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Spray droplet impaction outcomes for different plant species and spray formulations

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ABSTRACT

A track-sprayer combined with a high-speed camera were used to visualize and identify droplet impaction outcomes for three formulations (water, 0.1% LI 700® (lecithin, a mixture of soya oils, propionic acid and surfactants) in water and 0.1% Pulse® (non-ionic surfactant, trisiloxane ethoxylate) in water) on four plant species (bean (*Vicia faba* L.), avocado (*Persea americana* L.), barnyard grass (*Echinochloa crus-galli* L. P. Beauv.) and cabbage (*Brassica oleracea* L.)) selected to represent a wide range of leaf surface characters. Droplet sizes and velocities were measured by image analysis and a multiple hypothesis tracking algorithm. Impaction outcomes were categorized into adhesion, bounce, or shatter. The probability of each outcome was estimated from logistic regression models related to the dimensionless Weber number. This approach is in contrast to various deterministic threshold criteria for droplet bounce or shatter that have been used to model droplet impaction events on leaves. It also provides a simple visual and numerical presentation of the complexity of impaction processes, and the relative influence of leaf surface character versus formulation for droplets with different impaction energies.

1. Introduction

Weed and pest control is important in crop production to maximize yield potential and quality. The spraying of agrochemicals remains the most common approach to achieve this outcome. However, a better understanding of the processes involved is required to maximize biological efficacy while minimizing adverse effects on the environment.

The spray application and efficacy of foliar pesticides depends on four processes, namely the deposition, retention, uptake and translocation of the actives in the applied formulation (Zabkiewicz, 2007). The retention of most plant protection products on plant leaves is a key to their efficient use. Retention efficiency can be between 10% and 100%, depending on the application technique and plant properties (Butler Ellis et al., 2004; Knoche, 1994). Several factors contribute to the variability of spray retention by plants. These primarily include spray nozzle kind and size, the volume applied per hectare, and the formulation (Matthews, 2008; Spillman, 1984). Some plant characteristics can also lessen retention of spray by the foliage, namely plant and leaf size (Dorr et al., 2014; Massinon and Lebeau, 2013), vertical architecture (Massinon et al., 2015) and the low or variable wettability of their leaf surfaces (Gaskin et al., 2005). The spray parameters must therefore be tailored and optimized to maximize foliar retention and coverage.

Predominant parameters related to the droplet, viz. size and velocity, its direction relative to the surface, or the liquid surface tension and viscosity, play significant roles in the behaviour of droplets impacting onto dry and solid surfaces (Josserand and Thoroddsen, 2016; Rioboo et al., 2001; Yarin, 2006). Other factors, such as air inclusion or complex formulations (e.g. emulsions), may also affect outcomes (Miller and Butler Ellis, 2000; Holloway et al., 2000). As the droplet spreads on impact with the leaf surface, the

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liquid and surface properties affect the liquid flow and lead to various scenarios of droplet impact. If the droplet kinetic energy overcomes the capillary forces, the droplet shatters into smaller secondary droplets that are detached radially from the expanding lamella. When the kinetic energy of the droplet is partly dissipated by viscous forces and partly converted into surface energy, capillary forces promote the droplet receding of its area of contact. If the remaining energy is not dissipated during the receding stage, the droplet can bounce. Otherwise the droplet adheres.

From an agronomic perspective, droplets reflected from a leaf surface on impact are direct losses if not recaptured by the plant canopy. Surfactants are commonly included in spray formulations to improve the retention and spreading of droplets, especially when the target is difficult-to-wet (Gaskin et al., 2005). The droplet impact and spreading of surfactant-laden formulations is complicated and the possible mechanisms are still being debated (Gatne et al., 2009; Ivanova and Starov, 2011; Kovalchuk et al., 2016). The effects that leaf surface roughness and chemistry have on the liquid dynamic wetting, and subsequently on the droplet impaction outcomes such as adhesion, bounce or shatter, are still not fully defined. However, it is known that droplet adhesion decreases with increasing droplet impact velocity, diameter, leaf angle, formulation surface tension and leaf roughness factor (Forster et al., 2005; Nairn et al., 2013).

Laboratory retention trials can reveal the actual response of a plant system, when the spray formulation, nozzle, volume applied, plant species and growth stage are controlled, but they provide a limited understanding of the complexity involved since there are many competing physical and chemical processes. It is therefore difficult to attribute the effect of each particular factor to the spray retention outcomes. High-speed cameras have been used to visualize droplet impaction on leaf surfaces (Dong et al., 2015; Reichard et al., 1998; Wirth et al., 1991) and provide some insight into the physics of droplet impaction. However, most studies have used single droplet generators resulting in droplets impacting at, or below, terminal velocity (which is in the range of 0.5–3 m s^{-1} for 160 μm - 750 μm droplets) at impaction. Thus, these studies do not illustrate all the possible droplet impact outcomes that would result from a broader range of droplet impact energies that are relevant for real applications.

The current study relied on conventional spray equipment with higher droplet velocities so that the full range of impaction outcomes could be obtained within a spray application treatment. The aim was to document the droplet impact outcomes for three spray formulations ranging in equilibrium surface tension from 22 to 72 mNm^{-1} impacting a range of leaf types. A further objective was to estimate the probability of these outcomes as computed from logistic regression models related to the dimensionless Weber number. Here, the Weber number (We_n) is defined as the dimensionless ratio between droplet kinetic energy in the direction normal to the surface and its surface energy according to $We_n = \rho V_n^2 D/\sigma$, where ρ is the liquid density, V_n is the droplet velocity normal to the impacted surface, D is the droplet diameter and σ is the formulation equilibrium surface tension.

2. Material and methods

2.1. Plants

Four species were chosen to cover a range of leaf wettabilities: bean (*Vicia faba* L.), avocado (*Persea americana* L.), barnyard grass (*Echinochloa crus-galli* L. P. Beauv.), and cabbage (*Brassica oleracea* L.). All plants, except avocado, were grown from seed in individual pots containing PPC_{NZ}/Bloom potting mix (Daltons, NZ), and raised under controlled environment conditions with 70% relative humidity, watered daily each morning prior to use, and 12 h photoperiod at ca. 450 μmol m^{-2} s^{-1} light intensity. Day/night temperatures were 20°C/15 °C for bean and cabbage, and 23°C/15 °C for barnyard grass. The plants were used at approximately four weeks of age. Avocado leaves were harvested from an adult tree grown in Rotorua (New Zealand) under natural conditions.

Table 1 shows the relative wettability of each species as defined by Gaskin et al. (2005). This technique is used to discriminate between leaf surface wetting based on the measurement of the static contact angle of 20% v/v acetone in water. A low contact angle (<60°) is indicative of easy wetting, up to 80° is regarded as moderate, measurements around 100° are regarded as difficult and angles over 120° are very difficult-to-wet. Contact angles were averaged over 21 measurements (2 μl droplets) across 3 leaves each taken from different plants to minimise variations between individual plants and hysteresis in individual measurements. Leaf roughness and polarity, fundamental factors known to govern leaf surface wettability (Holloway, 1970), are assessed using the wetting tension-dielectric (WTD) technique (Nairn et al., 2011; Nairn and Forster, 2016) which is based on contact angle trends, using solutions with varying dielectric constant (used as a surrogate for polarity), measured on each leaf surface.

2.2. Spray formulations

The three formulations used were: water, water plus LI 700® (lecithin, a mixture of soya oils, propionic acid and surfactants; Etec Crop Solutions Ltd, NZ) and water plus Pulse® (non-ionic surfactant, trisiloxane ethoxylate, Nufarm Ltd, NZ). Both adjuvants were used at 0.1% (w/v) in water. These were chosen to provide a representative range of solution properties (chemistries and surface tensions). Agrichemical formulations can have equilibrium surface tension (EST) ranging from 72 mNm^{-1} (no adjuvants), more typically around 40–50 mN m^{-1}, and in the 20's for organosilicone formulations. The values for the EST and dynamic surface tension (DST) at 50 ms, determined using a Krüss bubble pressure tensiometer (BP2 MKII), are shown in Table 2 for each spray formulation. The DST values are provided as an insight of the variation of surface tension with time; an average time of 50 ms has been chosen as representative of flight times based on previous work (Dorr et al., 2016). Although the role of DST is evident in governing the time-dependent processes of droplet impact and film-spreading for surfactant-laden droplets, only EST has been used in this study. A fundamental contention remains on the scaling between droplet impact dynamics, liquid properties and wetting for surfactant solutions, which requires surfactant chemistry, ionic and molecular structure, adsorption-physiosorption rates and electrokinetics be considered (Gatne et al., 2009).

2.3. Tracksprayer impaction study

Sprays were applied using a calibrated moving head tracksprayer (PPC_{NZ}, Rotorua, New Zealand) with a single flat fan XR11003VP nozzle (Sprayings Systems Co., Wheaton, USA) operating at 300 kPa (1.23 L min^{-1}), traveling at an average speed of 1.7 m s^{-1}, producing a range of droplet sizes. Respectively these were: water $D_{v0.5}$ = 202 μm, relative span 1.28, initial velocity 20.1 m s^{-1}; LI 700® $D_{v0.5}$ = 241 μm, relative span 1.19, initial velocity 21.9 m s^{-1}; Pulse® $D_{v0.5}$ = 221 μm, relative span 1.19, initial velocity 22.6 m s^{-1} (Dorr et al., 2016). In the current study, the droplet size and velocity of each observed impacting droplet was measured just prior to impact as described below (sections 2.5.1 and 2.5.2). The nozzle height was set at 500 mm above the leaf sample. Leaf samples (approximately 2 mm × 10 mm) were taken from an excised leaf immediately before spraying and attached to a