tested. The values showed a between-methods agreement (ICC) ranging from Poor to Excellent (Table 4). Spray parameters related with droplet size spectra ($D_{V0.5}$, $Dv_{0.1}$, $Dv_{0.9}$) showed an overall between-methods agreement that ranged from *Fair* to *Moderate*. All spray parameters tested in Spray_imageII showed a between-methods agreement level always equal or greater than the other programmes.

The Spray_imageII software provided between-methods differences for droplet density of 6.7% (±4.15; $p > 0.944$), with regression slope close to 1 and an excellent agreement value (ICC = 0.996; $p < 0.000$). For the nine WSPs tested with Spray_imageII, the descriptive statistics showed that 56% of cases had between-methods droplet density below 5% and that only one situation had difference higher than 10% (data not show). This largest deviation (14%, not showed) was observed in the WSP_{D3} (Fig. 1) that had a large droplet density (108 drops cm^{-2}).

There was a great difference between droplet density measured by the two versions of the Spray_image programme. The Spray_imageI showed between-method differences for the droplet density of 27.3% (±14.6%) about four times higher than Spray_imageII. Although the difference in droplet density measured manually and by Spray_imageI was not significant ($p < 0.051$), the level of agreement was slight (ICC = 0.046; $p < 0.046$) and the regression slope was far from 1 (Table 4). Moreover, Spray_imageI consistently underestimated droplet density (i.e. 9 cases, Table 4). This contrasted with the version II because the latter is more suitable for overlapping stains (Table 2). This underestimation of the number of droplets deposited could be mostly attributed to touching of the stains. Image systems that do not take into account stain overlapping (i.e. all except DropletScan, StainMaster and Spray_imageII), consistently underestimate droplet density (drops cm^{-2}) (Table 4). In software without overlapping procedures many small stains that touch larger stains are not counted since only droplets that are isolated are counted. This underestimation of droplet density by the software AgroScan and StainMaster was also reported by Leiva and Araujo (2009) where these authors attribute this lack of accuracy to the inability of the software to identify smaller droplets.

Overall, spray parameters related with droplet size spectra showed between-methods differences greater than droplet density. For all software tested the spray parameter $Dv_{0.9}$ produced the worst between-methods results. The differences were higher than 18.1% (±13.1%) and the ICC level ranged from *Poor* to *Fair* (Table 4). Therefore this spray parameter was considered to be unreliable for all programmes tested. This may be due to the heavy influence of a small number of large droplets on this parameter.

The $Dv_{0.5}$ between-methods differences for Spray_imageII (11.5 ± 7.6%) and DropletScan (9.0 ± 7.0%) produced the best results recorded for this spray parameter. However, in contrast to DropletScan ($p = 0.816$ for *t*-test), the mean

Table 4 – Statistics of between-methods comparison for the general spray parameters.

spray parameter	Gotas	StainMaster	Image tool	Stainanalysis	AgroScan	DropletScan	Spray_image I	Spray_image II
No of droplets								
MAD (%)	21.4 (9)	67.3 (9)	25.7 (8)	40.5 (5)	63.4 (9)	77.4 (5)	27.3 (9)	6.7 (4)
SD (%)	14.1	4.6	6.2	53.2	14.5	164.3	14.6	4.1
t_test	0.059	0.006	0.007	0.460	0.010	0.401	0.051	0.944
Slope	0.623	0.275	0.781	0.781	0.240	1.210	0.561	0.993
ICC_v	0.652	0.002	0.906	0.53	−0.129	0.543	0.046	0.996
ICC_p	0.016	0.493	0.000	0.049	0.638	0.044	0.526	0.000
Volume median diameter. $Dv_{0.5}$ (μm)								
MAD (%)	20.3 (1)	13.7 (4)	310.8 (0)	65.8 (0)	41.9 (1)	9.0 (4)	11.6 (9)	11.5 (9)
SD (%)	29.6	12.0	604.0	27.9	80.2	7.0	7.4	7.6
t_test	0.150	0.514	0.173	0.000	0.223	0.816	0.001	0.001
Slope	1.215	1.046	4.930	1.681	1.475	1.003	0.889	0.912
ICC_v	0.402	0.624	−0.041	−0.195	0.141	0.802	0.759	0.762
ICC_p	0.113	0.021	0.541	0.705	0.339	0.002	0.004	0.003
Volume diameter $Dv_{0.1}$ (μm)								
MAD (%)	–	14.7 (1)	234.6 (0)	66.0 (0)	22.1 (2)	22.9 (0)	8.3 (6)	7.8 (5)
SD (%)	–	9.6	508.9	26.8	45.8	10.3	4.1	4.3
t_test	–	0.025	0.227	0.000	0.258	0.000	0.239	0.514
Slope	–	1.14	4.45	1.64	1.29	1.21	0.97	0.99
ICC_v	–	0.566	−0.004	−0.499	0.282	−0.033	0.865	0.893
ICC_p	–	0.036	0.499	0.931	0.203	0.532	0.000	0.000
Volume diameter $Dv_{0.9}$ (μm)								
MAD (%)	–	20.2 (9)	219.2 (1)	60.7 (3)	31.6 (3)	18.1 (8)	23.5 (9)	22.9 (9)
SD (%)	–	16.0	328.0	35.2	58.1	13.1	11.8	12.1
t_test	–	0.013	0.101	0.131	0.361	0.015	0.002	0.002
Slope	–	0.769	3.588	1.379	1.251	0.799	0.730	0.736
ICC_v	–	0.110	−0.073	0.130	0.208	0.239	−0.088	−0.070
ICC_p	–	0.372	0.576	0.351	0.271	0.242	0.593	0.573

$D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$: droplet size spectra factors corresponding respectively to 10%, 50% and 90% of the cumulative spray liquid volume contained in droplets up to the indicated diameter. MAD: Mean Absolute Difference with the number of positive cases inside parentices and Standard Deviation (SD) between-methods for the nine WSP.
t-test (significance): *t*-test statistical significance of the paired *t*-test analysis between manual and each automatic image analysis considering each WSP ($n = 9$) as a repetition.
Slope: slope of the identity regression line between manual and automatic measurements.
ICC: Intra Class Correlation value (ICCv) and probability (ICCp).

differences for Spray_imageII were significant ($p = 0.001$ for *t*-test) and consistently higher (9 positives cases) than the corresponding manual measurements. The very low significant *t*-test and ICC in the face of near-excellent agreement arises when virtually all between-methods endorse low differences values with the same signal (Table 4).

3.3. *Between-methods comparison of area coverage*

Table 5 presents statistics of between-methods differences for the droplet size spectra and coverage parameters obtained for the overall WSPs and the WSPs grouped according to droplet density. For all spray parameters analysed, the between-

Table 5 – Statistics of between-methods differences for the droplet size spectra and coverage parameters for the overall WSPs and the WSPs grouped according the coverage.

Spray parameters	Mean absolute difference (MAD)				Standard deviations (SD)			
	Overall	Sparse	Medium	Dense	Overall	Sparse	Medium	Dense
No. of droplets	34.5	25.8	30.5	47.1	24.8	21.7	22.1	30.6
$D_{v0.5}$ (μm)	60.6	21.6	28.3	131.8	101.3	16.9	33.4	253.7
$D_{v0.1}$ (μm)	53.8	21.0	28.1	112.3	86.2	16.7	26.6	215.3
$D_{v0.9}$ (μm)	56.6	26.1	37.5	106.3	74.8	20.9	37.7	165.9
Coverage:								
Area Coverage (%)	21.2	12.7	14.3	36.4	14.9	11.1	8.3	25.3
Drop Density (droplets cm^{-2})	14.9	7.4	11.6	25.8	1.8	0.8	1.0	3.7

Droplet density: *Sparse*: <25 droplets cm^{-2}; *Medium* 25 to 50 droplets cm^{-2} and *Dense*: >50 droplets cm^{-2}
$D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$: droplet size spectra factors corresponding respectively to 10%, 50% and 90% of the cumulative spray liquid volume contained in droplets up to the indicated diameter.

methods differences consistently became much larger for more crowded images. These results indicate that coverage density was a major factor in the differences between manual and automatic measurements. Moreover, high coverage density resulted consistently in more variability of the spray parameters.

The differences between manual and image system measurements of coverage rate and coverage density are presented in Table 6. The software Stainmaster, ImageTool, StainAnalysis and AgroScan did not have an area coverage feature (Table 2). Despite the coverage results varying among the software tested, it is possible to infer that the different alternatives produce acceptable results for coverage. According to the results the overall between-methods agreement for coverage rate are *Excellent* (ICC >0.844) and the coverage density ranged from *Moderate* (ICC = 0.505) to *Excellent* (ICC = 0.996).

The overall between-methods differences of area coverage were lower than 4%. However, in all targets tested the image system analysis overestimated the area coverage compared with the manual measurements, and the paired *t*-test was significant for all but one software tool (DropletScan). Nevertheless, all of the between-methods comparisons for area coverage had ICC >0.844, which indicates an *Excellent* agreement between-methods.

According to the *R*-square parameter, between 93% and 97% of area coverage variability over the nine WSP tested can be explained by the image processing programmes tested. For the four programmes (a total of 36 data records), in 92% of the cases the differences of coverage rate between manual and automatic analysis were below 5% (data not shown). Higher between-methods differences were always observed in the WPS_{D3} (Fig. 1), where the mean difference was about 10% with a maximum of 22% (DropleScan). The WPS_{D3} has the highest droplet density (108 drops cm^{-2}) and large stains with irregular shapes. These good results for WSP-area coverage have also reported by several authors using automatic imaging systems (Fox et al., 2003; Hoffmann & Hewitt, 2005; Holownicki, Doruchowski, Swicchowski, & Jacken, 2002; Marcal & Cunha, 2008; Panneton, 2002).

The overestimation of area coverage differences can be explained by the low colour contrast of the background for large droplets, and the irregular shapes of the stains that came from underestimating the area coverage when stain circularity was assumed during the manual measurements.

In situations of high area coverage the WSP turned blue by impinging water droplets, but some stains also reacted to the moisture from adjacent stains and the original yellow surface turned into greenish blue (Fig. 1). Therefore, although the dark blue colour of the stains could still be differentiated from the background, their size became very sensitive to the background grey level set point (Fox et al., 2003; Panneton, 2002). In these situations, which are typical for coarse sprays, the contrast between the stained areas (blue) and the unstained area (yellow–green) is not strong, thus large areas of the WSP background are assessed by the image systems as stained area.

The overestimation of area coverage for all targets could also be explained by the process used to obtain this spray parameter (see Section 2). In the automatic method the area covered expressed as percentage value was calculated by dividing the total number of white pixels by the total number of image pixels. However, in the manual measurements the total area covered by spots was calculated by the sum of the area of each droplet. Calculated diameters were based on the assumption that the stained area was circular. This was not true for all stains, particularly for the WPS_{D3} (Fig. 1). Moreover, stain circularity increased as the diameter

Table 6 – Statistics of between-methods comparison for area coverage and droplet density.

Statistics	Gotas	StainMaster	Image tool	Stain analysis	AgroScan	DropletScan	Spray_image I	Spray_image II
Coverage rate (%)								
MAD (%)	2.27 (0)	–	–	–	–	3.94 (0)	2.43 (0)	2.43 (0)
SD (%)	1.37	–	–	–	–	6.83	2.25	2.25
t_test	0.011	–	–	–	–	0.122	0.021	0.021
Slope	1.15	–	–	–	–	1.41	1.20	1.20
R^2	0.989	–	–	–	–	0.934	0.938	0.938
ICC_v	0.969	–	–	–	–	0.844	0.958	0.958
ICC_p	0.000	–	–	–	–	0.001	0.000	0.000
Coverage density (droplets cm^{-2})								
MAD	11.6 (9)	7.2 (7)	10.9 (8)	31.4 (5)	14.1 (8)	24.3 (5)	15.9 (9)	2.4 (4)
SD	17.2	12.6	7.0	67.9	21.7	36.5	20.2	1.7
t_test	0.078	0.151	0.007	0.498	0.105	0.401	0.046	0.944
Slope	0.66	0.78	0.78	1.75	0.58	1.21	0.56	0.99
R^2	0.718	0.860	0.956	0.582	0.213	0.358	0.583	0.993
ICC_v	0.701	0.865	0.906	0.505	0.507	0.543	0.526	0.996
ICC_p	0.009	0.000	0.000	0.059	0.058	0.044	0.051	0.000

MAD: Mean absolute difference with the number of positive cases inside prentices and Standard Deviation (SD) between-methods for the 9 WSP.
t-test (significance): t-test statistical significance of the paired *t*-test analysis between manual and each automatic image analysis considering each WSP ($n = 9$) as a repetition.
Slope: slope of the identity regression line between manual and automatic measurements.
ICC: Intra Class Correlation value (ICC_v) and probability (ICC_p).
The software tools StainMaster, ImageTool, Stainalysis and AgroScan do not compute area coverage.

decreased. In this context, during the manual counting, smaller stains were closer to their nominal sizes (closer to being perfect circles), but the larger stains tended to have an irregular shape that underestimated their area when circularity is assumed.

The droplet density (drops cm^{-2}) gave a between-methods agreement, according to ICC levels *Moderate* (ICC = 0.505) to *Excellent* (ICC = 0.996) and the paired *t*-test statistics on the mean of the two measurements confirmed the absence of a systematic bias with exception for ImageTool (Table 6). Despite this high level of agreement, some software tools gave higher between-methods differences and often higher standard deviations (Table 6).

A plot comparing between-methods differences in droplet density (drops cm^{-2}) against coverage rate (%) for each WSP, as manually measured, is shown in Fig. 2. From this plot it is possible to see, for each programme, the tendency of the amount of variation to change with the magnitude of coverage rate. For most tested software, the overall between-methods differences of coverage were small and stable up to a coverage rate of about 17% and, after this value, increased sharply. Even for coverage from 5 to 17%, some software (Spray_imageI and ImageTool) showed between-methods differences between 20 and 30%. Therefore, area coverage had a large impact on quality of the automatic image processing for some of the programmes tested. There are many pesticides that needed about 30% of area coverage to ensure satisfactory crop-protection (Holownicki et al., 2002). This area coverage problem was also reported by Salyani and Fox (1994) as a critical issue for the use of the automatic image processing with scanned WSP for spray monitoring.

The programme Spray_imageII gave between-methods mean absolute differences (%) for area coverage of 2% and these differences were always less than 14%. Moreover, the between-methods differences for this programme against the coverage rate showed any obvious trend. The sharp increase in the area coverage difference of about 17% for most of the programmes, and the good results from the Spray_imageII software, may have been due to the overlapping of stains.

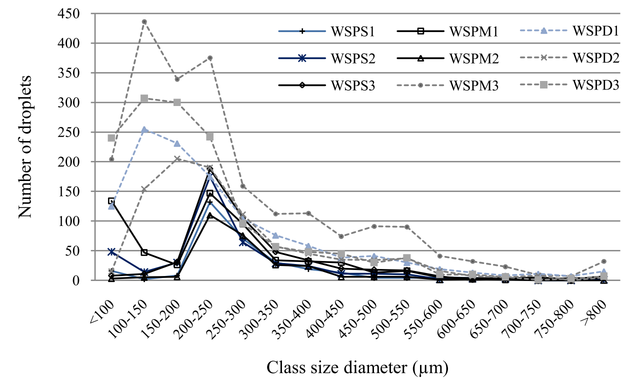

Fig. 3 – Number of droplets profile for each class size diameter measured manually on each WSP.

3.4. *Between-methods comparison of class size distribution*

In addition to assessing the parameters related to droplet size spectra and coverage, the between-methods differences for the droplet class size distribution are of interest. For this propose, the droplets determined manually and by each of the image analysis systems were grouped according to their diameter into 16 class sizes, ranging from <100 µm to >800 µm diameter with constant increments of 50 µm between class. The software Gotas did not have class size distribution features.

Fig. 3 shows the profile of the droplet class size diameter distribution for the 9 WSPs measured manually. The plot indicates that the five WSPs with lower droplet density ≤30 drops cm^{-2} (WSP_{S1}, WSP_{S2}, WSP_{S3}, WSP_{M1}, WSP_{M2}, see Fig. 1) had a similar droplet size profile, particularly for droplets size >100 µm diameter. For these WSPs the greater number of drops occurred in the class diameter range of 200–250 µm diameter and 41–68% of the total droplets measured were in the range 200–300 µm diameter. The others WSPs, with droplet density greater than 30 drops cm^{-2}

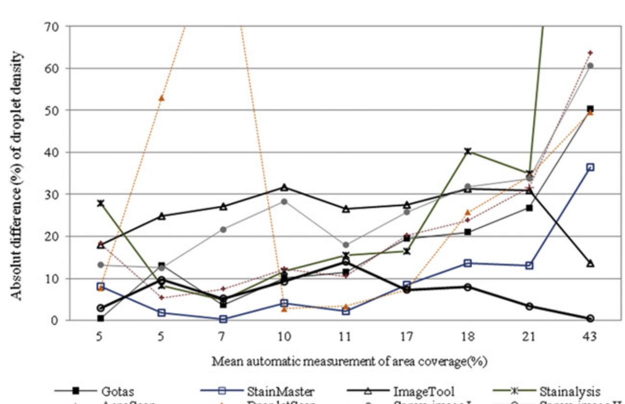

Fig. 2 – Effects of area coverage in the between-methods difference of the coverage density (droplets cm^{-2}). The results for the DropletScan and Stainanalysis are not fully represented because they peaked at more than 70% difference for area coverage of 6.6% and 21.3% respectively.

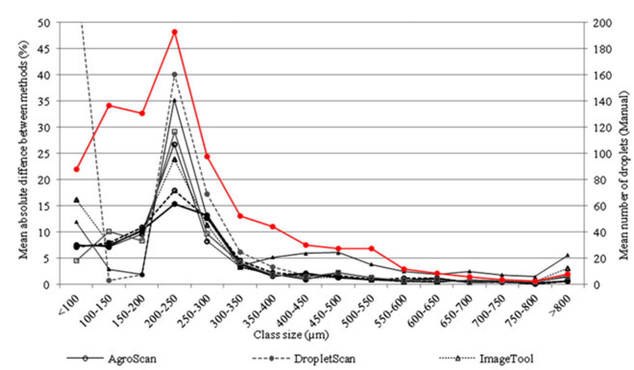

Fig. 4 – Between-methods mean (9 WSP) absolute differences profiles for stain class size and mean droplet number for each class in the manual measurements. The results for DropletScan are not fully represented in figure because, as they peaked at >70% MAD (%) for the size class diameter <100 µm.

(WSP_{M3}, WSP_{D1}, WSP_{D2}, WSP_{D3}, see Fig. 1) had 40–60% of the droplets with diameters <200 μm diameter and tended to follow a similar pattern as the other WSPs for class sizes greater than 350 μm diameter.

Fig. 4 shows, for each software package, the between-methods mean absolute difference MAD (%) profile for droplet class size compared with the mean droplet number for each class in the manual measurements. Overall, the MAD (%) profiles and the number of spots per class follow a similar pattern. As droplet density increased, the MAD (%) of the class increased sharply. For the class size between 100 and 200 μm diameter and class sizes >300 μm diameter the between-methods MAD (%) were always less than about 10%. For the class sizes <100 μm diameter, with exception of DropletScan, the MAD (%) was lower than 20%. This lack of accuracy by DropletScan for class size under 100 μm was also reported by Wolf (2003) and it could be related with pixel limitations. The discrepancy for this class could be limited if a higher scanning resolution was used.

The class size 200–250 μm diameter had a droplet number ranging from 132 drops (WSP_{M2}) to 375 drops (WSP_{M3}) (Fig. 3) being the class with highest average number of droplets (192) and higher MAD(%) that ranged from 15% (Spray_imageII) to 40% (DropletScan) (Fig. 4). For class sizes >350 μm diameter the between-methods MAD (%) was lower than 3%, except from the Stainalysis software where the differences could reach 5%.

The Spray_imageII software gave a between-methods MAD (%) lower than 15% for all classes tested. It was the programme that presented the best results for the droplet class size distribution measurements.

The 16 droplet size class distribution for each WSP was pooled together and the between-methods compared by the ICC, paired *t*-test and 1:1 regression line (Table 7).

These results of between-methods for illustrate the need to use complementary statistical tests in order to avoid misinterpretation of between-methods comparisons. The overall class sizes results for StainMaster provided an example of between-methods with high significant differences ($p < 0.000$), fair agreement but with high significant correlation (R-square = 0.781; $n = 144$; $p < 0.000$). These data also highlight the point that correlation does not imply between-methods agreement. Moreover, the overall classes results for DropletScan had a slope close to 1 (0.84) but the R-square was relatively small and the between-methods agreement was

Table 7 – Statistics of between-methods comparison for droplet class size distributions with all WSPs pooled together.

Image analysis system	*t*-test	Intra class correlation		1:1 Regression[a]	
		ICC_v	ICC_p	Slope	R^2
All class sizes ($n = 9 \times 16$)					
StainMaster II	0.000	0.291	0.000	0.246	0.781
ImageTool	0.000	0.625	0.000	0.487	0.581
Stainalysis	0.268	0.487	0.000	0.511	0.093
AgroScan	0.000	0.238	0.002	0.224	0.605
DropletScan	0.585	0.078	0.182	0.839	0.017
Spray_imageI	0.000	0.821	0.000	0.658	0.800
Spray_imageII	0.580	0.908	0.000	0.991	0.817
Class sizes <100 μm ($n = 9 \times 1$)					
StainMaster II	0.025	0.224	0.255	0.267	0.875
ImageTool	0.349	0.266	0.217	0.826	0.456
Stainalysis	0.390	−0.389	0.852	0.669	0.048
AgroScan	0.051	0.130	0.351	0.252	0.341
DropletScan	0.048	−0.133	0.641	2.941	0.379
Spray_imageI	0.075	0.805	0.020	0.664	0.786
Spray_imageII	0.164	0.812	0.010	1.356	0.807
Class sizes 100–300 μm ($n = 9 \times 4$)					
StainMaster II	0.000	−0.003	0.505	0.236	0.679
ImageTool	0.000	0.387	0.008	0.457	0.436
Stainalysis	0.000	0.417	0.005	0.475	0.368
AgroScan	0.000	−0.063	0.646	0.215	0.363
DropletScan	0.000	−0.236	0.921	0.125	0.095
Spray_imageI	0.000	0.712	0.000	0.570	0.440
Spray_imageII	0.100	0.888	0.000	0.788	0.756
Class sizes >300 μm ($n = 9 \times 12$)					
StainMaster II	0.000	0.346	0.000	0.323	0.542
ImageTool	0.019	0.481	0.000	0.512	0.110
Stainalysis	0.000	0.511	0.000	1.370	0.120
AgroScan	0.000	0.205	0.020	0.267	0.259
DropletScan	0.000	0.471	0.000	0.480	0.218
Spray_imageI	0.000	0.664	0.000	0.599	0.521
Spray_imageII	0.051	0.810	0.000	1.187	0.739

ICC: Intra Classe Correlation value (ICC_v) and probability (ICC_p).
a Regression line through the origin between manual and automatic measurements.

Table 8 – Classification of software according their between-methods agreement level for each spray parameter.

Parameters	Gotas	StainMaster	Image Tool	Stain Analysis	Agro Scan	Droplet Scan	Spray_imageI	Spray_imageII	Mean
Coverage and droplet size spectra									
Area Coverage	Excellent	–	–	–	–	Excellent	Excellent	Excellent	Excellent
Droplet Density	Substancial	Excellent	Excellent	Moderate	Moderate	Moderate	Moderate	Excellent	Substancial
No. of droplets	Substancial	Slight	Excellent	Moderate	Poor	Moderate	Slight	Excellent	Moderate
$Dv_{0.5}$	Fair	Moderate	Poor	Poor	Slight	Substancial	Substancial	Substancial	Moderate
$Dv_{0.1}$	–	Moderate	Poor	Poor	Fair	Poor	Excellent	Excellent	Fair
$Dv_{0.9}$	–	Slight	Poor	Slight	Fair	Fair	Poor	Poor	Slight
Class sizes distribution									
All class sizes	–	Fair	Substancial	Moderate	Fair	Slight	Excellent	Excellent	Moderate
Class sizes <100 μm	–	Fair	Fair	Poor	Slight	Poor	Substancial	Excellent	Fair
Class sizes 100–300 μm	–	Poor	Fair	Moderate	Poor	Poor	Substancial	Excellent	Fair
Class sizes >300 μm	–	Fair	Moderate	Moderate	Fair	Moderate	Substancial	Excellent	Moderate
Mean of grouped parameters									
Overall mean	Substancial	Fair	Fair	Slight	Slight	Fair	Moderate	Substancial	Moderate
Coverage and sprectra	Substancial	Moderate	Moderate	Slight	Poor	Substancial	Moderate	Excellent	Fair
Class dist ribuition	–	Fair	Moderate	Fair	Slight	Slight	Substancial	Excellent	Fair

The level of between methods agreement was classified according the Intra Class Coefficient Correlation (ICC) as: i) Excellent (0.81–1.00), Substantial (0.61–0.80), Moderate (0.41–0.60), Fair (0.21–0.40), Slight (0.00–0.20), and Poor (<0.00). The null hypothesis of ICC = 0 was also tested.

weak. The Spray_imageII software in addition to having a slope close to 1 (0.99) also had a significantly higher coefficient of determination (R-square = 0.817; n = 144; p < 0.000) and excellent between-methods agreement (ICC 0.908).

The traditional approach to assessing between-methods comparisons is the use of paired t_test and/or use of Pearson correlation (e.g. Hoffmann & Hewitt, 2005; Leiva & Araujo, 2009; Salyani & Fox, 1999), therefore these results should be used with caution. According to our results, although the use of paired t-test is important in the study of between-methods comparison, the results of the statistical test are difficult to interpret. If the t-statistic is significant, it may be said that the two aggregate measures do not agree. However, if the t-statistics are not significant, it cannot be said ipso facto that the two measures agree. In this context the information from a paired t-test is insufficient to make robust between-methods comparisons and our results highlight the point that correlation does not imply between-methods agreement. Hence, in order to avoid misinterpretation between-methods comparisons, our approach uses the ICC agreement in complement with the paired t-test and regression analyses.

According to the slope regression performed for all classes, when the droplet size spectra measured manually was compared with droplet size spectra measured on the same class size with the image system, generally, as droplet class number increased the regression slope decreased (Table 7). This dynamic of slope according the number of droplets in each class may be due to sensitivity of overlap. For all tested groups of class sizes, apart the Spray_imageII, the slope of the regression was far from 1.

The class sizes distribution showed a mean between-methods agreement, according the ICC value ranging from fair to moderate (Table 7). However, the Spray_imageII programme showed a between-methods agreement level substantial (ICC 0.664) or excellent (ICC 0.908) and always greater than the other programmes. Thus, for all class sizes analysed here the Spray_imageII software showed excellent between-methods agreement and the paired t_test on the mean differences confirmed the absence of systematic bias. This version of the Spray_image programme, according to the R-square, statistic accounted for up to 74–81% of the variability of droplet number over the size distributions tested.

The accuracy of most of the tested software decreased with the decreasing class size distribution. However, this problem was not shown for the Spray_imageII programme. This discrepancy trend according class size was also reported by Zhu et al. (2011) for other imaging programs using the pixel recognition technique. Moreover these authors demonstrated that because of pixel limitations, the accuracy of any image-processing program using the pixel recognition technique would decrease as stain sizes decreases. Therefore, the use of high resolution scanners can improve the accuracy of imaging software using pixel recognition, but the computational load could be unacceptably high.

Table 8 provides summary of the most relevant results of between-methods agreement for each spray parameters estimated and software evaluated. The authors reiterate that this analysis was not designed to determine the best and worst software and that each of the tested software tools has role in spray parameter measurement. However, it is critical that operators be aware of the differences in the software and selected the one that best fits their measurements needs and environments, mainly the computational load.

4. Conclusions

The relative performance of several commercial and experimental software tools for the image processing of WSPs used as artificial targets to assess agricultural spray quality parameters was investigated.

Among all the measured spray parameters, area coverage, although apparently affected by the assumption of circular stains, appeared to be the most accurate and consistent spray parameter. Based on the data presented here, it is recognised that WSP and a subsequent image analysis with appropriated programme are a sufficiently rigorous technique for the quantitative assessment of spray coverage and droplet size spectra measurements for area coverage between 3% and 40%.

As shown in the statistical analysis there were great differences in spray parameters measured by different programmes. These results provide evidence that Spray_imageII with its overlapped feature tended to provide the highest accuracy for coverage and droplet size spectrum measurement, when compared to the other software tested. This version of Spray_image also showed accurate results when estimating droplet size distribution.

The accuracy and between-methods agreement of Spray_imageII can provide useful information about spray parameters under a wide range of situations of coverage and droplet size spectra of WSPs. However, the use of WSPs involves image processing tasks that are time-consuming and the technology for image processing does not provide for real-time measurements. Further work is required for the automatic and rapid processing of WSPs in the field. In this context the low computational load required for image processing could be an important advantage.

Acknowledgements

The authors would like to thank Aldemir Chaim (Gotas), Bob Mickle (Stainalysis), Eduardo Araújo (AgroScan), Jeremias Garmendia (StainMaster) Robert Wolf (DropletScan) for their generous help during the image processing with the software. Thanks are also due to Ms Adelaide Duarte for helping with the manual counting.

Reference of proprietary products or company is included for the convenience of the readers and does not imply any endorsement of preferential treatment by the Authors.

REFERENCES

Araujo, E., & Araujo, R. (2001). *Análise de gotas em pulverizações agrícolas utilizando digitalização de imagen ("AgroScan")*. Pelotas, RS (Brasil): Agrotec Tecnologia Agrícola e Industrial, LTDA.

ASAE-Standards. (1997). *S.327.2: Terminology and definitions for agricultural chemical applications*. St Joseph, Michigan: ASAE.

Balsari, P., & Marucco, P. (2009). Making the most efficient use of pesticide applications in vineyards – experiences from Europe. In *Crop protection in Vineyards Plumpton College*. Brighton, UK: The Association of Applied Biologists.

Chaim, A., Pessoa, M., Neto, J. C., & Hermes, L. C. (2002). Comparison of microscopic method and computational program for pesticide deposition evaluation of spraying. *Pesquisa Agropecuaria Brasileira, 37*, 493–496.

De Moor, A., Langenakens, J., Vereeckle, E., Jaeken, P., Lootens, P., & Vandecasteele, P. (2000). Image analysis of water sensitive paper as a tool for the evaluation of spray distribution of orchard sprayers. *Aspects of Applied Biology, 57*.

Dougherty, E. R., & Sand, F. (1995). Representation of linear granulometric moments for deterministic and random binary euclidean images. *Journal of Visual Communication and Image Representation, 6*, 69–79.

Fisher, R. W., & Menzies, D. R. (1976). Effect of spray droplet density and exposure time on immobilization of newly-hatched oriental fruit moth larvae(Lepidoptera-Olethreutidae). *Journal of Economic Entomology, 69*, 438–440.

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. *Applied Engineering in Agriculture, 19*, 549–552.

Franz, E. (1993). Spray coverage analysis using a hand-held scanner. *Transactions of the ASAE, 36*, 1271–1278.

Furness, G. O. (2006). *Orchard and vineyard spraying handbook for Australia & New Zealand*, Vol. 54. Loxton: Sardi (Soutth Australian Reserch and Development Institute).

Giles, D. K., Akesson, N. B., & Yates, W. E. (2008). Pesticide application technology: research and development and the growth of the industry. *Transactions of the ASABE, 51*, 397–403.

Giles, D.K., & Crowe, T. (2007). Real time electronic spray deposition sensor for agricultural sprayers has electrically conductive pads that are disposed in array across sensing surface such that location of liquid on sensing surface may be determined: GILES D K (GILE-Individual) CROWE T (CROW-Individual) UNIV CALIFORNIA (REGC).

Giles, D., & Downey, D. (2003). Quality control verification and mapping for chemical application. *Precision Agriculture, 4*, 103–124.

Hoffmann, W. C., & Hewitt, A. J. (2005). Comparison of three imaging systems for water-sensitive papers – technical note. *American Society of Agricultural and Biological Engineers, 21*(6), 961–964.

Holownicki, R., Doruchowski, G., Swicchowski, W., & Jacken, P. (2002). Methods of evaluation of spray deposit and coverage on artificial targets. *Electronic Journal of Polish Agricultural Universities*, 1–9.

Landis, J. R., & Koch, G. G. (1977). Measurement of observer agreement for categorical data. *Biometrics, 33*, 159–174.

Last, A. J., Parkin, C. S., & Beresford, R. H. (1987). Low-cost digital image analysis for the evaluation of aerially applied pesticide deposits. *Computers and Electronics in Agriculture, 1*, 349–362.

Leiva, P. D., & Araujo, E. C. (2009). *Comparación de programas de computación para recuento y tipificación de impactos de aspersión sobre tarjetas sensibles (2009/23-11-2009)*.

Marcal, A. R. S. (2008). Alternative methods for counting overlapping grains in digital images. *Springer Lecture Notes in Computer Science, 5112*, 1051–1060.

Marcal, A. R. S., & Cunha, M. (2008). Image processing of artificial targets for automatic evaluation of spray quality. *Transactions of the ASABE, 51*, 811–821.

Matthews, G. A. (2000). *Pesticide application methods* (3rd impression ed.). Oxford: Blackwell.

Otsu, N. (1979). A threshold selection method from gray-level histograms. *IEEE Transactions on Systems, Man and Cybernetics, 9*, 62–66.

Panneton, B. (2002). Image analysis of water-sensitive cards for spray coverage experiments. *Applied Engineering in Agriculture, 18*, 179–182.

Panneton, B., Lacasse, B., & Piché, M. (2005). Effect of air-jet configuration on spray coverage in vineyards. *Biosystems Engineering, 90*, 173–184.

Panneton, B., Theriault, R., & Lacasse, B. (2001). Efficacy evaluation of a new spray-recovery sprayer for orchards. *Transactions of the ASAE, 44*, 473–479.

Prokop, M., & Veverka, K. (2003). Influence of droplet spectra on the efficiency of contact and systemic herbicides. *Plant Soil and Environment, 49*, 75–80.

REMSpC. (2002). *Stainalysis Manual*. Ayr, ON Canada: REMSpC Spray Consulting.

Salyani, M. (2000). Methodologies for assessment of spray deposition in orchard applications. In *2000 ASAE Annual International Meeting*, (Milwaukee, Wisconsin).

Salyani, M., Farooq, M., & Sweeb, R. D. (2007). Spray deposition and mass balance in citrus orchard applications. *Transactions of the ASABE, 50*, 1963–1969.

Salyani, M., & Fox, R. D. (1994). Performance of image-analysis for assessment of simulated spray droplet distribution. *Transactions of the Asae, 37*, 1083–1089.

Salyani, M., & Fox, R. D. (1999). Evaluation of spray quality by oil- and water-sensitive papers. *Transactions of the ASAE, 42*, 37–43.

Schick, R. J. (2008). *Spray technology reference guide: Understanding drop size*. Wheaton, IL (USA): ©Spraying Systems Co.

Sistler, F. E., Smith, P. A., & Rester, D. C. (1982). An image analyzer for aerial application patterns. *Transactions of the ASAE, 25*, 885–887.

Syngenta. (2002). *Water-sensitive paper for monitoring spray distributions*. Basel: Syngenta Crop Protection AG.

Turner, C. R., & Huntington, K. A. (1970). The use of water sensitive dye for the detection and assessment of small spray droplets. *Journal of Agricultural Engineering Research, 15*, 385–387.

UTHSCSA. (1997). *UTHSCSA Image Tool IT Version 2.0*. San Antonio, Texas (USA): University of Texas Health Science Center at San Antonio.

Whitney, R. W., & Gardisser, D. R. (2003). WRK DropletScan^{Tm} Version 2.2 Software Manual (4th Edition ed.): WRK, Inc.

Wolf, R. E. (2003). Assessing the ability of DropletScan (TM) to analyze spray droplets from a ground operated sprayer. *Applied Engineering in Agriculture, 19*, 525–530.

Zhu, H., Salyani, M., & Fox, R. D. (2011). A portable scanning system for evaluation of spray deposit distribution. *Computers and Electronics in Agriculture, 76*, 38–43.