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Towards a model of spray–canopy interactions: Interception, shatter, bounce and retention of droplets on horizontal leaves

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ABSTRACT

Pesticides used in agricultural systems must be applied in economically viable and environmentally sensitive ways, and this often requires expensive field trials on spray deposition and retention by plant foliage. Computational models to describe whether a spray droplet sticks (adheres), bounces or shatters on impact, and if any rebounding parent or shatter daughter droplets are recaptured, would provide an estimate of spray retention and thereby act as a useful guide prior to any field trials.

Parameter-driven interactive software has been implemented to enable the end-user to study and visualise droplet interception and impaction on a single, horizontal leaf. Living chenopodium, wheat and cotton leaves have been scanned to capture the surface topography and realistic virtual leaf surface models have been generated. Individual leaf models have then been subjected to virtual spray droplets and predictions made of droplet interception with the virtual plant leaf. Thereafter, the impaction behaviour of the droplets and the subsequent behaviour of any daughter droplets, up until re-capture, are simulated to give the predicted total spray retention by the leaf. A series of critical thresholds for the stick, bounce, and shatter elements in the impaction process have been developed for different combinations of formulation, droplet size and velocity, and leaf surface characteristics to provide this output.

The results show that droplet properties, spray formulations and leaf surface characteristics all influence the predicted amount of spray retained on a horizontal leaf surface. Overall the predicted spray retention increases as formulation surface tension, static contact angle, droplet size and velocity decreases. Predicted retention on cotton is much higher than on chenopodium. The average predicted retention on a single horizontal leaf across all droplet size, velocity and formulations scenarios tested, is 18, 30 and 85% for chenopodium, wheat and cotton, respectively.

1. Introduction

The challenges facing agrichemical users have increased in complexity over recent years. On the one hand, consumers require the highest quality of produce, while on the other, regulators insist on safety (to the consumer from residues) and risk reduction (to the operator, environment or ecosystem) (Zabkiewicz, 2007). The requirement to reduce detrimental ecological effects and retain or improve both biological efficacy and the economic viability of the grower can only be met by optimising spray efficacy through smarter and more cost effective spray formulation and application. These factors must be considered together as they are linked inextricably (Zabkiewicz, 2007) if optimal canopy penetration and coverage is the objective.

Many spray programmes currently employed in the agricultural industry appear to provide lesser control of pests than might be expected from laboratory trials, which can be attributed to inadequate canopy penetration and foliar coverage. Spray adjuvants and the correct choice and use of spray application equipment are powerful tools to maximise pesticide efficacy, reduce detrimental environmental effects and improve the economic viability of the grower.

Expensive field measurements of specific crop/environment combinations are currently required to determine optimal adjuvant formulations and spray application technology. The use of mathematical and computational models to help predict such behaviours could provide a more cost effective alternative, provided they can

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reliably predict total plant retention, within-canopy distribution, leaf coverage or spray solution run-off.

Previous studies have resulted in empirical models for initial adhesion (Forster et al., 2005) and spray retention (Forster et al., 2006; Pathan et al., 2009) by individual plants. These models utilise parameters that describe solution properties, spray droplet physical properties and leaf surface characteristics. Further progress has been made on various elements of the spray retention process. However, there is a need for a coherent overarching simulation package that is based on process-driven principles instead of empirical chemical-crop environment specific scenarios.

Models for spray deposition from aerial application do exist (Teske et al., 2002), however the focus has been on spray drift, not retention. Models of spray deposition through the plant canopy (Dorr et al., 2008), or impaction onto the plant (Bergeron et al., 1999) also exist. However, these models make the simplifying assumption that if a plant intercepts a droplet, it is always retained. Process-driven models for retention, taking into account droplet bounce and shatter, have recently been implemented within AGDISP (Schou et al., 2012). The focus of the current paper is on further developing process-driven models for droplet interactions with the plant, at or after interception. The innovation of the system presented here is that virtual leaf surface models have been developed and then subjected to virtual spray droplets, with predictions made of droplet interception and retention by the plant leaves. The model inputs include formulation, droplet and plant parameters, so the model will be able to help pick the best formulation and droplet size spectrum to be used for a given plant/crop. These inputs will need to be modified by intelligent operational choices to avoid excessive spray drift while maximising retention in reality.

The construction of a virtual surface with which the droplets may interact is, in itself, a challenging problem. In order to capture a large, accurate data set the technology of scanners and their operation requires a significant amount of experience. Work reported by Loch (2004), investigated the use of piecewise cubic elements to interpolate a point cloud by a surface with a continuous gradient. In that work the use of a hand held scanner was addressed and an initial investigation of pathways of surface droplets under gravity was made. A theoretical analysis of the interpolation technique was made by Turner et al. (2010) and Oqielat et al. (2011) who investigated two techniques for derivative estimation. In that paper a quasi one dimensional model of the movement of a droplet, incorporating gravity and some surface effects was presented. Experiments were made by putting water droplets onto a leaf and recording their paths. In Kempthorne et al. (2012) and Kempthorne et al. (2013) least squares approximation of point clouds by linear combinations of smooth splines was investigated. These were the surface fitting techniques used in the current work for which efficient numerical linear algebra algorithms have been constructed.

This paper reports on the development of process-based models for adhesion and retention, using a simplifying assumption of horizontal surfaces and droplets impacting perpendicular to the surface. The model is then tested for three different formulations on three plant leaf examples with differing surface shapes and impaction characteristics.

2. Model description

2.1. Overview

Mathematical models of droplet impaction processes at multiple scales are being developed and integrated to help quantify, optimise and predict the complexities of agrichemical spray retention by plants. Parameter-driven interactive software has been implemented to enable the end-user to study and visualise a variety of practical agrichemical scenarios. Actual plant leaves have been scanned to capture the surface topography and a realistic virtual leaf surface model generated as an integral component of a structural model of an entire virtual plant. Virtual spray droplets are then applied to the leaf model and predictions made of droplet interception and retention by the plant leaf.

2.2. Leaf surface models to provide virtual reproductions of leaf topography

A leaf surface representation was generated to act as the target for the droplet interception and impaction models. To generate these surface representations a large number of three-dimensional data points were captured from an actual leaf surface. Cotton and chenopodium leaves were scanned using an Artec S™, by Artec Group (www.artec3d.com), which is a 3D white light scanner. This scanning process produced a cloud of data points, which was then used as an input for a surface fitting algorithm (Kempthorne et al., 2013; Oqielat et al., 2011). This technique provides the ability to control the coarseness of the underlying mesh, with coarser meshes providing shorter simulation times for the spray droplet trajectory model. The surface is constructed using D^2-splines (Arcange et al., 2004), which minimises a combination of the squared residuals between the fitted surface and the collected data and the curvature of the surface.

This process is displayed for a chenopodium leaf in Fig. 1. A photograph of the scanned leaf is shown in Fig. 1(a). The point cloud of the scanned leaf contained 105,846 data points and is shown in Fig. 1(b). This dataset was then used to generate a mesh of 6921 points and 13,226 triangles, displayed in Fig. 1(c). The resultant surface is shown in Fig. 1(d), where the photograph in Fig. 1(a) has been texture mapped onto the surface. The surface can be presented in a format suitable for use with the spray droplet trajectory model described in the following section.

2.3. Modelling spray droplet trajectories and interception by leaves on virtual plants

L-studio, a Windows-based software environment for creating simulation models of plants (Prusinkiewicz, 2004; Prusinkiewicz et al., 2007), was used in this study. The leaf surfaces from Section 2.2 were imported into the 'cpfg' (plant and fractal generator with continuous parameters) component of L-studio using the Tsurface specification (Mech, 2005). L-system based models of the whole plants can be extended to incorporate the detailed leaf surface models and the spray interception model. A particle trajectory model that uses a combined ballistic and random walk approach, as described by Dorr et al. (2008), was used to model the movement of spray droplets through the air. It calculates the trajectory of the droplets from release to final impact and determines if they impact on any leaf; if so, their incidence angle and velocity is determined at impaction. Any droplets that are released through shatter or bounce are tracked until all droplets are accounted for, including those lost to the ground or that drift away from the sprayed area. A complementary output is the distribution of spray throughout the canopy. The single plant outputs can be also amalgamated into a multi-plant (same or different species) model to simulate spray retention by entire crops or crop/weed populations.

2.4. Spray droplet impaction models to calculate adhesion, bounce or shatter behaviour

When a droplet impacts on a leaf surface, there are three possible outcomes, namely adhesion, bounce or shatter. The model by Mao et al. (1997) is used to describe the droplet's interaction with