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Discrete element modelling (DEM) of fertilizer dual-banding with adjustable rates

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ABSTRACT

Multiple band fertilizer application has gained its popularity due to its advantages over other application methods. However, detailed information in this research area is currently scarce. In this study, a dual-band fertilizer applicator was developed to simultaneously deliver starter and base fertilizer as separate bands into the soil. The working process of the applicator was modeled using the discrete element method (DEM) to examine the effects of machine parameters on the ratio (ρ_s) of discharged starter and base fertilizer, as well as the separation distance (H) of the fertilizer bands. The DEM model results were validated using both laboratory and field measurements. Model results showed that ρ_s increased linearly as the working length of the meter roller increased; ρ_s remained nearly constant when the rotational speed of the roller changed. An increased H was observed at faster machine speeds and smaller spacings of the vertical and longitudinal fertilizer delivery tubes. The DEM model could generate the optimal machine parameters for fertilizer application in the given condition. For wheat, the optimum machine speed was 3.9 km h^{-1} and the optimum spacings of vertical and longitudinal fertilizer delivery tubes were 66 and 194 mm, respectively. Simulated values of H obtained from the DEM model had low relative errors (11.86% on average) with respect to the field measurements. This showed that the DEM model was able to simulate the dual banding fertilizer application with a reasonably good accuracy.

1. Introduction

There are several methods for applying granular fertilizer for crop production. Broadcasting is a common method. It spreads fertilizer on soil surface, which may result in some volatilization losses of nutrients. Due to this reason, tillage is sometimes used to incorporate the fertilizer into the soil, which however requires additional field operations. Pop-up method applies a small amount of fertilizer with seeds. It is commonly practiced in North America as it is a convenient way to apply fertilizer. Starter banding is a method of placing a band of fertilizer near the seeds in soil. The purpose of putting starter fertilizer is to give seedlings a boost at the early growth stage and to suppress weeds as well. Banding fertilizer minimizes the contact between soil and fertilizer, reducing fixation of phosphorus and potassium in soil, therefore increasing the efficiency of nutrient use. Besides starter fertilizer, crops need additional fertilizer for their growth during the growing season. Thus, post-emergence or in-crop fertilizer, also referred to as base fertilizer, is typically applied through surface broadcasting, also known as top-dressing, or side dressing.

Based on the above discussion, crops require both starter fertilizer and base fertilizer. The dual banding technique can apply these fertilizers in one operation, placing a band of starter fertilizer close to the seeds and a band of base fertilizer further down in the soil, so that the nutrients in the two bands are available to the crop at different times. Dual banding was a seldom-used method in the past, as it requires two lines of fertilizer delivery in one opener shank. However, it caught more attention in recent years as it is a one-time fertilizer application technique, which reduces the operation cost. Furthermore, it improves the fertilizer utilization rate and increases he crop yield (Wang et al., 2016; Dun et al., 2016). It is also suitable for conservation tillage systems. However, there were several challenging issues, such as fertilizer rate varying with crops and difficulties in separating the two bands in the soil. This study focused on developing a dual-band fertilizer applicator to apply starter fertilizer band and base fertilizer simultaneously.

Existing studies in fertilizer applications mainly focused on precisions of variable fertilization technology (Kim et al., 2008; Abbas et al., 2014; Chattha et al., 2014; Reyes et al., 2015). Applying fertilizer with multiple bands has not been well documented. There have been few studies that dealt with the design of multiple-band fertilization machines. One of the existing machines had sliding knife-type openers that placed fertilizer into different layers in the soil using a mechanical

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separator (Zhang et al., 2005). Openers with combined functions have also been designed, which could place seeds, starter fertilizer, and the base fertilizer all at the same time, and the base fertilizer was applied in a deeper layer (Yao et al., 2008). Attempts have been made to alter the ratio of the amounts of starter fertilizer and base fertilizer (Zhao and Zhang, 2012; Wang et al., 2016) and to optimize machine parameters for a better control of fertilizer mass ratios (Dun et al., 2016).

In these existing studies, there was lacking of relationships between machine parameters and the machine performance. Finding the relationships using experiments is difficult, as fertilizer metering and banding are complex processes dealing with moving fertilizer particles, non-homogeneous soil, and interactions of soil, fertilizer, and machine. Measurements of dynamics of such a complex system are also very difficult, if possible. Computer simulation would be a better approach for this, as computer simulation is capable of handling different types of particles in a system, and it is also able to capture the motion of these particles at any given time. The discrete element method (DEM) was considered to be an effective simulation tool for dealing with discrete particles in agriculture (Van Liedekerke et al., 2009; Pasha et al., 2016). For example, using the DEM, Landry et al. (2006) simulated the kinetic process of the organic fertilizer particles (manure compost) being discharged from a screw-type solid fertilizer applicator; Joseph et al. (2000) and Ketterhagen et al. (2008, 2009) simulated flows of seeds for various hopper geometries; Horabik et al. (2016) and Parafiniuk et al. (2013) modeled grain silos to investigate the load distributions in the silo and grain discharge rates from the silo. In recent years, the DEM has been used to simulate granular fertilizers (Lv et al., 2013), soil (Gursoy et al., 2017; Zeng et al., 2017), and their interactions with machines. Coetzee and Lombard (2011) used the DEM to model a centrifugal fertilizer spreader, focusing on the effects the model parameters have on fertilizer spreading patterns. Van Liedekerke et al. (2009) conducted a similar study on the effects of fertilizer properties on spreading patterns using a DEM model. Results from these studies demonstrated that the DEM was an effective tool to simulate granular fertilizer flows. However, existing simulations focused on fertilizer broadcasting. None of them dealt with fertilizer banding in soil involving soil-fertilizer-machine interactions. Furthermore, little research has been done on se lections of optimal machine parameters for a given crop.

The objectives of this study were to (1) design a dual-band fertilizer applicator capable of controlling the fertilizer ratio and band separation distance, (2) develop an integrated model to simulate the metering and banding processes of the dual-band applicator using the DEM, (3) validate the model using laboratory and field measurements, and (4) to use the model results to examine the relationships between machine parameters and machine performance.

2. Methodology

2.1. Design of a dual-band fertilizer applicator

2.1.1. Design requirements

The dual-band fertilizer applicator should be designed to have the function of banding starter and base fertilizers simultaneously as two separate bands in soil. The applicator should allow for adjusting the fertilizer mass ratios of two bands and the band separation distance, based on the agronomic requirements of the crop.

2.1.2. Mechanical components of the applicator

The dual-band applicator mainly consisted of a hopper, a metering assembly, and an opener assembly (Fig. 1). For metering fertilizer, a fluted roller was used, as this type of meter was able to handle various shapes and sizes of granules (Bansal et al., 1989). The hopper had two compartments, one for starter fertilizer and the other for base fertilizer. Accordingly, the meter was designed to have two sections as well. The total length of the roller was 570 mm, across the two hopper compartments. Each section of the roller had a sliding sleeve, a roller blocker, a housing, a flap under the roller, and a discharge box. As the sliding sleeve moved along the roller, the ratio of the relative working length of the two roller sections was altered, and in turn the ratio of the amounts of starter and base fertilizer (fertilizer mass ratio) was changed.

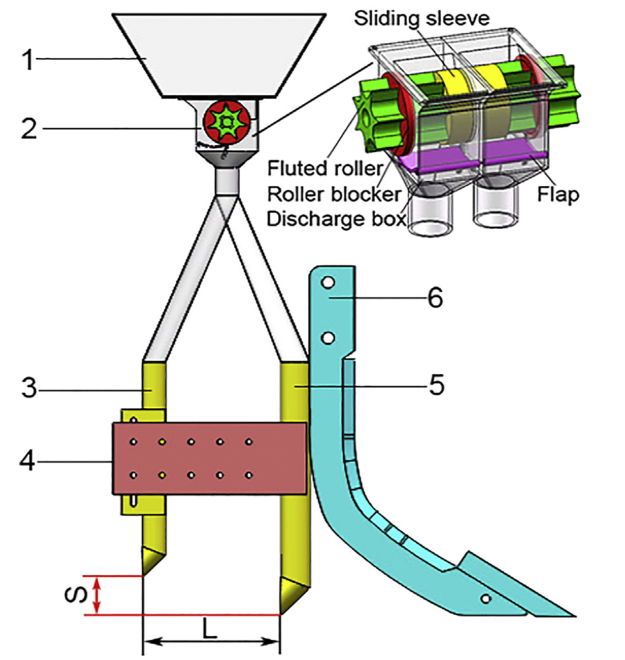

Fig. 1. The structural diagram of the dual-band fertilizer applicator; 1: hopper, 2: metering assembly, 3: starter fertilizer delivery tube, 4: connection plate, 5: base fertilizer delivery tube, 6: opener and shank, S stands for vertical tube spacing, L stands for longitudinal tube spacing.

The opener assembly consisted of a hoe opener and two tubes, one for delivering starter fertilizer in soil and the other for delivering base fertilizer in soil (Fig. 1). The base fertilizer tube was welded onto the shank of the opener. The two tubes were connected with a bolted plate. The longitudinal tube spacing (L) between the discharge points of the two tubes could be adjusted through the bolt holes of the plate, and the vertical tube spacing (S) could be adjusted using the slotted plate on the starter fertilizer tube.

In a field operation, the hopper was filled with starter fertilizer in one compartment and with base fertilizer in the other compartment. Before the operation, the position of the sliding sleeve on the roller was adjusted to obtain a desired length ratio of the roller sections corresponding to the pre-set fertilizer mass ratio. The longitudinal (L) and vertical (S) fertilizer tube spacings also needed to be set before operation to meet agronomic requirements of the crop. As the machine travelled at a given speed, the opener created a soil furrow; while the fluted roller rotated at a given speed, the starter and base fertilizers were delivered into soil through the perspective delivery tubes, forming two bands in soil. The separation distance between the bands is not necessarily equal to the S due to the dynamics of flowing soil particles around the opener and the tubes.

2.1.3. Performance indicators

One of the indicators used to evaluate the performance of the dual-band applicator was the fertilizer mass ratio that was defined as the amount of starter fertilizer over the total fertilizer discharged. It was calculated by the following equation:

$$\rho_s = \frac{m_s}{m_s + m_b} \tag{1}$$

where ρ_s is fertilizer mass ratio (%); m_s is the mass of starter fertilizer discharged from the metering assembly (g), m_b is the mass of base