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On-the-field simulation of fertilizer spreading: Part 1 – Modeling

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ABSTRACT

The field elevation and its variation represent a disturbance in the spreading process that is not handled yet by centrifugal spreaders. This stems in part from the knowledge gap regarding the possible application errors of fertilizer on non-flat fields. To address this issue, a new model has been developed, integrating both the field elevation and the tractor motion. The model was employed in the paper ("On-the-field simulation of fertilizer spreading: Part 2 – Uniformity investigation"). The model was based on transformation matrices to update the initial conditions of the ballistic flight of particles in the field coordinate system at each new position of the tractor, as it moves along a given trajectory on a given DEM (digital elevation model). An experimental validation was conducted using a radial bench in different static configurations, which also provided the unknown input data for the model. High correlation coefficients were found between the characteristics of the simulated and measured spread patterns, even where, in the simulation, the model parameters were fixed and the spreader inclination varied. Thus, in addition to proving the reliability of the model, the measurements also helped determining the limits of validity of the assumptions within which on-the-field simulations can be carried out.

1. Introduction

Nowadays, precision agriculture technologies are undeniably effective in optimizing profitability whilst being environmentally friendly and suitable for sustainable development. The development of such technologies shows overall steady growth to meet the challenges of the 21st Century such as food security for a world population expected to reach 10 billion by 2050 (Smith, 2013; Connor and Minguez, 2012) whereas decreased soil fertility (Maqsood et al., 2013) and changes in soil structure due to intensive fertilization (Hurni et al., 2008) have become alarming. Modern centrifugal spreaders contribute to resolving these issues as they rely heavily on information and technology, and may combine GPS and GIS (Geographic Information Systems) with VRT (Variable Rate Technology) to achieve site-specific fertilizer application by real-time adaptation of the spreader parameters to its surrounding environment and disruptive factors. These breakthroughs are based on several works of research which developed measurement techniques as well as simulation models. Both contributed in gaining insight into the influence of disruptive factors (Hofstee and Huisman, 1990; Grift et al., 2006), the spreader parameters and the fertilizer characteristics on the spread pattern (Olieslagers et al., 1996; Reumers et al., 2003b).

However, there have been few studies conducted dealing with the effects of non-flat fields on the spread pattern. A skewing of the spread pattern characterized by an increase in the value of the coefficient of variation (CV) was shown to always occur in the case of slope and side-slope (Grafton et al., 2015). The same disturbance was highlighted by Parish (2003) and Yildrim (2008) when the spreader was put in out of level configurations, which is likely to happen on a real-world field. Although these studies dealt with static spread patterns only, they imply that the overlapping of the spread patterns along the tractor path cannot produce a uniform overall spread pattern. No other results in literature investigated the uniformity of the overall spread pattern on non-flat fields, unlike in the case of flat fields (Lawrence and Yule, 2007; Grift and Hofstee, 2000). This knowledge gap stems from the use of collecting-tray-based measurement techniques (Reumers et al., 2003a) which are not suited to wide non-flat fields, especially non-regular ones. Consequently, the aim of our research is, on

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Notation

Notation	
$R_f = (O_f\boldsymbol{X_f Y_f Z_f})$	stationary field coordinate system [–]
$R_{f'} = (O_{f'}\boldsymbol{X_{f'} Y_{f'} Z_{f'}})$	moving field coordinate system [–]
$R_t = (O_t\boldsymbol{X_t Y_t Z_t})$	tractor coordinate system [–]
$R_{d_0} = (O_{d_0}\boldsymbol{X_{d_0} Y_{d_0} Z_{d_0}})$	stationary disc coordinate system [–]
$R_{d_i} = (O_{d_i}\boldsymbol{X_{d_i} Y_{d_i} Z_{d_i}}),\ i \in \{1,2,3\}$	intermediate disc rotating coordinate systems [–]
$R_v = (O_v\boldsymbol{X_v Y_v Z_v})$	vane coordinate system [–]
d_x, d_y, d_z	Cartesian parameters of the tractor position [m]
θ_p	tractor pitch angle [rad]
θ_r	tractor roll angle [rad]
θ_y	tractor yaw angle [rad]
α	horizontal outlet angle [rad]
α_p	pitch angle of the vane [rad]
Ω	vertical outlet angle [rad]
δ_{dist}	vertical distribution angle added to vertical outlet angle Ω [rad]
ϕ_{dist}	size distribution [m]
θ_{dist}	horizontal distribution angle [rad]
θ	angular position of a particle relative to the disc coordinate system [rad]
e	disc eccentricity [m]
β	disc cone angle [rad]
ω	disc rotation speed [rad.s^{-1}]
h	disc height [m]
R	disc radius [m]
r_0	radial position of a particle on the vane [m]
z_0	vertical position of a particle on the vane [m]
T	tilt angle [rad]
V_r	radial component of the velocity vector of a particle [m.s^{-1}]
V_t	tangential component of the velocity vector of a particle [m.s^{-1}]
V_v	vertical component of the velocity vector of a particle [m.s^{-1}]
C_x	drag coefficient [–]
ρ_a	density of air [kg.m^{-3}]
ρ_f	density of fertilizer [kg.m^{-3}]
S_p	projected surface area of a particle [m^2]
Q	application rate [kg.m^{-2}]
D	flow rate [kg.s^{-1}]
V_{tr}	tractor speed [m.s^{-1}]
LW	working width [m]
m	mass of a particle [kg]
n_d	number of discs [–]
N	number of particles at each revolution of each disc [–]
L	step width of tractor forward motion at each revolution of the discs [m]
$\rho_{M,S}$	Pearson correlation coefficient [–]

the one hand, to use simulation in the future to bridge the knowledge gap regarding application errors in the overall spread pattern due to non-flat fields. On the other hand, the aim is to design new active control devices like those proposed by Kweon and Grift (2006) and Koko and Virin (2009), and assess their effectiveness in terms of achieving an even distribution of the fertilizer on the field regardless of its elevation and regularity. No model previously developed handles, in simulation, both the motion of the tractor and the field elevation including its variation. The existing models like those of Patterson and Reece (1962) and Villette et al. (2005) considered a static spread pattern on a flat field, and each particle a time from its landing position on the disc until leaving it with final conditions of velocity and position. The ballistic flight phase was then simulated using Mennel and Reece (1963) model. Dintwa et al. (2004) considered in addition a collective flow of distinct particles, while Van Liedekerke et al. (2009) used a discrete element method in order to take account of interactions between granules. Other so-called hybrid approaches were studied by Reumers et al. (2003a) and Villette et al. (2008). They considered only the ballistic flight phase, and used measurement to provide some input data, such as the initial velocity of the particles and their angular distributions at the disc output. Recently, stereovision-based techniques were developed to determine in real-time the ejection parameters of particles (Hijazi et al., 2014; Cool et al., 2017).

In this study, a new model was developed that handles within some conditions, fertilizer spreading during the motion of the tractor on DEMs including non-flat ones, no other disturbances were considered. The first step focused on demonstrating the calculations needed at each point of the trajectory in order to obtain spread patterns whose overlapping gives the overall spread pattern on the field. These calculations consisted of expressing, in the field coordinate system, any vector of position and velocity related to a disc coordinate system. A geometrical parametrization of the spreader and the tractor degrees of freedom led to the calculation of the necessary transformation matrices. A link was then established with a ballistic flight model, whose initial conditions of velocity and position in the field coordinate system were derived using the calculated matrices. The second step focused on carrying out measurements in order to validate the reliability of the model in simulating spread patterns in different spreader configurations, and also to assess the relevance of using fixed parameter values for the drag coefficient and the horizontal angular distribution during on-the-field simulations. Only static measurements were carried out. The correlations between measurement and simulation in different spreader configurations were then analyzed. This enabled to deduce the limits of use of the developed model on the field, which are related to the shape of particles, the discs rotation speed and the steepness of the field inclinations.

2. Theoretical considerations

Considering a tractor moving on a given field with a rear-coupled fertilizer spreader, the following right-handed Cartesian coordinate systems were adopted:

- $R_f = (O_f\boldsymbol{X_f Y_f Z_f})$ is a stationary coordinate system associated with the field. The origin O_f and the vectors $\boldsymbol{X_f}$ and $\boldsymbol{Y_f}$, can be arbitrarily chosen on a given DEM but they must define a horizontal plane. The trajectory points of the tractor are given as input to the model in the coordinate system R_f, and the landing positions of the fertilizer particles are obtained as an output of the model in the same coordinate system.
- $R_{f'} = (O_{f'}\boldsymbol{X_{f'} Y_{f'} Z_{f'}})$ is a moving coordinate system always aligned with the field coordinate system R_f. The origin $O_{f'}$ is defined by the orthogonal projection onto the field of the mid-point between the right and left discs of the spreader.
- $R_t = (O_t\boldsymbol{X_t Y_t Z_t})$ is a coordinate system associated with the tractor. The origin O_t coincides with $O_{f'}$.