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A portable scanning system for evaluation of spray deposit distribution

Heping Zhu[a,*], Masoud Salyani[b], Robert D. Fox[a]

[a] USDA-ARS Application Technology Research Unit, Wooster, OH, USA
[b] University of Florida, Citrus Research & Education Center, Lake Alfred, FL, USA

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ABSTRACT

Preventing over- or under-spray applications on intended targets require a system to rapidly measure spray coverage and provide spray quality feedback information. A portable scanning system was developed that could quickly evaluate spray deposit distribution and coverage area on deposit collectors such as water sensitive paper or Kromekote® card. The system is integrated with a handheld business card scanner, deposit collectors, a laptop computer, and a custom-designed software package entitled "DepositScan". The software is composed of a set of custom plug-ins that are used by an image-processing program (ImageJ) to produce a number of measurements suitable for describing spray deposit distribution. The program worked with the handheld business card scanner to scan spray deposits on the collectors. After scanning the collectors, individual droplet sizes, their distributions, total droplet number, droplet density, amount of spray deposits, and percentage of spray coverage are displayed on the computer screen and saved in a spreadsheet. Spots smaller than 23.9 μm are ignored by DepositScan when 2400 dpi resolution was used. Observations of nominal size spots through a stereoscopic microscope verified the accuracy of the system, and demonstrated that because of pixel limitations, the accuracy of any image-processing program using the pixel recognition technique would decrease as the spot sizes decrease. The portable scanning system offers a convenient solution for on-the-spot evaluation of spray quality under various working conditions.

1. Introduction

The effect of pesticide on the environment is a major concern throughout the world. Several European countries have regulated a reduction of total pesticide use (Matteson, 1995; Falconer, 1998; Franzén, 2007). Improving the spray application process is the most feasible approach to achieve this reduction without reducing the efficacy of pest control. This can be accomplished by spraying only when pests reach a critical threshold in the crop and by applying the spray uniformly over the entire canopy. Typical spray applications generally provide over sprays to accessible parts of the target canopy and under sprays to hard-to-reach parts of the foliage. Hard-to-reach parts include the undersides of lower leaves of a field crop, the interior of dense bushes and tree canopies, etc. If sprays are applied uniformly throughout the canopy, significant reduction in the amount of applied active ingredient can be achieved without diminishing pest control.

Concerns about the overuse of pesticides also have led to increased use of biological or 'natural' materials for pest control. Often these materials are not as effective as their chemical counterparts (synthetic pesticides) and require extensive coverage of plant canopies. Albertsson et al. (2010) in studies using 'physically active' materials, such as soaps and oils, found that effective control of pests require nearly complete coverage of target canopies. The application of these materials requires quick and reliable techniques to detect their spray coverage quality.

Several investigators have studied the relationships between spray application parameters (droplet density and pesticide concentration) and the efficacy of pest control under laboratory and field conditions. In a laboratory study, Fisher and Menzies (1976) investigated the effects of the droplet density and exposure rate of newly hatched larvae of *Grapholitha molesta* (Busck) to carbaryl residues. When exposed continuously to carbaryl droplet residues, larvae reached a convulsive state in times inversely related to the number per cm^2 and to the percent area covered with droplets. Washington (1997), investigating the effects of fungicide spray droplet density, droplet size, and proximity of the spray deposit to fungal spores on banana leaf surface, concluded that calibrating agricultural spray aircraft to deposit fungicide spray droplets with a mean density of 30 droplets/cm^2 and a VMD of 300–400 μm would probably increase deposition efficiency on crop foliage and enhance disease control compared to aircraft calibrated to spray finer droplets.

Falchieri et al. (1995) studied the relationship between the feeding behaviour of gypsy moth larvae exposed to Bt pesticide deposits and spray application parameters. They found that feeding inhibi-

* Corresponding author. Tel.: +1 330 263 3871; fax: +1 330 263 3953.
E-mail address: heping.zhu@ars.usda.gov (H. Zhu).

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tion was more closely related to Bt concentration than to droplet density and dose per unit area. The highest feeding inhibition was achieved with 10 BIU/L at 9 droplets/cm^2. Koger et al. (2004) investigated the effect of glyphosate rate and coverage on pitted morning glory control. Increasing percent leaf exposure to glyphosate from 0 to 100% increased control from 57 to 75%. These results also demonstrated that inadequate control of pitted morning glory with glyphosate was more related to plant resistance to glyphosate than spray coverage. Hewitt and Meganasa (1993), using a motorized knapsack mist blower to discharge a 2.4% ULV spray (VMD 55 μm; NMD 25 μm) of cypermethrin within grass and maize canopies, found that a minimum of about 9 droplets/cm^2 was required to achieve 50% *Spodoptera exempta* larvae kill.

The quality of spray application in the field is usually measured by collectors (e.g., water sensitive paper or Kromekote® card) attached to selected target areas or leaves and inspected after spraying (Sundaram et al., 1987; Theriault et al., 2001). Imaging or scanning devices are used to measure spots on the collectors and to calculate the size distribution, area covered, or other measures of spray-coverage quality. Spot sizes are difficult to measure if spot density is too high, i.e., coverage is greater than 20% (Fox et al., 2003). However, in most of these cases, the coverage on the collectors is greater than required for effective pest control, so this is not a problem (Fox et al., 2008).

No spray coverage quality standard exists for a specific insect or disease. Coverage quality depends on droplet size, number of deposits and extent of coverage on target leaves or collectors. For effectiveness, a greater number of spray droplets per unit area will usually have a higher probability of reaching the critical threshold for pest control. Syngenta Crop Protection AG (Basel, Switzerland) recommended at least 20–30 droplets/cm^2 for insecticide or pre-emergence herbicide applications, 30–40 droplets/cm^2 for contact post-emergence herbicide applications, and 50–70 droplets/cm^2 for fungicide applications to provide satisfactory results.

Several spot size measurement systems and methods have been discussed by Franz (1993), Salyani and Fox (1994, 1999), Wolf (2003), and Hoffmann and Hewitt (2005). These systems are operated under laboratory conditions to provide valuable information about the quality of the spray coverage when comparing sprayers or treatments from one sprayer with different operating conditions. However, these systems are either too large or too slow to be valuable for spray coverage comparisons for growers at various training events or for comparative field studies. Also, the pixel resolution used in these systems is very low (less than 300 dpi), causing a great error in the spray deposition analysis. In contrast, a portable device that quickly scans collectors with a high pixel resolution and then calculates spray coverage data would be very useful to measure distributions of coverage during spray experiments or to demonstrate spray coverage at grower field days.

The objective of this study was to develop an easy-to-use and small portable device using a pixel recognition scanning technique to measure spray quality under various working conditions. This will enable users to quickly determine spray deposits on collectors such as water sensitive paper and Kromekote® card, and provide a baseline for the spray coverage quality required for effective control of insects or diseases and minimize off-target loss.

2. Materials and methods

A spray deposition recognition system was developed by integrating a portable business card scanner, a portable computer, and a program called "DepositScan" (Fig. 1). A publicly available image program (ImageJ) and a proprietary custom-developed program were combined to develop DepositScan. DepositScan specifically quantifies spray deposit distributions on any paper-type collector that could show visual differences between spray deposits and the background. Water sensitive paper, oil sensitive paper, or Kromekote® card could be used as collectors.

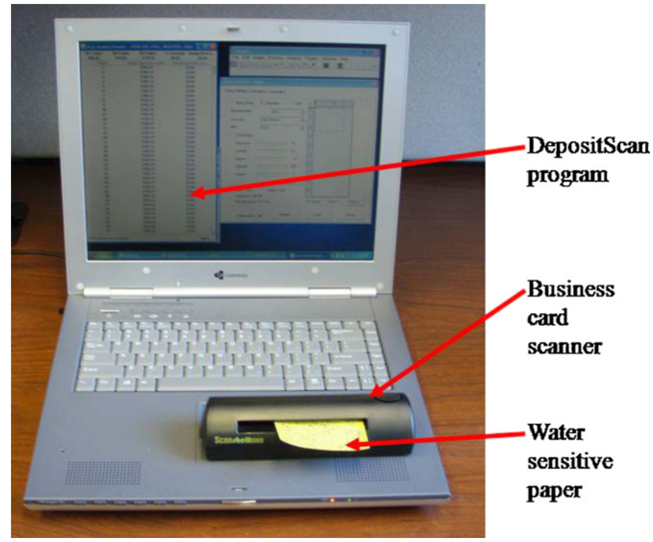

Fig. 1. The portable spray deposition scanning system consisting of a business card scanner, a computer, and the DepositScan program.

ImageJ is a Java-based image-processing program used for the acquisition and analysis of images. It was developed by the National Institutes of Health and is now freely available to public (Collins, 2007). ImageJ can be used to measure an area and count number of spots in the user-defined areas or throughout the entire image. The shape of selected areas could be rectangular, elliptical, or irregular. The program supports any number of images simultaneously and is limited only by the available random access memory. The image processing speed of ImageJ is 40 million pixels/s. A TWAIN driver, a standard software protocol and applications programming interface, is used to communicate between ImageJ program and the selected scanner. A detailed description of ImageJ can be accessed on the website http://rsb.info.nih.gov/ij/.

The proprietary custom-developed program in DepositScan incorporated a batch file that was developed with custom plug-ins using the Eclipse development platform and Java programming language. The program first opens the ImageJ (Fig. 2), then prompts the user to scan a water sensitive paper (or any other collector) and converts it into an 8-bit gray scale image. Next under the ANALYSIS feature in ImageJ, the user executes the function, COUNT BLACK AND WHITE PIXELS and then selects an area for analysis to obtain the number of spots and the area of each spot in the selected section. Finally, the program batch file calculates $D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$, and displays the results from the area of the selected section, the total number of spots and the percentage area covered by the spots. $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ represent the distribution of the droplet diameters such that droplets with a diameter smaller than $D_{V0.1}$, $D_{V0.5}$, and $D_{V0.9}$ compose 10%, 50% and 90% of the total liquid volume, respectively. The program has two options for choosing thresholds to adjust image detection quality. The first option allows the system to automatically select a detection threshold based on the image contrast. The second option is a user-defined threshold to select the image detection quality to match the actual deposit patterns.

The equation used to convert the spot area to the actual droplet diameter (d, μm) is,

$$d = 0.95 \quad d_s^{0.910} \tag{1}$$

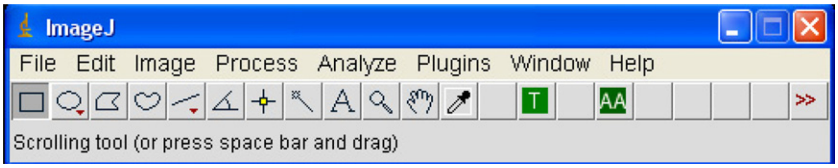

Fig. 2. The page heading of ImageJ program after DepositScan starts.

Where,

$$d_s = \sqrt{\frac{4A}{\pi}} \tag{2}$$

and A is the spot area (μm^2) acquired from ImageJ. The spot area was calculated from number of spot image pixels divided by the scanning resolution. In this program, the scanning resolution was chosen up to 2400 dots per inch (dpi), or 10.58 μm per pixel length.

The final equation to calculate the actual droplet diameter is,

$$d = 1.06 \quad A^{0.455} \tag{3}$$

The constants in the spread factor Eq. (1) were modified by Salyani and Fox (1994) to calculate sizes of droplets deposited on water sensitive papers. The constants were verified with known sizes of single droplets produced by a single droplet generator. There are alternatives of the spread factors for different collectors, and some were determined from the mid-points of ranges of droplets produced by spinning disc atomizers. To accommodate different spread factors, the DepositScan also reports the area of individual spots and allows the use of spread factor equations other than Eq. (1). In practice, some spots might be the result of overlapping deposits by several droplets and the resulting droplet diameter would then be a combination of several droplet diameters. Unfortunately, the program cannot distinguish a deposit originating from one droplet or from several overlapping droplets.

After all the deposits are converted into actual droplet diameters, the diameters are sorted from smallest to largest, and based on the calculated diameter, Eq. (4) is then used to calculate the volume of each droplet.

$$V_i = \frac{\pi d_i^{\,3}}{6}, \quad i = 1, \ldots, N \tag{4}$$

where, V_i is the individual droplet volume (μm^3), d_i is the individual droplet diameter calculated with Eq. (3), i is the order of the individual droplet in the sorted range, and N is the total number of droplets on the sample collector.

After the volume of each droplet is calculated, the cumulative volume (V_j) and percentage cumulative volume ($\%V_j$) of droplets are calculated with Eqs. (5) and (6), respectively,

$$V_j = \sum_{i=1}^{j} V_i, \quad j = 1, \ldots\ldots, N \tag{5}$$

$$\%V_j = \frac{V_j}{V_N} \times 100 \tag{6}$$

where, j is the sequenced order of the droplets in the sorted range.

The program then searches for droplet diameters at the point where $\%V_j = 10$ for $D_{V0.1}$, $\%V_j = 50$ for $D_{V0.5}$, and $\%V_j = 90$ for $D_{V0.9}$. If no value of $\%V_j$ exactly matches the10, 50, or 90 thresholds, the program will search for the closest higher and lower points to the value, and interpolate between the two closest points to obtain the $\%V_j$ value. By dividing the area of the selected section, spray coverage is calculated from the total of the spot areas, the droplet density was calculated from total number of droplets, and the amount of spray deposits per unit area is calculated from the cumulative volume V_j.

Any portable business card scanner with over 600 dpi resolution that supports for a Twain driver is suitable for this system. In this study, a ScanShell 800N business card scanner (CSSN, Inc., Los Angeles, CA) with imaging resolution at 2400 dpi and a scan capability width up to 10.5 cm was used to test the DepositScan program. A laptop computer with Windows 2000 or later operating system was used to operate the DepositScan program. The scanner was connected to the computer high power USB port. In the absence of a high power port, a port from a portable high power USB hub can be used.

A reference card containing spots with "nominal" sizes (Fig. 3) produced by Hoechst AG (Frankfurt, Germany) was used to test the accuracy of DepositScan. The reference card contained uniform spots ranging in size from 50 to 1000 μm in diameter. These spots are usually used for spray applicators to visualize droplet sizes on water or oil sensitive papers. The actual size of each spot was determined with a stereoscopic microscope (Model SZX12, Olympus, Japan) with a SPOT™ Insight color digital camera (Diagnostic Instruments, Inc., Sterling Heights, MI) to capture the spot images. The image area of each spot was then measured with the Polygonal Hand-trace feature of Image-Pro® Plus program (version 4.1,

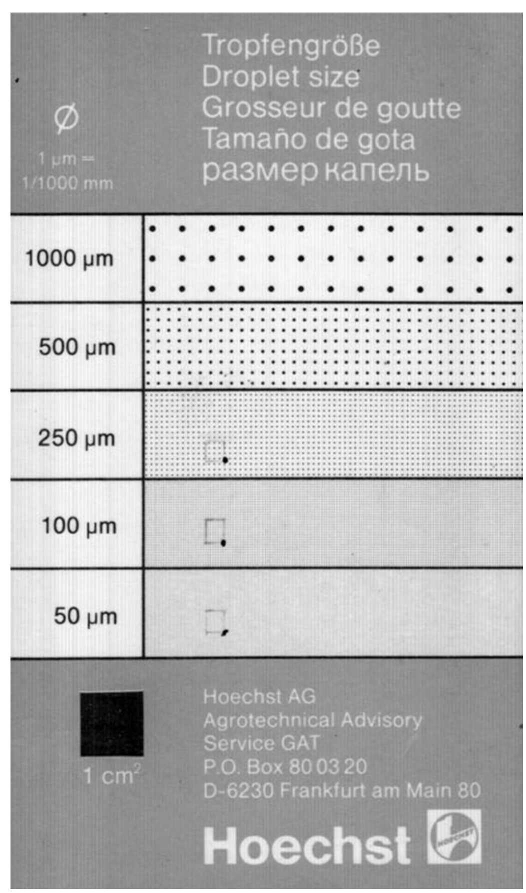

Fig. 3. Hoechst reference card containing "nominal" spot sizes of 50, 100, 250, 500, and 1000 μm used to test the accuracy of DepositScan.

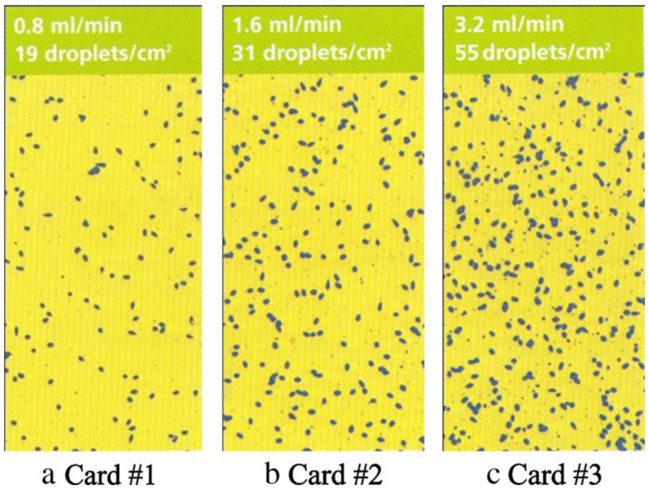

Fig. 4. Three different droplet densities from a brochure of Syngenta water sensitive papers.

Media Cybernetics, Bethesda, MD). The Image-Pro® Plus program was calibrated with a Zeiss 0.01 mm micrometer slide. The diameter of each spot was calculated from the measured area with the Hand-trace feature. Since the stereoscopic microscope measurements revealed some variation in the actual sizes of nominal 50 and 100 μm spots at different locations on the card, a group of 10 adjacent spots with similar sizes (predetermined by the stereoscopic microscope for each "nominal" size) was selected to test the accuracy of DepositScan. The stereoscopic microscope magnification was 90$\times$ for the nominal 50 and 100 μm spots and 63$\times$ for the nominal 250, 500 and 1000 μm spots, respectively.

Water sensitive paper samples from a brochure of water sensitive papers (Syngenta Crop Protection AG, Basel, Switzerland) with three different droplet densities (Fig. 4) were used to further test the system. Spots on the samples were produced with a disk sprayer spinning at 1800 rpm. The three droplet densities were 19, 31, and 55 droplets/cm^2 that were produced at flow rates of 0.8, 1.6 and 3.2 mL/min, respectively. The samples were then scanned with the ScanShell 800N and WorldCard Office (Penpower Technology LTD, Fremont, CA) business card scanners at 600 dpi resolution. Each card had an area of 13 cm^2. Spots on each image were counted and analyzed with DepositScan program.

3. Results and discussion

The actual average diameters of 50, 100, 250, 500 and 1000 μm spots on the Hoechst reference card were measured as 66, 142, 240, 507, and 1008 μm, respectively, by a stereoscopic microscope (Table 1). Fig. 5 shows the images of 50, 100, 250, 500 and 1000 μm spots on the Hoechst reference card as captured by DepositScan. The relative differences between average diameters measured by DepositScan and the stereoscopic microscope were 34.1, 16.3, 7.8, 1.4, and 1.2% for 50, 100, 250, 500, and 1000 μm spots, respectively. That is, the relative error by DepositScan decreased as the droplet size increased.

The DepositScan difference was due mainly to the resolution limitation of the scanner. Since a 2400 dpi resolution was used for this evaluation, each pixel length was 10.6 μm and the minimum spot area that could be reported was 10.6 by 10.6 μm, or an equivalent diameter of 11.9 μm droplet (calculated from Eq. (3)). Because of random locations of spots on the card, any spot with its coverage area smaller than 10.6 by 10.6 μm could be reported as covering two, three, or four pixels if it was not perfectly centered in one pixel. The equivalent diameter of four pixels is 23.9 μm. For this reason, any spot smaller than 23.9 μm was ignored by DepositScan. Based on Eq. (3), the actual droplet diameter of a spot taking a pixel (10.6 μm $\times$ 10.6 μm) area was 17 μm which was the smallest droplet diameter that could be reported by DepositScan.

The discrepancy would be greater if a lower scanning resolution was used. For example, each pixel length of 600 dpi scanning resolution is 42.3 μm. Spots with their diameter smaller than 42.3 μm would be measured as a four-pixel area, equivalent to a 95.5 μm diameter spot (or a 60 μm diameter droplet). For a 300 dpi resolution, the smallest droplet that would be reported was 60.2 μm (or 95.5 μm diameter spot), and any droplets smaller than 60.2 μm would be reported as 113.1 μm droplets (four-pixel area). This error is also true for other imaging programs using the pixel recognition technique because of the resolution limitation of the scanner; however, this problem has not been revealed for the spot size measurement systems and methods currently used to determine spray coverage quality. Therefore, the use of high resolution scanners can improve the accuracy of DepositScan. The accuracy of image measurements was also dependent on the calibration of scanners. Scanners are usually factory pre-calibrated or calibrated with standard size papers provided by scanner manufacturers.

The droplet sizes ($D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$), coverage of droplet deposits, and number of droplets per cm^2 on the three Syngenta water sensitive paper samples scanned with both ScanShell 800N and WorldCard Office business card scanners and analyzed with DepositScan were slightly different for each respective flow rate (Table 2). The maximum relative difference between the two scanners was 3.4% for $D_{V0.1}$, 4.2% for $D_{V0.5}$, 5.6% for $D_{V0.9}$, 3.9% for percent coverage, and 4.0% for number of droplets per cm^2. That is, the output of DepositScan did not vary with the type of scanner. For each flow rate, the number of droplets per cm^2 determined by DepositScan was slightly higher than that reported by Syngenta (Table 2), but the difference was smaller than 5% for the ScanShell 800N scanner and 9% for the WorldCard Office scanner. Due to the high resolution of the image scanner, DepositScan detected very small droplets that otherwise might be missed by Syngenta.

4. Operating DepositScan

Any laptop or desktop computer with Java 1.4 or a later version along with any handheld or table scanner can operate the DepositScan program. To fully take advantage of its portability function of this scanning system, a portable computer and a portable business card scanner are recommended so users can immediately determine the spray deposition quality under different working conditions in the field or in the laboratory. To make a spray analysis determination, users first load a card to the scanner, select a scanner source, choose the picture type as "grayscale", choose resolution as 600 (or up to 2400 dpi), scan the card, select area of the image for analysis, and lastly, display the resulting measurements. It takes less than 30 s to process the deposit analysis for a card. Fig. 6 is a sample of a water sensitive paper covered with spray deposits for the analysis with DepositScan, and Fig. 7 displays the results of spray deposits on the water sensitive paper including $D_{V0.1}$, $D_{V0.5}$, $D_{V0.9}$, percent coverage, image area of selected section, total number of deposits on the selected section, each individual spot area, actual droplet diameter for each spot, droplet density, and amount of deposits per unit area. The results could be saved as a data file.

Based on the scanning results from water sensitive paper collector, users could use them to compare spray deposition quality between different spray treatments, estimate the amount of spray deposition on targets, estimate spray drift potentials and off-target loss, and to perform other applications that enhance pesticide spray application efficiency. For example, for those who do not have

Table 1
Comparison of average areas and diameters measured by DepositScan and a stereoscopic microscope for nominal spot diameters of 50, 100, 250, 500 and 1000 μm shown on a Hoechst AG (Frankfurt, Germany) reference card. Percent coefficients of variation (CV) are presented in parentheses.

Nominal	Determined by DepositScan		Determined by stereoscopic microscope	
Diameter (μm)	Area (μm^2)	Diameter (μm)	Area (μm^2)	Diameter (μm)
50	6093 (25%)	88 (13%)	3390 (12%)	66 (6%)
100	21,505 (10%)	165 (5%)	15,906 (6%)	142 (3%)
250	52,688 (9%)	259 (4%)	45,342 (4%)	240 (2%)
500	196,236 (5%)	500 (2%)	201,924 (3%)	507 (2%)
1000	777,954 (2%)	995 (1%)	797,752 (3%)	1008 (2%)

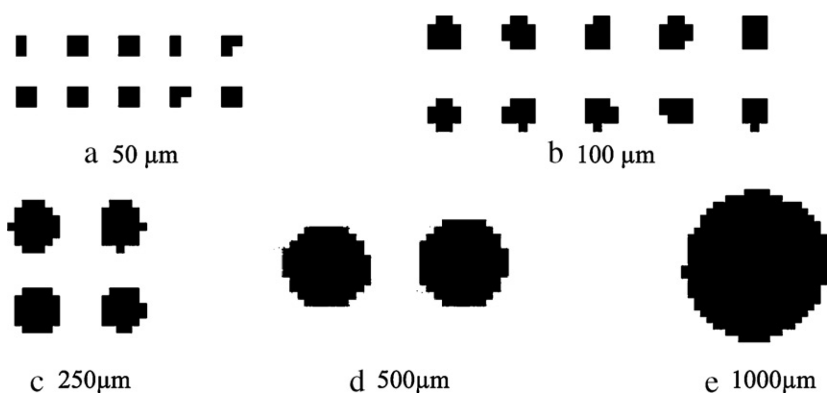

Fig. 5. Images of nominal 50, 100, 250, 500, and 1000 μm spots (not scaled) on Hoechst reference card captured with DepositScan.

Table 2
Comparison of results of DepositScan between two different scanners.

Scanner	Card#	Flow rate (mL/min)	Droplet size (μm)			Coverage (%)	Droplets/cm^2	
			$D_{V0.1}$	$D_{V0.5}$	$D_{V0.9}$		Measured	Labeled[a]
ScanShell 800N	1	0.8	341	388	506	3.57	19.9	19
	2	1.6	380	432	589	7.05	32.3	31
	3	3.2	364	485	646	11.13	56.4	55
WorldCard Office	1	0.8	338	381	490	3.43	20.7	19
	2	1.6	367	414	556	6.92	31.6	31
	3	3.2	359	487	670	10.92	56.7	55

[a] Shown on the card reported by Syngenta.

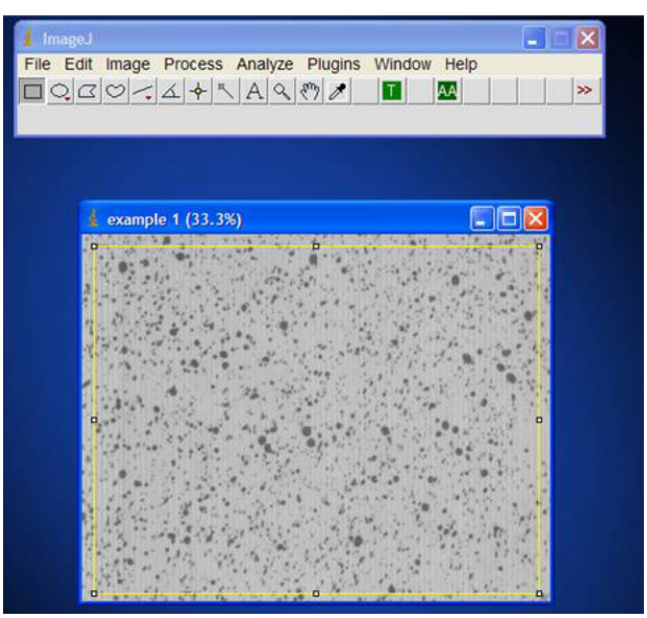

Fig. 6. A sample of spray deposit on a water sensitive paper for analysis with DepositScan.

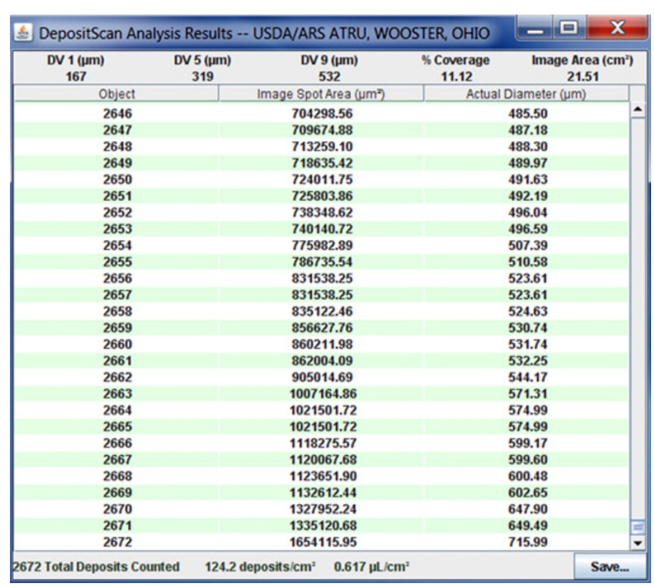

Fig. 7. Results of a spray deposit analysis on the water sensitive paper displayed by DepositScan.

access to facilities such as particle size measurement system and fluorescent analytical equipment, the scanning results could be used for estimation of droplet size classification and spray deposits on collectors. However, since the software does not correct for the droplet overlap, the estimate of droplet size and spray deposition may be inaccurate when the percentage spray coverage is large (for example, over 20%). The DepositScan software is available to the public without charge, and can be downloaded from the website http://www.ars.usda.gov/mwa/wooster/atru/depositscan.

5. Summary

DepositScan quickly analyzes distributions of spray deposits on collectors such as water sensitive papers or Kromekote® cards that are widely used for determinations of pesticide spray deposition quality on spray targets. The program was developed using Eclipse and the Java compiler to produce a set of plug-ins accepted by the ImageJ application. In operation, DepositScan first requires the user to scan samples and then converts them to produce an 8-bit gray scale images, then calculates the number of deposits and area of each deposit in the selected section. Finally, results such as individual droplet size, droplet distribution, total number of droplets, droplet density, amount of spray deposits per unit area and percentage of area coverage are displayed and saved. The program has two options for choosing thresholds to adjust image detection quality. The scanning resolution used in the program can go up to 2400 dpi, which would allow detection of a droplet that has a minimum diameter of 17 μm. The portable scanning system with the pixel recognition technique offers a convenient solution for on-the-spot evaluation of spray quality under various working conditions. The use of DepositScan also could improve accuracy of pesticide spray applications.

However, because of pixel limitations, the accuracy of DepositScan decreases along with the decreased size of the spot. This limitation would also apply to any other imaging program using pixel recognition. The program could not discriminate among overlapped deposits on water sensitive paper or other collectors. Its capability was also limited when spot coverage on collectors was too dense.

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