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Research Paper

A liquid injection dosing system for site-specific fertiliser management

Marcelo J. da Silva, Paulo S.G. Magalhães*

School of Agriculture Engineering, University of Campinas — UNICAMP, Campinas, SP, Brazil

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Based on the Best Management Practices (BMPs) for nitrogen fertilisation, site-specific management must consider the most appropriate placement as well as the appropriate application rate according to local agronomic recommendations. Nitrogen fertilization on the soil surface (e.g., broadcasting, side dressing) is a common practice associated with high N loss to the environment and a low fertiliser recovery efficiency compared to the deep placement of fertiliser. We have worked to implement site-specific fertiliser management that encompasses a mechanised soil punching process combined with liquid fertiliser injection, which causes minimal disturbance of the soil subsurface (i.e., roots, soil or straw) and harmonises with conservative tillage practice. The objective was to design a hydraulic injection system to enable site-specific management according to the BMPs, as applied to mechanised soil punching to implement soil injection fertiliser placement. In this context, an injection dosing system (conceptual design, laboratory evaluations and analyses) has been developed to perform liquid injection synchronised with soil punching and variable rate application. In general, the applications were satisfactory because (i) the liquid injection was synchronised with soil punching and the fluid was incorporated into the soil at a depth greater than 50 mm, which was an appropriate deep placement with the potential to reduce nutrient losses combined by increasing nutrient uptake. In addition, (ii) the application rate was varied in a representative range (5.0 up to 18 ml cycle^{-1}), which demonstrated a good potential for soil injection of fertiliser as a function of the local agronomic recommendations. Both conditions were aligned with the BMPs.

1. Introduction

Rational fertiliser management is essential in agriculture for environmental conservation coupled with a better fertiliser recovery efficiency by plants, especially for mineral nitrogen fertilization. In general, appropriate practices may help to: (i) increase biomass production, (ii) contribute to the restoration or maintenance of soil organic carbon (SOC), (iii) decrease ammonia volatilization (NH_3) and nitrous oxide emissions (N_2O, a greenhouse gas), and (iv) reduce the impact of soil disturbance via conservative tillage practices (Snyder, Bruulsema, Jensen, & Fixen, 2009). Nitrogen fertilization plays a key role in this context because the application of N fertiliser to the surface results in NH_3 volatilization losses of up to 50% depending on the N

* Corresponding author.
E-mail addresses: marcelojs@ica.ufmg.br (M.J. da Silva), graziano@g.unicamp.br (P.S.G. Magalhães).
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source. Especially Urea, the most commonly applied fertiliser, results in very high N losses. However, N losses can be significantly reduced using proper management strategies that include incorporation of the fertiliser into soil (Sommer, Schjoerring, & Denmead, 2004). Even though, the most common top dressing fertilization methods are broadcasting or side dressing, both of which are associated with less labour and cost compared to the soil injection of fertiliser (Bautista, Suministrado, & Koike, 2000).

Recent studies have used optical sensors (e.g., the vegetation index, such as NDVI) to correlate and map nitrogen requirements, to determine the local N-fertiliser rates on corn, sugarcane, rice, wheat crops (Amaral, Molin, Portz, Finazzi, & Cortinove, 2015; Cilia et al., 2014; Portz, Molin, & Jasper, 2012; Quebrajo, Pérez-Ruiz, Rodriguez-Lizana, & Agüera, 2015). Nitrogen fertiliser applied to the soil surface without considering appropriate fertiliser placement, may result in losses to the environment and low nitrogen recovery efficiency, so such practices may be responsible for the over-application of fertiliser. According to recommendations by the International Plant Nutrition Institute, the Best Management Practices (BMPs) for nutrient stewardship encourage the application of the right product (source), at the right rate, at the right time, and using the most appropriate placement (www.ipni.net). Thus, an appropriate process for site-specific fertiliser management must be aligned with BMPs principles.

Nitrogen fertiliser is currently commonly applied to ratoon cane during the initial sprouting stage after the mechanical green harvest. After surface application, in addition to N-fertiliser losses to the environment, a significant amount of crop residue remains after the harvest (up to 20 Mg ha^{-1}, according to Fortes, Trivelin, & Vitti, 2012) and it may produce a mulching layer that impedes fertiliser contact with the soil surface. On the other hand, incorporation of N fertiliser applied to ratoon cane can significantly reduce NH_3 losses and promote better nitrogen recovery efficiency (Prasertsak et al., 2002). However, soil injection of fertiliser with a continuous drilling process (i.e., opening and closing furrows) is also hampered by the presence of the mulching layer. Furthermore, continuous drilling adjacent to the rows may partially damage the root system that could be used for nutrient uptake. Because of the perception of a technology gap, a strategy for site-specific management is proposed, that uses a mechanised soil punching to provide nutrients near to the plant roots using liquid fertiliser injection, with minimal disturbance of the roots, soil or straw, that harmonises with conservative tillage practices. To accomplish this, a soil punching mechanism has been designed to enable liquid fertiliser injection (Silva, Franco, & Magalhães, 2017).

Although this strategy was based on a technology gap perceived in sugarcane cropping, it may augment other conservative practices (e.g., no-tillage) as an alternative for the common top dressing of nitrogen fertiliser on corn, sorghum, rice, and wheat crops. Analogous to nitrogen fertiliser management in sugarcane, a nitrogen fertiliser top dressing in wetland rice is commonly applied by broadcasting or side dressing. Such fertiliser management practices have been associated with N-fertiliser loss via NH_3 volatilization, ammonium nitrogen concentration in floodwater ($NH_4^+{-}N$) and water pH alteration (Liu et al., 2015). However, floodwater does not favour continuous drilling for the soil injection of fertiliser due to problems with clogging, difficulty of incorporation and partial damage to the roots. In this context, by using a semi-automatic process for soil injection of N fertiliser in wetland rice, the authors demonstrated a significant improvement of the environmental conditions, as well as a better nitrogen recovery efficiency.

Using a similar approach, other recent studies have highlighted technologies or devices for the soil injection of fertiliser by liquid injection (Chunfeng & Xiu, 2015; Liu, Wang, Wang, & Ge, 2011; Niemoeller, Harms, & Lang, 2011; Nyord, Søgaard, Hansen, & Jensen, 2008; Wang, Ju, & Wang, 2011; Xi, Wang, & Lang, 2011). However, the perception is that the available variable rate technologies are commonly focused on broadcasting or side dressing, or technologies for site-specific management that use continuous drilling for the soil injection of fertiliser are generally applied at sowing stage. However, based on the BMPs recommended by IPNI, we believe that site-specific management of nitrogen fertilisation must take into account the most appropriate placement of fertiliser as well as variable rate application according to local agronomic recommendations that conform to plant requirements. In this context, the objective of this study was to design a hydraulic injection system to enable site-specific management according to the BMPs, as implemented by mechanised soil punching for soil injection. This study encompassed the conceptual design, laboratory evaluation and analyses of the injection system.

2. Material and methods

2.1. *Hydraulic injection system descriptions*

For the point placement of liquid fertiliser, the hydraulic system must synchronise the liquid injection with the displacement of the probe injector into soil (Fig. 1a). Additionally, liquid injection must be performed according to required fertiliser rate (i.e., the application rate must be variable). To meet these specifications, an injection dosing system based on a reciprocating piston pump has been designed. The proposed hydraulic system was composed of a reservoir, an injection dosing pump and an injector (Fig. 1b). Briefly, the injection dosing pump comprised a piston, a chamber, a spring, three directional check valves installed in hydraulic lines (suction, injection and return) and an eccentric cam transmission that allowed the liquid injection phase to be synchronised with the displacement of the probe injector into the soil.

The soil punching process was established with an application distance of 300 mm (an average distance between ratoon canes) and liquid injection up to a depth of 100 mm (Fig. 1a). These operating characteristics were used to assist the design of the piston pump axial displacement according to the eccentric cam cycle. In the soil punching cycle ($0{-}2\pi$rad), probe injector displacement above the ground mainly occurs between $0{-}3\pi/2$rad. This interval was used for liquid suction in the piston pump via the upward movement of the piston implemented by the spring and controlled by the eccentric cam. In the subsequent phase ($3\pi/2 - 2\pi$rad), when the soil is