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Research Paper

The impact and retention of spray droplets on a horizontal hydrophobic surface

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Spray retention, i.e. the overall capture of spray droplets by plants on initial or subsequent impact, and after loss due to run-off, is an important stage in the spray application process as droplet losses may result in reduced efficacy, economic loss, and environmental contamination. The aim of this exploratory study is to determine whether a new method based on calculating the volumetric proportions per impact type, i.e. adhesion, rebound and shatter, can be used to predict spray retention. These volumetric proportions are calculated based on logistic regression models, derived from vision-based droplet characteristics and impact assessments, and laser-based spray characteristics. The advantages and limitations of such a method are explored. The volumetric proportions per impact type on a horizontal, synthetic hydrophobic surface were determined for four different nozzles (XR 110 01 VS flat-fan nozzle, XR 110 04 VS flat-fan nozzle, XR 110 08 VS flat-fan nozzle and AI 110 08 VS air-induction nozzle) under controlled realistic conditions, and compared to the results of a retention test. The volumetric proportions of adhesion were much lower than the relative retentions, indicating that a considerable amount of rebound and shatter also contributed to final retention. The method should thus be improved by including the droplets retained after first impact and the retained proportions of partial droplet fragmentation but it is nevertheless considered a promising technique.

1. Introduction

Efficient and sustainable crop protection requires that the various stages in the spray application process are performed optimally and without detrimental effects on subsequent stages (Forster, Mercer, & Schou, 2012). These stages are (1) *deposition* (the amount impacting the target area, i.e. application volume minus drift), (2) *retention* (the amount of spray droplets captured by plants on initial or subsequent impact,

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Nomenclature

We	Weber number
ρ	liquid density (kg m^{-3})
$\mathbf{u}$	droplet velocity (m s^{-1})
d	droplet diameter (m)
σ	liquid surface tension (N m^{-1})
PTFE	polytetrafluoroethylene, Teflon®
PDPA	Phase Doppler Particle Analyser
θ_0	static contact angle (°)
θ_{adv}	advancing contact angle (°)
θ_{rec}	receding contact angle (°)
BSF	Brilliant Sulfo Flavine
$We_{A/R}$	Weber number of transition between adhesion and rebound
$We_{R/S}$	Weber number of transition between rebound and shatter
$\Delta\theta$	contact angle hysteresis (°)

after loss due to run-off), (3) *uptake* (the fraction of retained material taken up into the plant foliage), and (4) *translocation* (the amount of absorbed material translocated from absorption site to site of biological activity) (Forster et al., 2012; Forster, Steele, Gaskin, & Zabkiewicz, 2004). Poor efficiency in any stage may result in economic losses, environmental contamination, food safety issues or reduced biological efficacy (Reichard, Cooper, Bukovac, & Fox, 1998; Zabkiewicz, 2007). This paper will focus on the process of retention.

When a droplet impacts on a surface, three outcomes are possible: (1) *adhesion*, (2) *rebound* or (3) *shatter*. When a droplet hits a surface, the kinetic energy of the droplet, defined by its mass and velocity, causes it to spread out across the surface. The droplet reaches its maximum spread when all the available kinetic energy is converted to potential energy. Simultaneously, the contact angle of the droplet decreases from being advancing to receding. Subsequently, the droplet will recoil due to surface tension. During both the spreading and recoiling phases the droplet loses energy. If the energy losses are low enough the droplet will bounce off the leaf. If the losses are too great then insufficient energy remains for rebound and the droplet adheres (Forster et al., 2012; Spillman, 1984). If a droplet hits the surface in a highly energetic state surface tension can be insufficient to maintain its integrity and it can shatter into finer droplets (Bergeron, 2003; Durickovic & Varland, 2005; Mercer et al., 2007). For optimal spray retention, droplets that impact the plant surface must remain on the plant and thus the volume percentage of adhering droplets should be maximised (Boukhalfa, Massinon, Belhamra, & Lebeau, 2014; Massinon & Lebeau, 2013).

The type of impact outcome depends on the characteristics of the liquid (surface tension, viscosity), droplet (size, velocity) and surface (roughness, wettability, orientation). Each impact event can be characterised by a Weber number ($We = \rho|\mathbf{u}|^2 d/\sigma$) which represents the ratio between kinetic energy and surface energy of the droplet, where ρ (kg m^{-3}), $\mathbf{u}$ (m s^{-1}), d (m) and σ (N m^{-1}) are respectively the liquid density, droplet velocity, droplet diameter and liquid surface tension. Rioboo, Voué, Vaillant, and De Coninck (2008) proposed for a certain surface and in the absence of viscosity modifications, a constant critical Weber number for transition between impact outcomes. Based on droplet Weber numbers and impact outcomes, logistic regression models can be established which describe the probability of droplets to belong to each impact class according to their Weber number. For example, in the models, a droplet with critical Weber number would have an equal probability of belonging to one of two different impact classes (Massinon & Lebeau, 2012b). In combination with data on the droplet size and velocity spectra of a spray, the volumetric proportions of the spray in each impact class could be determined from these regression models.

The aim of this exploratory study was to determine whether a new method based on calculated volumetric proportions per impact type, i.e. adhesion, rebound and shatter, could be used to predict spray retention. These volumetric proportions are calculated based on logistic regression models, derived from vision-based measurements of droplet characteristics and impact assessments, and laser-based measurements of spray characteristics. The advantages and limitations of such a method are discussed. The development of such a method might allow spray characteristics and settings that could result in improved retention on different crop surfaces to be identified without the need for time-consuming and costly retention studies. The surfaces of leaves vary widely in wettability, from superhydrophilic to superhydrophobic (Koch & Barthlott, 2009). However, difficult-to-wet leaves are of great concern in agriculture since they are difficult to treat with crop protection products. Hence, this study focuses on hydrophobic surfaces. Because of the variability inherent to natural leaf surfaces (Taylor, 2011), a synthetic hydrophobic surface is used to perform tests under controlled but realistic conditions.

2. Materials and methods

The study consisted of different steps which are described here but they will be discussed in more detail in the subsequent sections. Firstly, high-speed images of droplets of tap water impacting on horizontal, synthetic, hydrophobic polytetrafluoroethylene, Teflon® (PTFE) coated slides were acquired for four different nozzle–pressure combinations as described by Massinon and Lebeau (2012b). Then, droplet size and velocity data were obtained using image analysis and the types of impact were visually assessed and classified into adhesion, rebound or shatter. From the droplet characteristics, Weber numbers were calculated. Subsequently, logistic regression models were developed with the impact outcomes adhesion and shatter as binary dependent variables, with droplet Weber numbers as independent variable. Based on these logistic regression models, the probability of a droplet to belonging to each impact class was established. From the probability distribution of the different impact outcomes, two critical Weber numbers of transition were determined. The droplet size and velocity characteristics of the whole spray were then determined using a Phase Doppler Particle Analyser (PDPA) laser for the same nozzles at 400 kPa and the