ELSEVIER
Agricultural and Forest Meteorology 97 (1999) 9–19
AGRICULTURAL AND FOREST METEOROLOGY
www.elsevier.com/locate/agrformet

Characterization of splash droplets from different surfaces with a phase doppler particle analyzer

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Received 4 January 1999; received in revised form 4 January 1999; accepted 3 June 1999

Abstract

A phase doppler particle analyzer (PDPA) was used to obtain information needed to characterize water splashed from various surfaces with the aim of expanding our knowledge of the spore dispersal process. Simulated rain was generated with flat-fan nozzle which produced a cumulative volume distribution similar to that of natural rains with 45 mm/h intensity. Thirteen different surfaces exhibited large differences in size distribution and total mass of splashed droplets produced. Surfaces were: bare soil, straw, plastic, sand, deep water, loosely stacked strawberry leaflets, leaflets placed horizontal on soil, healthy and rotten (diseased) strawberry fruits, and four combinations of height and planting density of a sudangrass cover crop. In general, sand, straw, leaflet, and fruit surfaces had low splash responses, while the water surface and the plastic cover had the highest responses. From 0.8% (sand) to 41.5% (plastic) of the incident rain mass was splashed >1 cm above the surfaces. For all surface treatments, droplet size distribution was positively skewed, with many more small droplets (<1 mm diameter) than large ones; however, larger droplets provided a greater contribution to the total mass than the smaller ones, resulting in bimodal volume distribution. Differences among treatments were observed for some percentiles of the cumulative volume distribution of droplets, even when the shapes of the curves were similar. The water treatment and the tall sudangrass at high planting density had the largest mean D_{50} values (volume median diameter). The straw, leaflet, sand, and fruit surfaces had the smallest D_{50} values. Percentiles of the mass distribution reflected differences in the movement of spores across different surfaces, even when the mass of water splashed was fixed. Mean number flux density (N_D) and mean mass flux density (R) varied considerably among the surface treatments, with the plastic cover having significantly higher N_D and R values than those for the other treatments. Results validated previous findings regarding the splash from selected surfaces, showed that a cover crop affected splash, indicated that plant parts differed in the properties of produced splash droplets, and showed how splash dispersal of plant pathogenic fungi could be affected by a wide range of surface conditions.

Keywords: Epidemiology; Fungal pathogens; Spore dissemination; Rain splash dispersal; Phase doppler particle analyzer; Plant disease

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0168-1923/99/$ – see front matter
PII: S0168-1923(99)00053-2

1. Introduction

Spores of many economically important plant pathogens are dispersed by rain splash (Campbell and Madden, 1990; Fitt and McCartney, 1986; Fitt et al., 1989). A key feature of this form of spore dissemination is the short distance that splash droplets travel from individual splashes. For instance, the mean flight of splash droplets with spores is $\leq$15 cm in many cases (Fitt et al., 1986; Madden, 1992). Thus, spores move to new infection sites primarily by a series of splashes and re-splashes. Because of the continual resplashing of droplets across the ground and through the canopy, the physical properties of the crop system (topography) have a profound influence on water transport and spore dispersal (Madden, 1992; Romkens and Wang, 1987).

Currently, with increasing interest in cover crops for horticultural reasons (Pritts and Kelly, 1993), intercropping has been suggested as a possible tactic for cultural control of some plant pathogens (Vandermeer, 1989). Sudangrass and other plants species (Freyman, 1989; Newenhouse and Dana, 1989; Pritts and Kelly, 1993) have been tested in strawberry management as a living mulch (cover crop) for a replacement of straw ground cover (Newenhouse and Dana, 1989; Pritts and Kelly, 1993). Our previous work with a rain simulator showed that a sudangrass cover was characterized by lower spore dispersal than found for a bare soil (Ntahimpera et al., 1998), due to the barrier effect of the plants (Boudreau and Madden, 1995). However, there was greater volume of splashed water with tall sudangrass, presumably due to the high kinetic energy at impact of large water drops dripping from the upper leaf surfaces (Yang et al., 1991; Yang et al., 1990a). Such increased splashing partially negated the barrier effect of the cover crop. Interestingly, the cover crop treatment with the greatest spore dispersal (although less than for bare soil) also had the greatest water transport (Ntahimpera et al., 1998). These results demonstrated, therefore, that a cover crop affects droplet transfer in a more complicated way than does simple variation in surface roughness. This conclusion is supported by the multifaceted effects that strawberry plant density has on disease spread (Boudreau and Madden, 1995; Madden and Boudreau, 1997).

Characterization of the mass (volume) of water splashed relative to the incident rain mass is critical for assessing the magnitude of splash dispersal (Huber et al., 1997; Madden, 1997). Methods used with rain simulators or in the field for measuring water splashed have been described by various researchers. They include a mass-based method (Huber et al., 1997; Madden et al., 1996; Ntahimpera et al., 1997, 1998; Yang et al., 1990a), use of water sensitive paper (Reynolds et al., 1987a; Yang and Madden, 1993; Yang et al., 1992), or photographic film (MacDonald and McCartney, 1988; Fitt et al., 1982). As discussed in the cited papers, all of these methods have some shortcomings — such as the need for laborious measuring and counting of sampled droplets (photographic film) or the lack of information on droplet size distribution (mass method) — which limit their usefulness.

We have previously measured mass (volume) transfer of splash droplets for homogeneous surfaces of soil, straw, and plastic, in addition to the sudangrass cover crops, using one or more of the above-mentioned measuring techniques (Madden and Ellis, 1990; Yang and Madden, 1993, Yang et al., 1990a; Yang et al., 1990b; Ntahimpera et al., 1998). We have not, however, determined mass transfer from strawberry leaves or fruits, even though these plant structures are important components of the system where splash dispersal occurs. Assessment of the splash process for leaves and fruits, as well as for the previously studied structures, is needed using methods that sample droplets immediately above the point of drop impact with little perturbation of the sampling area. Laser based interferometry is a method that provides an opportunity to perform such a research.

Various methods involving the use of lasers have been developed to measure and characterize droplet spectra of spray clouds (Lefebvre, 1989). The laser velocimetry or phase/Doppler interferometry method is used in the phase doppler particle analyzer (PDPA, Aerometrics, Sunnyvale, CA) system. This device has been successfully used to determine the droplet spectrum characteristics of pesticide spray nozzles (Chapple and Hall, 1993; Downer and Hall, 1994). Besides giving real-time measurements of splash droplets, the great advantage of the PDPA device is that it can be used to directly measure droplets splashed from a surface that is being simultaneously impacted by water drops without incorrectly interpreting incident drops as splash droplets. This is because only particles that have vertical component in the selected direction (toward or away from the surface) are recorded. Thus, no shielding is needed. To better understand the mechanisms of the splash process from a range of ground surfaces and a plant canopy, we used the PDPA device to characterize splash of water, with the aim of expanding our knowledge of the spore dispersal process. Treatments were designed specifically to evaluate splashing in the strawberry fruit rot system which we have previously studied.

2. Materials and methods

2.1. Rain generation system

The rain simulator developed at The Ohio State University, Ohio Agricultural Research and Development Center (Reynolds et al., 1987b) was slightly modified to fit a flat-fan nozzle rather than a wide-angle spray nozzle. The VeeJet 2530 flat-fan nozzle (Spraying Systems, Wheaton, IL), was operated at 69 kPa pressure at the nozzle orifice, determined using a precision water pressure gauge that was placed near the nozzle orifice. The nozzle, pointing downward, was positioned at a height of 3.3 m directly above the sampling probe volume of the PDPA device. The nozzle and water pressure were chosen to duplicate the volume distribution of natural rain (discussion in Madden, 1992). Drops produced by the nozzle travel faster than terminal velocity at the point of formation; they slow down to terminal velocity at a rate dependent on initial size and velocity (Madden, 1992; Yang et al., 1991). Using the PDPA system described below, it was determined that 1 mm diameter incident drops had a mean velocity of 1 m/s at the point of impact (3.3 m below the nozzle), close to the published values for 1 mm raindrops (Yang et al., 1991). To determine intensity of incident rain generated by the nozzle, a 10 cm-diameter funnel was placed in a 1 l cylinder at the center of the ellipsoidal rain area below the nozzle. Rain was generated for 5 min, and the volume of water collected was determined and converted to ml/cm^2/s. This procedure was done six times.

The cumulative volume distribution of drops produced by this nozzle at 69 kPa water pressure was obtained from the manufacturer (Fig. 1), and was found to be similar to the distribution for natural rains

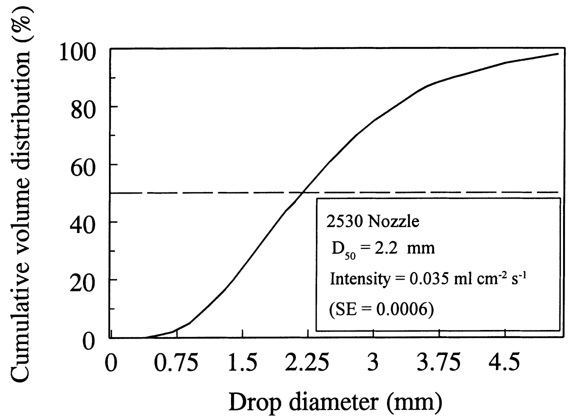

Fig. 1. Cumulative drop volume distribution of rain generated by the 2530 flat-fan nozzle based on the manufacturer's data (Spraying Systems, Wheaton, IL). Intersection of the horizontal line and the curve corresponds to D_{50}, the 50th percentile (mass median diameter).

at an intensity of about 45 mm/h (Madden, 1992). The volume (mass) median diameter was 2.2 mm (Fig. 1). The actual intensity of generated rain depended on the distance of the nozzle from the surface because of increase in coverage area by simulated rain as distance increased. With the conditions used in this study, the surfaces became saturated within a minute. Thus, no attempt was made to measure splash from dry surfaces.

2.2. Treatments

Thirteen different surface treatments were tested in this experiment. Treatments included two ground covers commonly used in strawberry production, plastic and straw mulch (Madden and Ellis, 1990), together with a bare soil treatment. These surfaces were previously tested for splash dispersal and splash droplet transport (Yang and Madden, 1993; Yang et al., 1990a) using other techniques. As controls, splash studies were also performed on a coarse sand surface (mean particle size of 1.2 [±0.4] mm) and a 10 cm deep water layer. The water layer was obtained by filling a 5 liter plastic container (15 cm depth) two-thirds full with water. The bare soil, sand, and straw surfaces were prepared by filling a 52 cm × 26 cm × 7 cm seeding flat with a soil mix, sand, or with loosely placed straw. For plastic, a soil-filled flat was covered with a 0.15 mm thick clear plastic (Sunbelt Plastics, Monroe, LA). Other treatments consisted of a sudangrass (*Sorghum bicolor* var. *sudanensis*) cover-crop, at two planting densities and plant heights, as in our previous study (Ntahimpera et al., 1998). Sudangrass was seeded in 52 cm $\times$ 26 cm $\times$ 7 cm flats at 140 or 280 kg/ha (787 or 1575 plants/m^2). Then, 4–6 weeks after planting, sudangrass plants were cut at either a height of 5 or 20 cm from the soil base for both planting densities. The labels '140/5', '140/20', '280/5', and '280/20' were used for the combination of planting density and height.

Additional surfaces included healthy and diseased strawberry fruits, as well as strawberry leaflets, either stacked loosely or lying flat on soil. For the fruit treatments, a cluster of 90 to 100 greenhouse-grown immature healthy fruits, covering an area of about 20 cm in diameter, were placed flat on soil (filling one of the above described flat) directly beneath the nozzle. A similar fruit-surface treatment was prepared by inoculating fruits as in our previous studies with a suspension of 10^5 conidia/ml of *Colletotrichum acutatum*, causal agent of anthracnose fruit rot (Madden et al., 1996; Ntahimpera et al., 1997, 1998; Yang et al., 1990a, 1990b, 1992). After a one week incubation period, the fruits (covered with sporulating lesions) were placed on the surface as done with the healthy fruits. There were no gaps between fruits.

For the surface of loosely-arranged leaflets, an empty flat (52 cm $\times$ 26 cm $\times$ 7 cm) was used and strings were first tightly attached in the long and short directions at two depths ($\sim$2 and 6 cm), with about 10 cm between strings on the horizontal plane. Strawberry leaflets collected in the field were placed, approximately horizontally, on and between the strings in several layers. The strings prevented the leaflets from becoming compressed. About 300 leaflets were used per flat ($\sim$2,300 leaflets/m^2 for each replication of the rain simulation). For the leaflets on the soil, a flat was first filled with soil mix, and then leaflets were arranged horizontally on the soil so that their edges were touching. This resulted in 63 leaflets per flat (466 leaflets/m^2). The purpose of using the loosely-arranged leaflets was to simulate water splash from the plant canopy and the purpose of the leaflets on the soil was, obviously, to simulate splash from leaflets that had been detached from the plants. At least four repetitions of the rain simulation were performed for each treatment.

2.3. Data collection system

The measurement of droplet characteristics was done by using the Aerometrics PDPA (100-1D) device. The PDPA is a laser-optical system consisting of a transmitter, receiver, signal processor, motor controller box, and computer (Bachalo and Houser, 1984; Chapple and Hall, 1993; Downer and Hall, 1994). The PDPA was operated using a 1000 mm focal length transmission lens and 160 mm collimating lens. The receiver had 495 mm focal length lens and was located at a 30° angle (off-axis) from the laser beam path (detection angle). The photomultiplier voltage was 375 V; velocity offset was 10 m/s; and velocity measurement range was 0 to 8.2 m/s. With the conditions used with our study, particles from 0.057 to 2 mm in diameter could be measured (Downer and Hall, 1994). Because splash droplets smaller than 0.05 mm in diameter typically do not contain spores (Fitt et al., 1982, 1989), and splash droplets are seldom larger than 2 mm (Fitt et al., 1982; Huber et al., 1996; Yang et al., 1991), this was considered a reasonable range of droplet sizes to detect.

The PDPA utilizes the light scattered by spherical particles to obtain, simultaneously, size and velocity measurements (vertical component) at the position where the two in-phase laser beams from the beam splitter are focused (Downer and Hall, 1994; Lefebvre, 1989). This point is called the 'probe volume'; in the current study, this point was 2 cm above the surface. Droplets are measured as they pass through the horizontal plane of the probe volume (Bachalo and Houser, 1984). The dual measurements of size and velocity in relatively dense particle environments is made possible by using large off-axis scatter detection angles (Lefebvre, 1989). Because only particles with a 'positive' or 'negative' velocity component are measured (with the direction $\pm$ chosen by the investigator), only droplets splashing away from the surface were recorded in the standard use of the PDPA. In separate tests, only incident drops were recorded. It was not possible to measure the actual trajectory of the splash droplets. In order to obtain reliable statistics, sampling was done until at least 2,500 droplets were detected for each repetition of rain simulation. A typical sampling interval lasted around 1–3 min. A high intensity was needed since the laser sensor system requires a minimum number of droplets per minute to operate correctly.

2.4. Data analysis

Various droplet distribution parameters were estimated by the PDPA software for each repetition of each treatment. These included the average droplet velocity in the direction away from the surface (vertical component) V (m/s); volume (mass) flux density M (cm^3 s^{-1} cm^{-2}); droplet number flux density N_D (s^{-1} cm^{-2}); number median droplet diameter D_M (mm), i.e., droplet size that divides the droplet distribution in half; and volume (mass) median diameter D_{50} (mm), which is the droplet size such that 50% of the total splash volume is accounted for by droplets of smaller (or larger) diameter. Additionally, D_{10} and D_{90} were calculated which are, respectively, droplet diameters such that 10 and 90% of total volume was in droplets of smaller diameter (Lefebvre, 1989). Volume flux density was expressed as a proportion of the incident I (cm^3 s^{-1} cm^{-2}) water flux ($R = M/I$) for analyses. A dispersion index (Δ) of droplet diameters was also calculated as follows:

$$\Delta = \frac{D_{90}-D_{10}}{D_{50}}$$

which is a unitless measure of the breadth of the volume distribution relative to the 'typical' size of drops.

Means and standard errors (SE) of the droplet responses were calculated across the repetitions of each treatment. Analysis of variance (ANOVA) was performed on these responses, after transformation in some cases to stabilize variances. Significant differences of means were determined with Fisher's protected least significant difference (LSD). The square-root transformation was used for R and N_D prior to ANOVA.

For presentation purposes, data from individual repetitions were pooled for each surface treatment using utility programs of the PDPA software system. Frequency and cumulative frequency distributions of droplet sizes, on a count or volume basis, as well as average droplet velocity for each droplet category size were determined and graphed.

3. Results

3.1. Incident generated rain

The mean intensity of incident rain was 0.035 ml cm^{-2} s^{-1} (SE = 0.0006) which equals 1,276 mm/h. This high intensity was needed to produce sufficient number of splash droplets in a reasonable amount of time for sampling with the PDPA. However, the cumulative volume distribution (Fig. 1) of drop sizes was representative of natural rains with much lower intensity (~45 mm/h). Thus, the generated rain had a high intensity because a large number of drops were produced in each size class, although the proportions of the total in each size class were typical for a 45 mm/h rain.

3.2. Frequency distributions

Frequency distributions of droplet diameters produced from soil, plastic, and straw covers are reproduced in Fig. 2. These are representative of the droplet responses for all surface treatments. Frequency distributions were highly skewed, with many more small than large droplets. Mean velocities were very stable for droplet diameters less than 1.2 mm (Fig. 2). Above this size, mean velocities were erratic, likely reflecting the fewer number of droplets in these large size

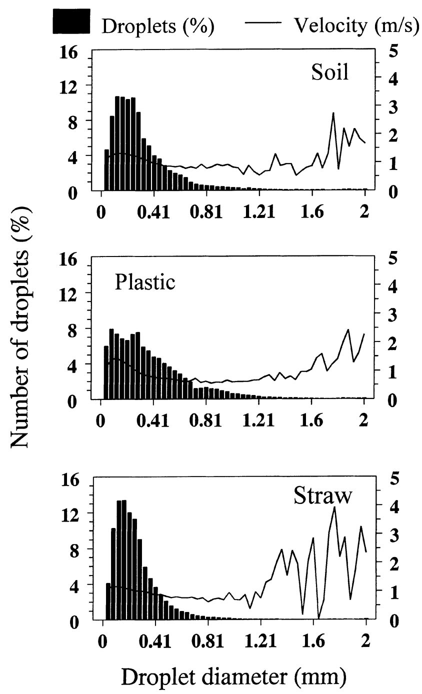

Fig. 2. Distribution of number (left axis), and mean velocity (right axis) of droplets splashed from the bare soil, plastic, and straw covers with a rain generated by the 2530 flat-fan nozzle.

Table 1
Mean velocity (V), number median (D_M) and 10th (D_{10}), 50th (D_{50}), and 90th (D_{90}) and percentiles of mass (volume) diameter distribution of splash droplets from various surfaces

Surface treatment	Velocity (V; m/s)	D_M (mm)	D_{10} (mm)	D_{50} (mm)	D_{90} (mm)	Δ[a]
Bare Soil	1.15 (0.014)[b]	0.214 (0.009)	0.394 (0.013)	1.141 (0.072)	1.916 (0.015)	1.380 (0.070)
Plastic	0.98 (0.003)	0.232 (0.003)	0.443 (0.004)	0.931 (0.012)	1.786 (0.043)	1.444 (0.037)
Straw	1.04 (0.010)	0.198 (0.005)	0.286 (0.008)	0.740 (0.026)	1.888 (0.032)	2.201 (0.102)
Sand[c]	1.35 (0.018)	0.154 (0.009)	0.227 (0.010)	0.481 (0.033)	1.727 (0.132)	3.134 (0.254)
Water[d]	0.96 (0.006)	0.290 (0.001)	0.608 (0.007)	1.291 (0.013)	1.896 (0.010)	0.998 (0.011)
Cover crop[e]						
140/05	1.10 (0.016)	0.227 (0.014)	0.376 (0.010)	1.099 (0.047)	1.925 (0.018)	1.418 (0.051)
140/20	1.06 (0.024)	0.232 (0.021)	0.413 (0.023)	1.239 (0.086)	1.932 (0.013)	1.247 (0.103)
280/05	1.08 (0.018)	0.252 (0.013)	0.399 (0.014)	1.050 (0.041)	1.909 (0.031)	1.445 (0.046)
280/20	1.11 (0.016)	0.245 (0.015)	0.410 (0.015)	1.141 (0.039)	1.945 (0.006)	1.352 (0.063)
Leaflets[f]	1.08 (0.021)	0.202 (0.006)	0.339 (0.007)	0.855 (0.013)	1.910 (0.019)	1.844 (0.032)
Leaflets on soil	1.04 (0.018)	0.217 (0.011)	0.400 (0.009)	0.960 (0.015)	1.819 (0.020)	1.479 (0.021)
Healthy fruits	1.08 (0.014)	0.226 (0.019)	0.360 (0.035)	0.908 (0.058)	1.683 (0.094)	1.469 (0.097)
Diseased fruits[g]	1.08 (0.023)	0.202 (0.006)	0.327 (0.008)	0.834 (0.022)	1.769 (0.117)	1.727 (0.120)
LSD[h] ($P = 0.05$)	0.05	0.038	0.045	0.178	0.127	0.249

[a] Dispersion, $\Delta = (D_{90} - D_{10})/D_{50}$.
[b] Standard errors of the means (across repetitions) in parentheses.
[c] Water contained in 5 liter plastic container of 15 cm depth.
[d] Coarse sand in 52 cm × 26 cm × 7 cm flat.
[e] Planting density (140 or 280 kg/ha) and height (5 or 20 cm) of sudangrass.
[f] Loosely arranged and layered.
[g] Strawberry fruits infected by *Colletotrichum acutatum.*
[h] Pairs of means within a column that are different by more than the LSD are significantly different from each other at $P = 0.05$.

categories. The erratic velocities were especially noticeable for loosely arranged straw (Fig. 2). Mean velocities (across all droplet sizes) were fairly similar among the surface treatments (Table 1). The bare soil treatment had the highest mean droplet velocity, except for the sand surface. Plastic and water surfaces had the lowest mean velocities (Table 1).

Frequency distributions of droplets sizes on a volume (mass) basis were shifted to the right (Fig. 3) compared to distributions based on counts; this was expected because volume is proportional to diameter cubed. Substantial water volume, therefore, was attributed to large splash droplets ($D > 1$ mm), even though there were very few droplets this large. In most cases, the volume distribution was bimodal, with the small number of large droplets contributing a large proportion of the total volume.

Differences could be seen in some of the percentiles (e.g., D_{50}) of the cumulative volume distribution of droplets, even when the shapes of the curves were similar. For instance, mean D_{50} (based on the mean of 50th percentiles from the individual repetitions) ranged from 0.5–1.3 mm for the various surface treatments (Table 1). The largest mean values of D_{50} were for water, soil, and the tall sudangrass treatments (‘280/20’ and ‘140/20’). The sand treatment had significantly lower D_{50} value than the others. The next lowest D_{50} means were for the leaflet and fruit surfaces, as well as the straw ground cover. This indicates that the cumulative volume distributions of droplets for sand, straw, leaflets, and fruits were shifted to the left of the distributions for soil and similar treatments (data not shown). Other surfaces had intermediate mean D_{50} values.

Number median droplet diameters (D_M) were about 0.2 mm for 12 of the 13 surface treatments (Table 1). Estimates of D_{90} were about 1.8 to 1.9 mm, except for healthy fruits and sand treatments which were slightly lower than the others. Because the values of D_{90} were close to the sensor limit (2 mm), results for D_{90} may be restricted to be more similar than would occur with a higher upper limit. However, because there were very

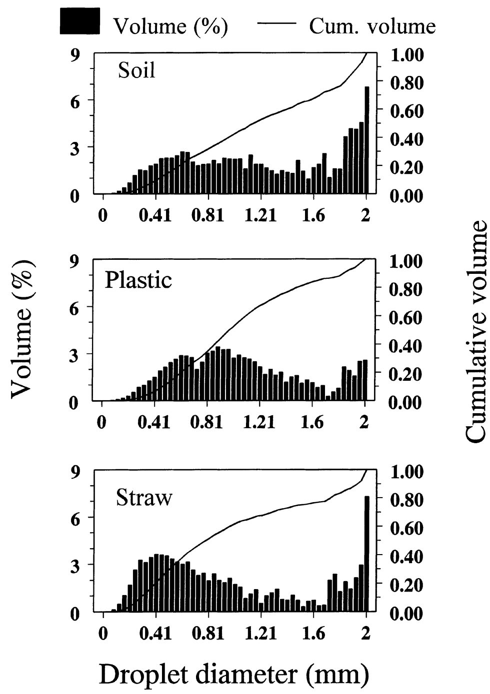

Fig. 3. Distribution of volume flux densities (left axis) and cumulative volume distribution (right axis) for droplets splashed from the bare soil, plastic, and straw covers with a rain generated by the 2530 flat-fan nozzle.

few individual droplets with diameters near D_{90} (Fig. 2), the sensor limit probably did not have a great effect on results. The mean dispersion index (Δ) was significantly higher for droplets produced from the sand and the straw surfaces than other treatments (Table 1). Other treatments had very similar mean Δ values, except for the water surface which had the lowest.

3.3. Number and mass flux densities

Splash droplet number flux density (N_D) varied considerably among the surface treatments. Mean N_D (cm^{-2} s^{-1}) from the plastic cover was substantially higher than for the other treatments (Table 2); it was about twice the value for sudangrass treatments and bare soil, which had the next highest means. Mean N_D values for strawberry leaflets (loosely arranged), sand, and straw covers were considerably lower than those of other surface treatments.

Mean mass (volume) flux density relative to the incident rain mass flux density (R) varied from ~0.01 for straw and sand, to a high of ~0.42 for plastic (i.e., 42% of incident rain falling on the plastic cover was splashed in droplets) (Table 2). After plastic, the highest mean R values were for the water and the '280/20' sudangrass surface treatments. The other sudangrass treatments had mean R values similar to those for bare soil, leaflets on soil, and healthy fruits, but significantly lower than for '280/20' or plastic. The sand, straw, and loosely-arranged leaflets treatments had the lowest R (Table 2).

4. Discussion

The production of splash droplets depends on characteristics of both the incident drop (diameter, velocity, kinetic energy) and the target (surface), including its wetness status (Huber et al., 1997, 1998; Yang et al., 1991). The surface of a plant (e.g., leaf) plays an especially important role in splash droplet formation (Stedman, 1979). For rain falling onto a crop canopy rather than a single leaf, the process is more complicated because of spatial variability of the canopy structure, as well as the temporal variability in the size distribution of incident drops (Huber et al., 1997).

Our previous results with a rain generator clearly showed that surface properties and the presence of a crop affected rain splash (Boudreau and Madden, 1995; Madden and Ellis, 1990; Ntahimpera et al., 1998; Yang and Madden, 1993; Yang et al., 1990a, 1990b). Here, we refined the results by measuring individual droplets immediately above the surface rather than those traveling a certain horizontal distance from the point of formation into samplers (mass balance and water-sensitive paper methods). Results showed that the PDPA system satisfactorily characterized water splashed from different surfaces with a high intensity incident rain. Although the generated rain had an unrealistic intensity, the cumulative drop size distribution on a volume basis was characteristic of a natural rain with an intensity of ~45 mm/h, indicating that usable information can be obtained with this rain simulation system if the rain generation was restricted to 2–3 min, as done in our study. Longer time periods would have resulted in flooding of the experimental area. Various droplet size distribution parameters were estimated here and compared for splash from different treatments (Table 1). The sand and water surfaces

Table 2
Mean number and relative mass (volume) flux densities of splash droplets from various surfaces, and the mean of the square-root transformed variables

Treatment	Droplet flux density		Mass (volume) reflection[a]	
	Mean N_D (cm^{-2} s^{-1})	$\sqrt{N_D}$	Mean R	$\%R$
Bare soil	30.8 (1.32)[b]	5.53	0.085 (0.005)	0.290
Plastic	63.3 (1.06)	7.96	0.415 (0.017)	0.644
Straw	12.3 (1.56)	3.42	0.015 (0.002)	0.120
Sand[c]	10.9 (0.95)	3.29	0.008 (0.002)	0.089
Water[d]	25.2 (0.67)	5.02	0.139 (0.005)	0.373
Cover crop[e]				
140/05	31.8 (2.61)	5.62	0.079 (0.009)	0.279
140/20	26.1 (4.12)	5.06	0.081 (0.011)	0.282
280/05	25.9 (2.32)	5.07	0.068 (0.005)	0.261
280/20	32.5 (5.60)	5.64	0.113 (0.016)	0.334
Leaflets[f]	6.48 (0.94)	2.53	0.016 (0.002)	0.124
Leaflets on soil	18.4 (2.27)	4.26	0.072 (0.011)	0.265
Healthy fruits	29.9 (2.41)	5.45	0.082 (0.012)	0.283
Diseased fruits[g]	21.5 (0.85)	4.64	0.048 (0.003)	0.220
LSD[h] ($P = 0.05$)		0.69		0.042

[a] Mass flux density of droplets divided by estimated incident mass flux density of generated rain.
[b] Standard errors of the means (across repetitions) in parentheses.
[c] Water contained in 5 liter plastic container of 15 cm depth
[d] Coarse sand in 52 cm × 26 cm × 7 cm flat.
[e] Planting density (140 or 280 kg/ha) and height (5 or 20 cm) of sudangrass.
[f] Loosely arranged and layered.
[g] Strawberry fruits infected by *Colletotrichum acutatum.*
[h] Pairs of means within a column that are different by more than the LSD are significantly different from each other at $P = 0.05$.

provided, in general, the bounds for all the other surfaces in terms of these distribution parameters. Our results on droplet diameter distributions were in general agreement with those previously published for surfaces that had been studied (Huber et al., 1996; Yang et al., 1991). Splash droplet distribution was positively skewed, with many more small droplets than large droplets. However, large droplets contributed significantly to the total mass (volume) as revealed by the cumulative volume distribution.

When the count-based distribution was converted to a mass-based distribution, the positive skewness disappeared (Fig. 3). In fact, the distribution typically became bimodal. Velocities of the splash droplets were erratic for larger droplets. Mean velocities across all droplet sizes were around 1 m/s (Table 1), similar to published results for other types of surfaces or properties of the incident water drops (Allen, 1988; Fitt et al., 1989). Since velocities were characterized based on their vertical component only, the low mean velocity of droplets splashed from the plastic cover is an indication that their trajectories were flatter (larger horizontal component) than those traveled by droplets produced from other surfaces. This is supported by the larger mass of water splashed from plastic as discussed below.

On a count basis, there was little evidence that the surface affected the size distribution of droplets (Fig. 2), or the median droplet diameter, D_M (Table 1). Large differences could be seen among surfaces, however, in the droplet size distribution on a mass basis (Table 1, Fig. 3). This is highly relevant for splash dispersal because the number of spores per splash droplets is directly related to droplets size (Fatemi and Fitt, 1983; Fitt and Lysandrou, 1984; Fitt et al., 1982, 1989; Huber et al., 1996; Yang et al., 1992). Thus, differences in percentiles of the mass distribution (e.g., D_{50}) may reflect differences in the movement of spores across different surfaces, even when the mass of water splashed is fixed.

Both the number (N_D) and mass flux density (R) were strongly affected by the surface (Table 2). As with the droplet-size distributional results, the sand and water surfaces provided lower and upper bounds on the results for the surface treatments of interest. In agreement with Yang and Madden (1993), R was much higher for a plastic surface than the others; over 40% of the incident rain was splashed in droplets with plastic. This is compared with 1.5% mass reflection for the straw treatment. Our results confirm previous work with ground covers and supports the consistent observation that spore dispersal and anthracnose disease incidence is higher with plastic than other ground covers (Madden et al., 1993; Yang and Madden, 1993; Yang et al., 1990a, 1990b).

Reflected mass flux density from bare soil was intermediate between plastic and straw, and was similar to mean R from healthy fruits and leaves placed horizontally on soil (Table 2). Mean R from soil was also similar to three of the four treatments with a sudangrass cover crops. However, with the tall sudangrass at high density (‘280/20’), mean R was significantly higher than the others, although droplet distribution parameters were very similar among the four sudangrass treatments (Table 1). Results generally support our previously reported determination of R for these cover crops heights and planting densities (Ntahimpera et al., 1998), although a cruder estimate of R was obtained in our prior study. The ‘280/20’ cover crop treatment was also associated with greater spore dispersal (Ntahimpera et al., 1998). It seems reasonable to us, based on this and other work (Armstrong and Mitchell, 1987; Morgan, 1982; Morgan, 1985; Noble and Morgan, 1983), that the increased R was due to the dripping of large water drops from the leaves of the tall sudangrass. These large drops would have considerably higher kinetic energy at impact compared with drops only falling 5 cm. For instance, a 4 mm diameter drop — common for canopy drip, and rare for rain (Armstrong and Mitchell, 1987; Morgan, 1982; Morgan, 1985) — would have kinetic energies of 75 and 151 mJ with fall heights of 5 cm and 20 cm, respectively. Thus, the increased R with some surfaces reflects the influence of impacting drop kinetic energy on formation of splash droplets. Interestingly, R for the tall plants at lower density (‘140/20’) was not different from the bare soil; presumably, there were not sufficient drips per unit area to result in measurable changes in R with this lower planting density.

Mean R and N_D values were dependent not just on the type of surface, but also its condition at the time of the study. For instance, mean R from strawberry leaflets placed on the soil and from healthy fruits were about the same as for bare soil (Table 2). On the other hand, mean R (and N_D) was substantially lower from diseased than healthy fruits, presumably because of the less rigid surface of rotten fruits. These values also were lower from leaflets loosely arranged in several layers compared with leaflets on the soil (Table 2), which also could have been due to the less rigidly combined surface comprising of the collection of leaflets.

Models of rain splash dispersal, whether based on the principles of diffusion (Yang et al., 1991) or random jumps (Pielaat and van den Bosch, 1998; Pielaat et al., 1998), have the assumption that rain splash is the same at all spatial positions. Specifically, the probability of a spore being splashed per unit time and the distances that spores travel in a single splash are considered to be the same at the inoculum source and all other positions in the area of interest. Because our results clearly showed that the splash process from diseased fruits is different than from soil (Tables 1 and 2), models may need to be extended to separately represent splash from other sources. Modeling research will be needed to determine if ‘averaged’ splash parameters can be used or if spatially explicit terms must be incorporated into models. The latter will be a mathematical challenge.

Use of laser technology was found to be an accurate way of obtaining splash droplet diameter, velocity, and mass data (Downer and Hall, 1994) directly above a surface. In particular, the PDPA system provided a fast method of measuring droplet characteristics while generated raindrops were impacting on the surface. Results validated previous findings regarding the splash from selected surfaces, it showed that a cover crop affected splash, and indicated that properties of splash droplets differed for different plant parts.

Acknowledgements

Research support and salaries provided by state and federal funds (especially USDA-NRI competitive grant 95-37303-1788) appropriated to Ohio Agricultural Research and Development Center (OARDC), The Ohio State University.

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