Evaluation of process-driven spray retention model on early growth stage barley

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Abstract

The efficiency of spray application of foliar plant protection products with hydraulic nozzles on vertically oriented and hydrophobic plants at early growth stages can be very low. The spray retention by crop leaves is affected by application parameters resulting from nozzle kind, size and operating pressure as well as spray mixture physicochemical properties. When optimizing the spray application, such targets are often used to perform retention trials for comparative purpose, i.e. indoor grown monocotyledonous at two leaves stage. A typical arrangement consists in spraying few plants sufficiently spaced underneath the nozzle to avoid interference due to secondary droplets from impacts on other plants. However, retention trials turn out to ineffective for significantly discriminating between application methods and mixtures due to the high variability between trials resulting from the different droplets retained by each plant. An alternative to retention trials is to tackle spray retention with a physical approach at the droplet scale. Such tests are often performed using high speed imaging with high magnification optics to characterize droplet impacts; adhesion, rebound or shatter on small excised leaf areas and neglect, however, the overall plant architecture. The aim of this paper is to evaluate a droplet interception model connecting actual spray retention with process-driven retention models. In this study, barley plants (BBCH11) were sprayed with 2 formulations using the same nozzle. The actual spray retention was assessed by dosing a fluorescent tracer added to the sprayed mixture. The plants were placed linearly below the center of a single moving nozzle during sprayings. Each plant was reconstructed in 3D afterwards using a structured light 3D scanner and used as input for the model. A virtual nozzle was built on the base of droplet size distributions measured with high speed shadow imaging by performing an adjustment of the distribution by the method of moments. A random droplet distribution was allocated for each spraying of a barley plant. Droplet velocities were given to droplets on the basis of the droplet velocity – diameter correlation by resolving the droplet transport equations for different droplet sizes. Initial droplet positions were randomly given. The interception model is based on a mathematical formalism for the interception between triangles of the 3D plant and droplet directions. If the droplet impacts a leaf, the amount actually retained by the leaf was computed on the basis of the droplet impact energy and impact behavior from experiments with high speed shadow imaging. In conclusion, the interception model allowed determining the spray retention by plants and discriminating application parameters by explaining the variability resulting from various droplet size distributions intercepted by single plant.

Keywords: spray retention, droplet impact, barley leaf, nozzle

1. Introduction

Agrochemicals are generally applied to cover the target as uniformly as possible using hydraulic nozzles. On early growth stage super-hydrophobic plants, only a very small fraction of the applied volume may contribute to the actual retention, what leads to low efficiency of the spray application process.

Spray retention is mainly determined by droplet impact behavior (Figure 1). As such, a droplet may directly adhere on leaves, rebound or splash depending on the droplet size and velocity, the physicochemical properties (essentially the dynamic surface tension) and the leaf surface properties, such as its roughness and wettability but also the plant architecture (Wirth et al. 1991; Massinon and Lebeau 2013).

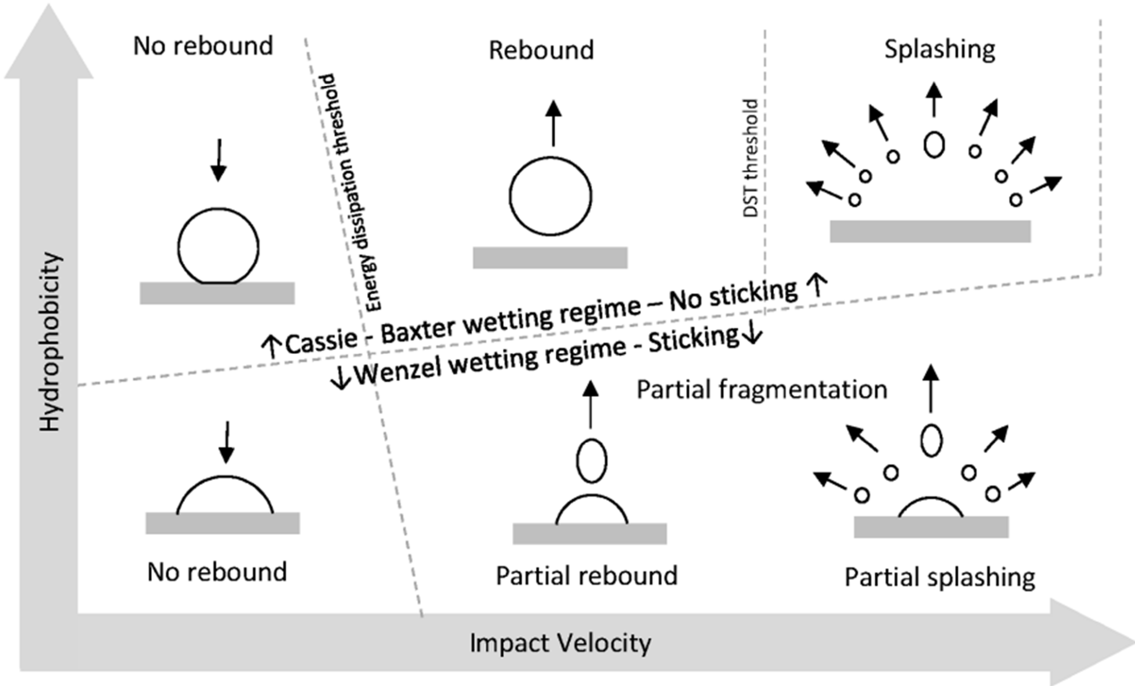


Figure 1: Possible droplet impact outcomes depending on leaf hydrophobicity and droplet impact velocity on a super-hydrophobic leaf surface (Boukhalfa et al. 2014).

Small droplets are known to adhere better but are subject to drift resulting in environmental concerns. Very fine sprays are therefore avoided. For widely used nozzles, producing fine and medium spray coarseness, a significant part of the droplets lies in the bouncing and splashing region for water-based formulations. This issue can be solved using efficient surfactants in the formulation or tank-mixed, maximizing the retention of foliar applied agrochemicals. Furthermore, too coarse sprays may result in an unacceptable amount of losses caused by drops splashing. The economically and environmentally driven reduction of applied doses must be performed carefully to keep high efficacy. This must be done according the plant species and growth stage as some operating choices on a given target can be inefficient (Knoche 1994). Therefore, comprehensive spray retention trials become a resource consuming task (Nairn et al. 2013).

A process-driven spray retention model considering all the factors influencing retention would be useful for discriminating between all the possible treatment efficiencies. Some advances have been done in this way by Forster et al. (2005) and Nairn et al. (2013). However there are still based on crude approximations of the actual plant architecture. Some authors have developed droplet interception models on theoretical plant architecture, as the Lindenmayer system, to relate different spray techniques to various vegetative structures (Dorr et al. 2007), but used a basic description of droplet behavior at impact.

As each plant is different, even for a similar growth stage, a comparison between actual and modelled retention remains a challenge. The development of fast 3D scanning systems could overcome this limitation (Paulus et al. 2014). In this paper, a process-driven spray retention model based on spray drops behavior at impact on the actual plant architecture is presented. The model evaluation is performed on barley plants by comparing the actual to the predicted retention as a function of the spray mixture for the same single nozzle.

2. Materials and methods

2.1 Model overview

The model was developed in Matlab® (R2012a) on a standard personal computer. This is a stochastic model with three mains experimental inputs from laboratory measurements: the droplet size distribution, the plant architecture and the spray droplet impact behaviors.

2.1.1 Droplet features and virtual nozzle

Droplet size distributions were measured by high-speed shadow imagery immediately before impact 500 mm downwards the outlet of the nozzle (Massinon and Lebeau 2012). Then, a virtual nozzle was built by drawing droplet diameters randomly until a given volume per hectare was reached using the Pearson system for random numbers. Random droplet diameters were generated to provide a good match with the initial size distribution parameters: the measured mean, standard deviation, skewness and kurtosis.

The virtual sprayed area was chosen at 1 square meter. Droplet coordinates were drawn within this area using uniformly distributed random numbers $U(0,1000)$ in millimeters. Then, the sprayed area was divided into a grid of squares of identical size. Each grid cell gathers therefore different droplet size distributions resulting in various applied volumes representative of the field variability.

Droplet velocity for each diameter was randomly drawn from normally distributed pseudorandom numbers $N(\mu,\sigma)$, where the mean μ was computed from droplet transport and evaporation equations (Guella et al. 2008) with still air hypothesis at 21°C and 55% RH, water droplets at 20°C with 16 m/s of initial velocity and the standard deviation σ was chosen at 0.1 m/s. Droplet trajectories were assimilated as straight lines with random directions, representative of the actual moving nozzle spray.

2.1.2 Plant architecture

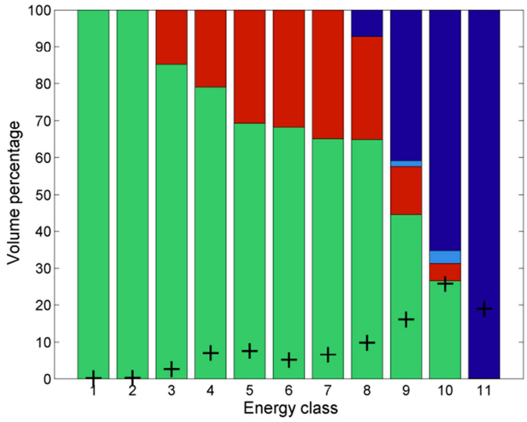
A DAVID Structured Light Scanner SLS-2 (DAVID Vision Systems GmbH, Koblenz, Germany) was used to reconstruct barley plants in 3D. It is composed of an industrial USB CMOS monochrome camera (1280 x 960 pixels, 25 FPS) with a focusable lens (12mm) and a HD video projector providing the structured light patterns. This 3D system allows a scan size of 60-500 mm with accuracy up to 0.1% of the object size, down to 0.06 mm. The calibration was performed using the DAVID calibration panels set.

Each barley plant was placed on a rotating table and scanned at 30° steps over 360°. The scans were merged afterwards using the DAVID-Laserscanner Pro Edition 3 software and exported in STL format (Figure 2, right). The virtual plant surface was therefore composed of a triangle mesh. The total leaf area was computed as the sum of the areas of each triangle of the 3D mesh and compared with a destructive measurement of leaf area based on image analysis.

Figure 2: Picture of a barley plant (left) and the corresponding 3D scan (right).

2.1.3 Spray impact on 3D leaves

The droplet impact on the 3D plant involved to test whether a droplet direction intersects or not each triangle of the 3D plant mesh. The implemented method is detailed by Möller and Trumbore (1997). To reduce the computational cost of the spray interception algorithm, the number of triangles of the 3D plant was reduced by 90% using the quadratic edge collapse decimation filter (Garland and Heckbert 1997) implemented in MeshLab (free and open-source 3D mesh processing software).
If a droplet intersects the leaf surface, the impact behavior was included to determine the amount of product remaining on the plant. On a leaf, a droplet may either adhere, rebound or splash depending on his impact energy at impact represented by the dimensionless Weber number $We = \rho V^2 d / \sigma$, where ρ is the liquid density, V is the droplet velocity at impact, d is the droplet diameter and σ the liquid surface tension, and the leaf surface wetting regime (Massinon and Lebeau 2013), as shown in the figure 1. The spray impact behavior (Figure 3) was assessed with high-speed imaging according to the method described in Massinon and Lebeau (2012) and impact behavior probabilities were implemented in the algorithm depending on the droplet impact angle according to Massinon et al. (2014). The impact phase diagram (Figure 3) is divided into eleven energy classes whose boundaries correspond to a constant Weber number (*We*). The first limit was set at *We* = 0.02. The first energy class contains droplets with a *We* below 0.02. Successive boundaries correspond to a three times increase of *We*.



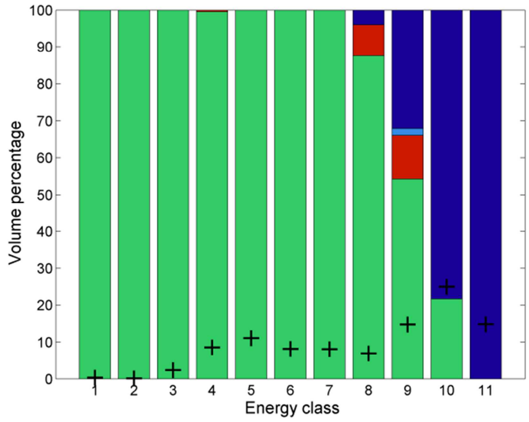


Figure 3: Droplet impact behaviors on a horizontal barley leaf (green; adhesion, red; total rebound, dark blue; total splashing and sky blue; partial splashing): impact outcome probability as a function of droplet energy classes. Tap water (left) and Break Thru S240 (right). + is the volume proportion of each energy class relative to total volume observed before impact (Boukhalfa et al. 2014).

2.2 Retention trials

The model evaluation was performed by applying two contrasted formulations to barley plants using with a single flat-fan 110-03 nozzle at 2 bars: tap water and tap water plus 0.1% v/v of Break-Thru S240® (organosilicone surfactant, Evonik Industries AG, Essen, Germany). Natrium fluorescein was incorporated into the two tank-mixes for quantifying the spray mixture actually retained by plants. Spring malting barley plants (variety Quench) were grown indoors in individual pots. Barley plants at growth stage BBCH 11 were sprayed 500 mm underneath the nozzle outlet for each mixture to assess the retention variability between plants. The actual volume per hectare applied, input of the model, was evaluated during the trials using 6 pieces of glass veil of 20 cm². Barley plants and pieces of glass veil were transferred afterwards in 20 ml of buffer solution (K_2HPO_4 at 8.71 g/L). Each solution was analyzed using a spectrophotometer (RF-1501, Shimadzu Corporation) at 460 nm excitation wave length and 540 nm emission wavelength.

3. Results and discussions

Simulations were performed on the 3D plant architectures identically positioned to the barley plants during the retention tests. For each plant, 144 different droplet size distributions were applied by the algorithm, while only one measure is possible for the actual retention. The first way to evaluate the model is therefore to see whether the measured retention belongs to the range of the simulations within 99.9% confidence interval and to compare the regression line to the 1:1 perfect match line (Figure 4). At first glance, predicted and measured retentions are in good agreement. As expected, the retention is greater for the surfactant. Furthermore, the variability between simulations seems greater than for water, which has a greater surface tension.

The model evaluation can also been performed by comparing observed and simulated values according different criteria (Willmott 1981):

- the root mean square error (Eq. 1), where N is the number of observations, Z_i and $\hat{Z}_i$ represent the observed and simulated variables respectively. RMSE should be as minimal as possible.

- the decomposition of the RMSE between the systematic mean square error (Eq. 2) and the unsystematic mean square error (Eq. 3), with the parameters of the linear regression: slope a and intercept b. the relative RMSE (Eq. 4)
- the normalized deviation (Eq. 5), should be < 0.1
- and the model efficiency (Eq. 6), should be > 0.5

$$RMSE = \sqrt{\frac{1}{N}\sum_i \left(Z_i - \hat{Z}_i\right)^2} \qquad \text{(Eq. 1)}$$

$$RMSEs = \sqrt{\frac{1}{N}\sum_i \left(b + a.Z_i - Z_i\right)^2} \qquad \text{(Eq. 2)}$$

$$RMSEu = \sqrt{\frac{1}{N}\sum_i \left(b + a.Z_i - \hat{Z}_i\right)^2} \qquad \text{(Eq. 3)}$$

$$RRMSE = RMSE / \overline{Z} \qquad \text{(Eq. 4)}$$

$$ND = \frac{\sum_i Z_i - \sum_i \hat{Z}_i}{\sum_i Z_i} \qquad \text{(Eq. 5)}$$

$$EF = 1 - \frac{\sum_i \left(\hat{Z}_i - Z_i\right)^2}{\sum_i \left(Z_i - \overline{Z}_i\right)^2} \qquad \text{(Eq. 6)}$$

In a general way, the model provides an average underestimation of about 7% (see ND) with model efficiency (EF) of about 0.9. A systematic error (RMSEs, systematic) attributed to a bias in the model appears to be greater than the random error (RMSEu, unsystematic).

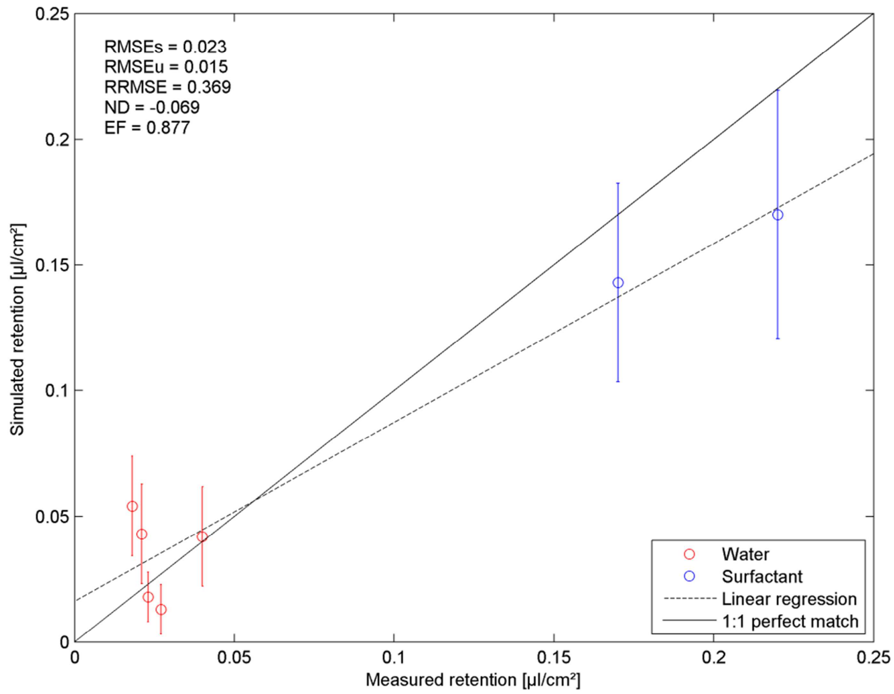


Figure 4: Predicted versus actual retention on barley plants (BBCH 11) for water (5 plants) and the organosilicone surfactant (2 plants) with 99.9% confidence intervals.

4. Conclusions

The aim of this paper was to develop and evaluate the potential of a droplet interception model linking actual spray retention with process-driven retention models and including the actual plant architecture. In this regards, a case study was chosen and the model was parameterized to fit at best the situation.
The model was able to discriminate between mixture surface tension and provided a good prediction of retention. However, the number of trials was clearly not sufficient to validate the model. To reach this objective, a great number of plants have to be sprayed in order to consider the variability of the spraying process. The plant orientation relative to the main spray direction should be investigated in the future. The greater RMSEs indicates that some work is required, especially in droplet impact behavior modification as a function of the impact angle. The under-estimation of the model for the surfactant retention has to be studied further. Other parameters should be investigated, for instance the leaf bending, the effect of hairs on droplet impact outcome.
The proposed modeling approach provides a suited tool for sensitivity analysis: nozzle kind, pressure, volume per hectare applied, spray mixture physicochemical properties, plant species, growth stage could be screened to determine the best spraying characteristics maximizing the retention.

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