UNIVERSIDADE ESTADUAL DE CAMPINAS
FACULDADE DE ENGENHARIA AGRÍCOLA

MARCELO JOSÉ DA SILVA

PROCESSO PARA APLICAÇÃO LOCALIZADA DE FERTILIZANTE LÍQUIDO NITROGENADO EM CANA-SOCA

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Tese apresentada à Faculdade de Engenharia Agrícola da Universidade Estadual de Campinas como parte dos requisitos exigidos para a obtenção do título de Doutor em Engenharia Agrícola, na área de concentração em Máquinas Agrícolas.

Orientador: Prof. Dr. Paulo Sérgio Graziano Magalhães
Coorientador: Dr. Henrique Coutinho Junqueira Franco

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A Ata da defesa com as respectivas assinaturas dos membros encontra-se no processo de vida acadêmica do discente.

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em especial aos meus pais,
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SONHAR

“Sonhar é transportar-se em asas de ouro e aço
Aos páramos azuis da luz e da harmonia;
É ambicionar o céu; é dominar o espaço
Num vôo poderoso e audaz da fantasia.
Fugir ao mundo vil, tão vil que, sem cansaço,
Engana, e menospreza, e zomba, e calunia;
Encastelar-se, enfim, no deslumbrante Paço
De um sonho puro e bom, de paz e de alegria.
É ver no lago um mar, nas nuvens um castelo,
Na luz de um pirilampo um sol pequeno e belo;
É alçar constantemente o olhar ao céu profundo.
Sonhar é ter um grande ideal na inglória lida:
Tão grande que não cabe inteiro nesta vida,
Tão puro que não vive em plagas deste mundo”.

Helena Kolody
Poeta Paranaense, natural de Cruz Machado
۞ *12-10-1912*
┼ *15-02-2004*

RESUMO

Nas áreas de cana-soca, a adubação nitrogenada geralmente é realizada junto às linhas de cultivo, utilizando aplicação na superfície ou incorporada em sulcos. Na superfície, o fertilizante é exposto a condições que podem favorecer perdas do nutriente. A melhoria na adubação nitrogenada pode ser alcançada com a incorporação do fertilizante no solo. Entretanto, a camada de resíduos vegetais deixada após a colheita mecanizada pode prejudicar a eficiência da operação. Ademais, a abertura de sulcos pode danificar parcialmente as raízes das plantas. Neste contexto, considerando a hipótese que o processo mecanizado de puncionamento no solo combinado a injeção de fertilizante líquido é uma alternativa tecnológica para a aplicação localizada de nutrientes em cana-soca, (i) desenvolvemos um protótipo mecânico para viabilizar o acesso à subsuperfície do solo com mínima mobilização do sistema (solo, raízes e resíduos vegetais), (ii) um sistema hidráulico dosador injetor e (iii) realizamos análise comparativa da estratégia proposta em relação aos métodos convencionais de adubação em área comercial de cana-soca. A operação mecanizada foi fundamentada no puncionamento a cada 300 mm (uma distância média entre as soqueiras) com injeção do fluido na profundidade de 50 a 100 mm. Tais especificações foram consideradas suficientes para reduzir perdas do fertilizante e disponibilizar os nutrientes próximos às raízes das plantas, com mínima mobilização. O sistema hidráulico dosador injetor foi centrado em uma bomba de pistão, projetada para aplicar o fluido sincronizado ao puncionamento no solo e controlar a dosagem através do retorno hidráulico. Os resultados (avaliações em bancada e caixa de solo) revelaram que o sistema tem potencial para melhorar a qualidade da operação de adubação em cana-soca (profundidade de injeção maior que 50 mm, coeficiente de variação da dosagem em torno de 11%). Em geral, a aplicação na camada subsuperficial resultou em maiores níveis de N-foliar, produtividade de colmos e potencial de produção de açúcar; os quais, associados à disponibilidade do N mineral no solo através dos métodos de adubação nitrogenada. O método de puncionamento alcançou resultados equivalentes à incorporação convencional, sob a condição de aplicação em um lado das linhas de cana-de-açúcar. Sendo assim, a estratégia representa uma alternativa tecnológica para superar dificuldades ao acesso à subsuperfície do solo em áreas com cobertura de resíduos vegetais na superfície, além disso, a operação é fundamentada no cultivo conservacionista e boas práticas de manejo dos nutrientes.

Palavras-chave: cana-de-açúcar, agricultura de precisão, máquinas agrícolas, método de aplicação.

ABSTRACT

Nitrogen fertilization of sugarcane ratoon is generally performed at the side band of the rows by means of placement on the surface or continuous incorporated inside the furrows. At the surface, the fertilizer is exposed to conditions that may favor N losses to the environment. N fertilization improvement can be achieved with incorporation of the fertilizer into the soil. However, crop residues left on the soil surface after the mechanical green harvest may decrease the nitrogen use efficiency (NUE). Furthermore, the common opening furrows may cause damage to the root system of the sugarcane plants. Considering the hypothesis that mechanized soil punching combined with liquid fertilizer injection is a technological alternative for deep placement of fertilizer in sugarcane ratoon fields, (i) we developed a mechanical prototype to enable access in the soil subsurface with minimal disturbance of the soil, roots and crop residues, (ii) a hydraulic injection dosing system for N fertilization according to the plant needs and (iii) performed a comparative analysis in a commercial sugarcane field of the proposed strategy with respect to the conventional placement methods (at the surface and incorporated into the furrows). Primarily, the mechanized soil punching distance was based an average between the ratoons of 300 mm, with liquid injection at 50 to 100 mm deep (soil subsurface), considered sufficient to provide the N fertilizer near the cane roots and reduce N losses to the environment (especially ammonia volatilization). The hydraulic injection dosing system was centered in the piston pump design, which was developed to synchronize the liquid injection as a function of the punching cycle, with dosing being controlled by the hydraulic return through a groove area designed in the plunger. The results (at the laboratory bench and the soil bin) revealed that the proposed system has potential to improve quality of the N fertilization in sugarcane ratoon fields (injection depth greater than 50 mm and coefficient of variation approximately 11%). In general, fertilizer deep placement resulted in a higher leaf N content, cane stalk yield and potential for sugar yield (tons of pol per hectare); these were associated with the soil mineral N availability. The soil punching method had results equivalent to the continuous incorporation when the N fertilizer was applied parallel to the cane rows on a single side. Thus, the proposed strategy represents an alternative technology to overcome difficulties for accessing the soil subsurface under crop residues on the surface. Moreover, soil punching for liquid fertilizer injection is fundamentally based on conservation tillage and better management practices for nutrient stewardship.

Keywords: sugarcane, precision agriculture, agricultural machinery, placement method.

APRESENTAÇÃO

A Tese descreve o desenvolvimento de “Processo para aplicação localizada de fertilizante nitrogenado em cana-soca”. O trabalho representa uma continuação da minha Dissertação, focada na viabilização da “Aplicação de fluidos em profundidade com mínima mobilização do solo”. O conteúdo dividido em capítulos está apresentado essencialmente como:

Capítulo I – Introdução sobre as práticas atuais de adubação nitrogenada em cana-soca, incluindo relatos de problemas que reduzem a eficácia da operação. No capítulo é descrita uma hipótese para a melhoria no processo de adubação nitrogenada em áreas de cana-soca.

Capítulo II – Revisão bibliográfica centrada no processo de aplicação nitrogenada em cana-de-açúcar. No texto são descritos tecnologias envolvendo a agricultura de precisão, o emprego de fertilizantes líquidos e mecanismos utilizados na operação.

Capítulo III (em inglês) – Artigo publicado na revista *Soil & Tillage Research* (*Vol. 165, Jan. 2017, Pages 279–285*). O trabalho descreve os resultados alcançados através de operação mecanizada de puncionamento no solo[1]. A estratégia de aplicação é fundamentada no acesso a subsuperfície para a injeção do fertilizante líquido, utilizando mínima mobilização do solo, raízes e resíduos vegetais.

Capítulo IV (em inglês) – O artigo apresenta um sistema hidromecânico dosador-injetor de fertilizante líquido, desenvolvido para aplicação do fluido sincronizada à operação mecanizada de puncionamento no solo. No sistema, a dosagem é realizada em função da recomendação agronômica, possibilitando a aplicação com taxa variável. O artigo foi submetido na revista *Biosystems Engineering*.

Capítulo V (em inglês) – O artigo apresenta essencialmente a análise comparativa entre os métodos de adubação nitrogenada em cana-soca; entre os quais, o puncionamento no solo. O trabalho contribui no desenvolvimento de processo para a aplicação localizada de fertilizante.

Capítulo VI – O texto é uma compilação das principais discussões relatadas nos artigos.

Capítulo VII – Contém a conclusão geral alinhada à hipótese central, a lista de bibliografia completa, além de apêndices com informações sobre o processo desenvolvido para a aplicação localizada de fertilizante.

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[1] Informações detalhadas sobre o sistema mecânico puncionador podem ser alcançadas através de busca pelas referências:

SILVA, M. J. **Processo de aplicação de fluidos em profundidade com mínima mobilização do solo**. 82 p. Dissertação (Mestrado em Engenharia Agrícola) – Universidade Estadual de Campinas “UNICAMP”, Campinas. 2013.

SILVA, M. J.; MAGALHÃES, P. S. G. Design of a mechanical system for liquid fertilizers injection in ratoon cane. ASABE and CSBE/SCGAB Annual International Meeting.10p, 2014. Montreal-CAN.

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1 INTRODUÇÃO GERAL

Desde o século XVI, a cana-de-açúcar cultivada no Brasil é utilizada na produção do açúcar, uma das principais atividades da economia nacional (mercado interno e exportações). Nos últimos anos, a partir de incentivos do programa Proálcool (instituído na década de 1970), a cana-de-açúcar tem sido empregada na produção do etanol, um combustível com origem em matéria prima renovável, alternativa ao aumento dos preços dos combustíveis derivados do petróleo. Atualmente, subprodutos da produção agrícola e industrial também têm sido utilizados na geração de energia através do processo de cogeração, no qual, o vapor excedente produzido nas caldeiras pode ser transformado em eletricidade, exportada à rede de transmissão integrada ao sistema elétrico nacional.

Nos últimos anos, entre as mudanças significativas na produção de cana-de-açúcar, tivemos a introdução da mecanização agrícola, praticada sob o modelo da agricultura intensiva (subsolagem, aração, gradagem, plantio, colheita, pulverização, adubação, e.g.). Atualmente, a cana-de-açúcar é cultivada de modo semi-perene, com colheita anual, ao longo de quatro a seis ciclos, antes de reforma do canavial. Após a colheita mecanizada, sem despalha com fogo, durante a brotação e crescimento dos perfilhos das soqueiras, geralmente é realizada a adubação nitrogenada, para suplementar os nutrientes que são exportados pela colheita, perdidos no sistema solo-planta-atmosfera (volatilização, desnitrificação e lixiviação) e imobilizados por microrganismos.

Em geral, o processo de adubação nitrogenada sob o contexto da agricultura intensiva, pode produzir impactos no meio ambiente, como na emissão de gases do efeito estufa (N_2O), acidificação dos solos agrícolas, contaminação das águas superficiais e subterrâneas, além do esgotamento da fertilidade natural dos solos. Tais processos podem ser incrementados quando o fertilizante nitrogenado é aplicado sobre superfície, sobretudo, quando utilizado fontes amídicas, como a ureia, fertilizante nitrogenado com maior difusão entre a produção agrícola brasileira, atribuído a vantagens, como o custo unitário e concentração de N.

O emprego do fertilizante sobre a superfície pode favorecer a volatilização de amônia (NH_3), devido à intensidade da hidrólise da ureia causada pelo contato com a urease, uma enzima originada na decomposição de material orgânico pelos microrganismos, presente principalmente nos resíduos vegetais deixados após a colheita mecanizada da cana-de-açúcar.

Além disso, a aplicação sobre a superfície pode aumentar a ação microbiana na decomposição dos resíduos vegetais. O processo reduz a disponibilidade do N mineral no solo associado à imobilização do N fertilizante e perdas por desnitrificação (emissões do N_2 e N_2O).

Mesmo assim, a aplicação do fertilizante nitrogenado em superfície é comumente empregada nas áreas de cana-soca no Brasil. A prática tem sido intensificada nos últimos anos devido ao incremento na dificuldade ao acesso a subsuperfície do solo para a incorporação dos fertilizantes através da camada de resíduos vegetais deixada após a colheita mecanizada. Em geral, a adubação nitrogenada incorporada pode reduzir o impacto de fatores que favorecem as perdas ou diminuem a disponibilidade do N mineral no solo, tais como: a ação da urease originada pela decomposição dos resíduos vegetais, imobilização do N fertilizante pelos microrganismos e trocas gasosas facilitadas pela ventilação na superfície do solo.

Todavia, a eficiência da incorporação contínua de fertilizante no solo pode ser prejudicada, quando: os resíduos vegetais não são totalmente cortados para acessar a subsuperfície do solo; ou, se o fertilizante é incorporado junto aos resíduos vegetais no sulco, ou então, se o fertilizante é incorporado em torrões de solo seco que permitem emissão do NH_3 para a atmosfera; ou ainda, se as raízes da subsuperfície são danificadas na abertura dos sulcos.

Neste contexto, o emprego de boas práticas de manejo para a adubação nitrogenada pode contribuir para melhorar a eficácia da operação em áreas de cana-soca. Em instrução sobre o manejo dos fertilizantes, o Instituto Internacional para Nutrição de Plantas (*International Plant Nutrional Institute*) recomenda a deposição do fertilizante em local favorável à absorção pelas raízes das plantas, disponibilidade do nutriente no solo e menor exposição às perdas ao meio ambiente. As melhorias do processo de adubação também podem ser alcançadas por meio das práticas de cultivo conservacionista, que possui princípios fundamentados na mínima mobilização do solo e manutenção dos resíduos vegetais, as quais contribuem na reciclagem de nutrientes (mineralização do N, e.g.) e redução no impacto do processo de erosão do solo.

Na busca pela melhor eficácia da adubação nitrogenada em cana-soca, os princípios do cultivo conservacionista e boas práticas de manejo dos nutrientes podem auxiliar na concepção de processo para aplicação localizada de fertilizante, por conseguinte, fundamentar o desenvolvimento de adubadora. Para a operação em cana-soca, atualmente, não existe processo mecanizado para aplicação de adubo líquido incorporado no solo que contemple a mínima mobilização, mínimos danos ao sistema radicular das plantas e eficácia de absorção dos nutrientes.

Considerando a lacuna tecnológica, uma estratégia para a adubação é o processo mecanizado de puncionamento no solo combinado com a injeção de adubo líquido, para fornecimento dos nutrientes próximo às raízes da cana-de-açúcar utilizando mínima mobilização do sistema (raízes, solo ou resíduos vegetais). Nesse contexto, a presente pesquisa possui como hipótese que o processo mecanizado de puncionamento no solo combinado com a injeção do adubo líquido é uma alternativa tecnológica para aplicação localizada em áreas de cana-soca.

Para comprovar a hipótese, os objetivos do trabalho foram: (i) desenvolver um protótipo para o processo mecanizado de puncionamento no solo, para alcançar a aplicação com mínima mobilização da subsuperfície do solo; (ii) desenvolver um sistema mecânico-hidráulico para injeção de fluido sincronizada ao puncionamento no solo e dosagem de acordo com a recomendação de adubação; e (iii) realizar análise comparativa entre métodos para aplicação de adubo líquido nitrogenado em área de cana-soca, considerando a adubação em superfície, incorporação em sulco e injeção por meio de puncionamento no solo.

CAPÍTULO II

2 REVISÃO BIBLIOGRÁFICA

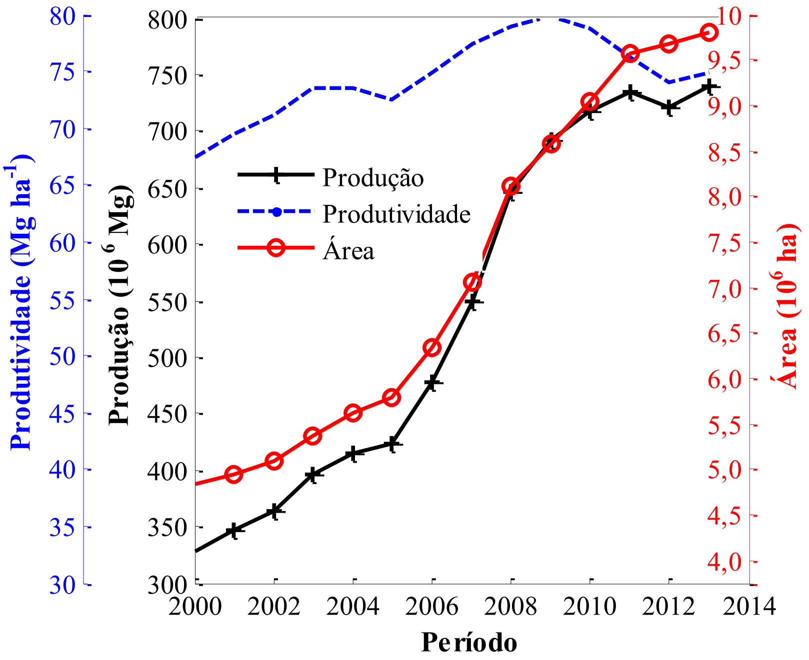
2.1 Adubação nitrogenada sob a perspectiva da produção da cana-de-açúcar

A adubação é uma prática realizada para suplementar a disponibilidade natural dos nutrientes nos solos, atender a demanda dos cultivos agrícolas com alto potencial de rendimento, compensar perdas dos nutrientes para o meio ambiente, ou melhorar as condições dos solos para a produção agrícola (IFA, 2000). Nitrogênio (N), potássio (K) e fósforo (P) são considerados macronutrientes devido a maior demanda pelas plantas. Apesar da alta disponibilidade do gás N_2 na atmosfera, a assimilação ocorre principalmente a partir do N mineral: o amônio (NH_4^+) e nitrato (NO_3^-). No meio ambiente, tais fontes são obtidas pela mineralização de compostos orgânicos, fixação biológica do nitrogênio por bactérias e fixação atmosférica através de descargas elétricas combinadas a precipitação de chuva. Mesmo assim, os fertilizantes químicos são importantes para a manutenção e aumento da produtividade nos cultivos agrícolas, sobretudo no modelo empregado da agricultura intensiva.

Contudo, o uso intensivo das áreas agrícolas, em especial, a aplicação dos fertilizantes químicos, pode produzir efeitos negativos nos solos, como o esgotamento dos nutrientes, acidificação, erosão, contaminação das fontes de água, e emissão de gases de efeito estufa. Essencialmente, as perdas dos fertilizantes nitrogenados ocorrem a partir das vias de lixiviação do nitrato, volatilização da amônia e perdas pela emissão de óxido nitroso (N_2O) a partir da desnitrificação. De acordo com os relatores do Painel Intergovernamental em Mudanças Climáticas (*Intergovernmental Panel on Climate Change*, *IPCC*), a emissão de N_2O possui contribuição significativa no processo de aumento médio da temperatura global (7,5% do efeito estufa). Neste contexto, aproximadamente 65% das emissões de N_2O são originadas nos solos, nos quais, a aplicação dos fertilizantes nitrogenados é uma das fontes do processo de desnitrificação. Além disso, a produção dos fertilizantes nitrogenados químicos é fundamentada no uso de fontes de energia não renováveis, como o gás natural (IFA, 2000).

No Brasil, atualmente as fontes nitrogenadas comercializadas em maior quantidade, são: a ureia ($CO\,(NH_2)_2$), o nitrato de amônio (NH_4NO_3) e o sulfato de amônio ($(NH_4)_2\,SO_4$). Nos últimos anos, a expansão da produção agrícola sobre áreas destinadas à pecuária extensiva na região Centro-Sul tem contribuído no aumento do consumo de fertilizantes nitrogenados. Entre os cultivos agrícolas, a cana-de-açúcar é incluída neste contexto. No intervalo de 2003 a 2013, e.g., a área de cana-de-açúcar foi expandida de 5,4 para 9,8 milhões de hectares, um acréscimo de aproximadamente 80% (Figura 1).

Figura 1 – Características da produtividade, produção e área cultivada com cana-de-açúcar no Brasil, ao longo dos últimos anos

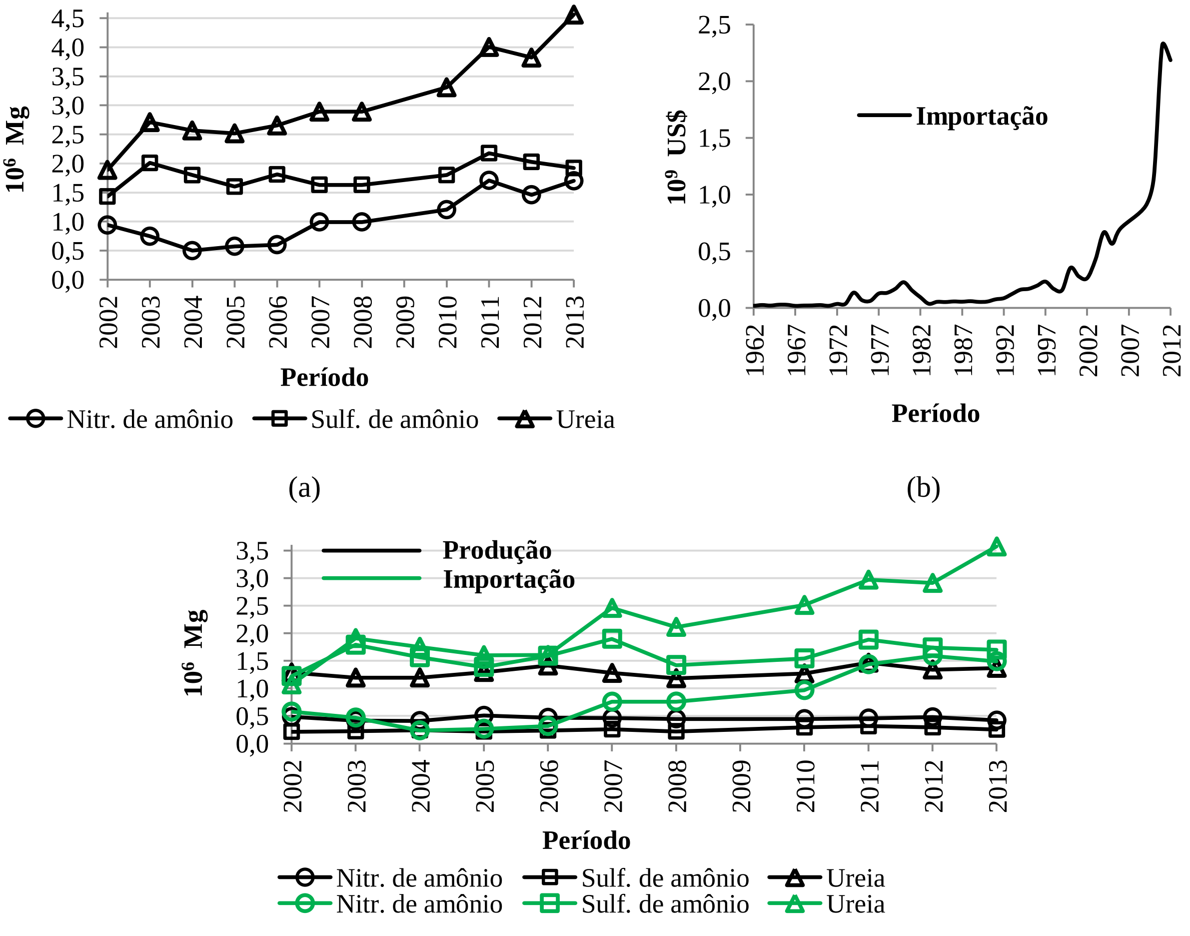


Fonte: FAO (2016).

Na produção agrícola brasileira ou mundial, a ureia é a principal fonte de fertilizante nitrogenado. A difusão do fertilizante está fundamentada no menor preço e maior concentração de nitrogênio (45% de N), quando comparada às outras fontes comuns, como o sulfato de amônio (21% de N) e nitrato de amônio (35% de N) (CHIEN et al., 2009). Contudo, quando a ureia fertilizante é aplicada sobre a superfície dos resíduos vegetais pode favorecer perdas significativas devido à emissão de amônia (NH_3). O processo de volatilização do NH_3 é originado a partir da hidrólise da fonte nitrogenada por meio da urease, uma enzima produzida por micro-organismos, associada à decomposição dos resíduos orgânicos (COSTA et al., 2003). Neste contexto, a aplicação do nitrato de amônio é uma alternativa para a redução de perdas. Tal condição tem fundamentado o aumento no emprego do nitrato de amônio nas áreas de produção agrícola (Figura 2a), em especial, na adubação de soqueiras de cana-de-açúcar.

Entretanto, apesar do aumento no consumo de fertilizantes nitrogenados pela agricultura, a capacidade brasileira de produção foi mantida inalterada, sendo necessário o emprego de importações para atendimento da demanda (Figura 2c). Em 2013, e.g., a importação de ureia representou um valor mássico 160% maior que a produção nacional. Nos últimos anos, houve também acréscimos nas importações do nitrato de amônio e sulfato de amônio em função da demanda nacional. No mesmo sentido, o mercado de importações de fertilizantes nitrogenados aumentou em uma proporção exponencial (Figura 2b), com taxa maior que a demanda crescente. Esses valores repassados para os agricultores, contribuem negativamente na rentabilidade e capacidade de investimento na produção agrícola.

Figura 2 – Contexto sobre o consumo, mercado e produção de fertilizantes nitrogenados no Brasil. a. Consumo total dos principais fertilizantes. b. Mercado de importações dos fertilizantes nitrogenados. c. Contribuições da produção e importação de fertilizantes



(a) (b)

(c)

Fonte: FAO (2016).

Atualmente, o Brasil é o maior produtor mundial de cana-de-açúcar, destinada principalmente para a produção de açúcar e bioenergia (etanol e eletricidade). Nos últimos anos, o aumento da produção brasileira de cana-de-açúcar foi principalmente influenciado pela expansão das áreas, contudo, a manutenção e acréscimo da produtividade é um desafio para o setor sucroenergético. Neste contexto, o uso racional dos fertilizantes nitrogenados pode contribuir para atender a necessidade das plantas, reduzir efeitos negativos na rentabilidade ou no meio ambiente. Para tanto, a racionalização pode ser alcançada pelo aumento na eficácia no uso do fertilizante pelas plantas de cana-de-açúcar. De acordo com Chien et al. (2009), o emprego da adubação nitrogenada (inorgânicas ou orgânicas) possui perspectivas de aumento nos próximos anos, principalmente para a manutenção da produção agrícola em função da demanda mundial por alimentos e bioenergia. Os autores adicionam que inovações tecnológicas com fundamentos na produção agrícola sustentável e redução dos impactos no meio ambiente podem contribuir com métodos e práticas para aplicação apropriada dos fertilizantes.

2.2 Adubação nitrogenada em cana-soca

Desde o início da revolução verde (período pós 2ª guerra mundial), o principal objetivo da aplicação dos fertilizantes sob a perspectiva da agricultura intensiva é o aumento ou manutenção dos índices de produtividade. Contudo, o manejo não apropriado dos fertilizantes nitrogenados podem produzir impactos negativos no meio ambiente, principalmente associado à lixiviação do nitrato até os reservatórios de água subterrâneos, emissão de gases de efeito estufa (N_2O) e escoamento superficial das águas da chuva. As perdas do N fertilizante são favorecidas quando o local de deposição recebe uma concentração maior que a capacidade de absorção pelas raízes, ou então, quando a aplicação é realizada em local onde as raízes não estão disponíveis.

Na adubação em cana-de-açúcar, o nitrogênio é o nutriente de manejo mais complexo devido às interações com a matéria orgânica do solo e rotas de perdas no sistema solo-planta (CANTARELLA e ROSSETTO, 2010). Nas áreas de cana-soca, a adubação nitrogenada é complementar à contribuição da mineralização do N orgânico do solo. Em geral, a exigência em adubação nitrogenada pela cana-soca está compreendida na faixa de 60 a 150 kg ha^{-1} (CANTARELLA e ROSSETTO, 2010). Contudo, no estado de São Paulo, onde está concentrada aproximadamente 53% da produção de cana-de-açúcar brasileira (CONAB, 2015), a taxa de adubação é realizada geralmente em torno de 100 a 120 kg ha^{-1} de N.

Nos últimos anos, os avanços tecnológicos empregados na colheita da cana-de-açúcar produziram impactos no manejo da adubação nitrogenada. Atualmente, a colheita mecanizada sem despalha com fogo representa acima de 85% das áreas cultivadas no estado de São Paulo (CTC, 2012). O modelo foi incrementado com maior intensidade desde a assinatura do protocolo agroambiental (2007) pelo setor sucroenergético paulista. Além da capacidade operacional, a colheita mecanizada de cana crua possui benefícios para a conservação do meio ambiente, como: a preservação da umidade do solo pela manutenção dos resíduos vegetais sobre a superfície, contribuições na matéria orgânica, reciclagem dos nutrientes, adição de carbono orgânico e melhoria na qualidade do ar local devido à redução nas emissões de materiais particulados originados na queima da palha.

Em contraposição aos benefícios da colheita mecanizada, a camada de resíduos vegetais deixados sobre a superfície do solo, pode reduzir a eficácia da adubação nitrogenada, sobretudo, nas operações com aplicação do fertilizante na superfície, em especial, quando a relação C:N dos resíduos orgânicos é maior que 44:1 devido ao potencial de imobilização do N mineral pelos microrganismos (CHEN et al., 2014). A condição é verificada aos resíduos vegetais da cana-de-açúcar, os quais possuem relação C:N em aproximadamente 100:1 (FORTES, C. et al., 2012). Desse modo, mesmo utilizando uma fonte nitrogenada com baixa emissão de NH_3 (nitrato de amônio, e.g.), a disponibilidade do N mineral no solo pode ser prejudicada.

Além da imobilização, a aplicação de ureia sobre a superfície dos resíduos vegetais da cana-de-açúcar pode adicionar perdas por volatilização do NH_3 (COSTA et al., 2003). Essencialmente, a taxa de emissão de NH_3 depende da velocidade da hidrólise da ureia (conversão do $[(NH_2)_2CO]$ para NH_4HCO_3) influenciada pela temperatura, umidade do solo, presença de resíduos vegetais em decomposição (atividade microbiana), condições de ventilação sobre a superfície do solo, pH, concentração do fertilizante (CHIEN et al., 2009). Em monitoramento da emissão de NH_3, Lara Cabezas et al. (2000) observaram perdas de 54% e 17%, quando os fertilizantes (ureia e uran, respectivamente) foram aplicados sobre a superfície; contudo, a incorporação no solo (profundidade de 50 a 70 mm) reduziu as perdas para 5 e 3,5%.

Em geral, a aplicação dos fertilizantes nitrogenados incorporados na camada superficial do solo pode diminuir o impacto da atividade da urease originada dos resíduos vegetais em decomposição. Mesmo assim, a incorporação incompleta do fertilizante nitrogenado pode contribuir com a manutenção das perdas por volatilização de NH_3 (ROCHETTE et al., 2009). A incorporação dos fertilizantes nas áreas de cana-soca, geralmente envolve operações, como: o corte da palha, abertura de sulco, deposição do fertilizante, incorporação do solo mobilizado e retorno dos resíduos vegetais sobre a cobertura. No entanto, o processo pode adicionar resíduos vegetais dentro do sulco, resultando na redução da eficiência da adubação devido à contribuição da atividade da urease originada na decomposição.

A operação de adubação é conduzida após a colheita mecanizada, durante o período de perfilhamento das soqueiras de cana-de-açúcar. Entre os dispositivos utilizados na incorporação do fertilizante no solo, estão: os discos para o corte da palha (dentado, liso ou serrilhado), hastes sulcadoras ou discos desencontrados para abertura contínua do solo e deposição de fertilizante (Figura 3a). Em geral, quando comparada à adubação em superfície, a operação de incorporação do fertilizante exige maior potência. Ademais, a adubação em superfície possibilita uma maior capacidade operacional, associada à velocidade de deslocamento, número de linhas e menor complexidade dos mecanismos de aplicação (Figura 3b).

Apesar da importância do N fertilizante para a cana-de-açúcar, a principal fonte do N mineral para suprimento das plantas possui origem no N orgânico do solo (VIEIRA-MEGDA et al., 2015), sobretudo, devido ao extenso sistema radicular das soqueiras (OLIVEIRA et al., 2013), combinado ao maior intervalo de crescimento vegetativo, quando comparado a outros cultivos agrícolas anuais (cereais e grãos, e.g.). Além disso, nos ciclos de cana-soca, reservas nos rizomas e raízes também podem contribuir no suprimento da necessidade nutricional das plantas (VITTI et al., 2007).

Mesmo assim, a adubação nitrogenada possui efeito positivo, principalmente na fase inicial e intermediária de desenvolvimento (perfilhamento e crescimento), quando a contribuição do N fertilizante pode representar até 60% do N total da planta; contudo, na fase de senescência (próximo à maturação), a contribuição do N fertilizante é reduzida para aproximadamente 20% (FRANCO et al., 2011). Ademais, a adubação nitrogenada pode contribuir com efeito residual nos ciclos subsequentes (FRANCO et al., 2011). Em áreas com aplicação de nitrato de amônio na superfície, a característica pode ser originada na imobilização dos nutrientes, seguido pela disponibilização do N mineral a partir da taxa de mineralização (VITTI et al., 2007).

Figura 3 – Exemplo de equipamentos utilizados na adubação em cana-soca. a. Adubadora para aplicação incorporada (DMB, modelo 1250-H, Sertãozinho-SP). B. Equipamento para aplicação em superfície (Jacto, modelo Uniport 3000 NPK, Pompéia- SP)

(a) (b)

Nos estágios iniciais da cana-de-açúcar, a maior demanda pelo N mineral do solo está associada principalmente à fotossíntese (aumento na área de dossel) e crescimento das plantas; ao longo do ciclo, o nutriente possui funções importantes na estrutura dos tecidos vegetais (lignina, celulose, e.g.) e armazenamento nos colmos, rizomas e raízes (OLIVEIRA et al., 2013). No entanto, mesmo no período de maior demanda pela absorção do N mineral pelas plantas, o conteúdo de N no tecido vegetal é relativamente baixo (aproximadamente de 2% nas folhas +1, Franco et al., 2010). No estágio próximo à senescência, o acúmulo de N na biomassa superior (ponteiros, folhas secas e colmos) é aproximadamente 100 a 150 kg ha^{-1}de N (FRANCO, et al., 2011; OTTO et al., 2014; MARIANO et al., 2015; VIEIRA-MEGDA et al., 2015). A reposição destes nutrientes exportados com a colheita é uma das funções da adubação nitrogenada. O processo representa a busca pelo equilíbrio entre a produtividade e conservação da fertilidade do solo. De acordo com Jat et al. (2014), a recomendação de adubação pode ser fundamentada na quantidade de nutrientes exportados na colheita, nível residual de nutrientes no solo e taxa de reciclagem dos nutrientes.

Em revisão de 45 estudos realizados sobre adubação nitrogenada em cana-soca em condições de manutenção de cobertura de resíduos na superfície, Otto et al. (2016) revelaram que 75% dos experimentos apresentaram uma resposta baixa ou moderada para a produtividade (acréscimo de até 25%). Em geral, o aumento na taxa de adubação não significa um ganho proporcional na produtividade ou na eficiência de absorção de nutrientes pela cana-de-açúcar. Mesmo assim, nas áreas com colheita mecanizada sem despalha a fogo, o aumento da taxa de adubação (~20%) tem sido empregado empiricamente para reduzir os efeitos das perdas do N fertilizante e imobilização do nitrogênio (OTTO et al., 2016).

Entretanto, a melhoria na eficiência no uso dos nutrientes é um processo elaborado, influenciado pela habilidade na absorção do fertilizante, fluxo dos nutrientes na planta, processamento e armazenamento. O incremento da eficiência no uso dos nutrientes pode contribuir no crescimento e produtividade, em contraposição, o estresse relacionado ao desequilíbrio dos nutrientes pode produzir efeitos negativos (MEENA et al., 2015).

Em geral, a eficiência no uso do N fertilizante pelas plantas não é alta (aproximadamente 50%), contudo, a absorção do N fertilizante pelas plantas pode ser abaixo de 30% de acordo com o manejo (CHIEN et al., 2009). Para melhorar a eficiência no uso do fertilizante nitrogenado pela cana-de-açúcar, Otto et al. (2016) destaca: a racionalização dos fertilizantes nitrogenados, a aplicação de subprodutos orgânico-minerais (fertilizante Ajifer, e.g.), a rotação de culturas, o cultivo de plantas leguminosas com capacidade de fixação biológica de nitrogênio, a manutenção da cobertura de resíduos vegetais, além de estratégias para redução das perdas do N fertilizante e aumento na disponibilidade do N mineral no solo.

As boas práticas de manejo para adubação (“*Best Management Practices*”) podem contribuir positivamente na produção agrícola e conservação do meio ambiente. Em síntese, tais práticas podem ser alcançadas quando a taxa de aplicação é compatível com a necessidade das plantas, a deposição do fertilizante é realizada em local que favorece a absorção pelas raízes, com aplicação durante período com maior necessidade pelo nutriente (CHIEN et al., 2009). Segundo os princípios das boas práticas de adubação, a incorporação do fertilizante pode melhorar a disponibilidade do N mineral no solo para absorção pelas plantas, em especial, quando o nutriente é distribuído próximo às linhas de cultivo de cana-de-açúcar (OTTO et al., 2016). Neste contexto, a “agricultura de precisão” pode contribuir com conceitos, métodos e tecnologias para o manejo dos insumos nas lavouras de cana-de-açúcar.

2.3 A adubação nitrogenada sob a perspectiva da agricultura de precisão

A agricultura de precisão (AP) é fundamentada em práticas para melhorias da produtividade, rentabilidade, racionalização dos insumos agrícolas (fertilizantes, corretivos, água, pesticidas, e.g.) e conservação do meio ambiente. Essencialmente, os benefícios podem ser alcançados pelo manejo localizado da variabilidade espacial das áreas agrícolas. Entre as principais tecnologias aplicadas na AP, estão: os monitores de produtividade, sensoriamento (resistência à penetração, condutividade elétrica do solo, refletância, e.g.), informações georreferenciadas (levantamento, gerenciamento e aplicação) e aplicação localizada de insumos (fertilizantes, corretivos, pesticidas).

As tecnologias podem contribuir significativamente no manejo da variabilidade espacial em áreas de cana-de-açúcar. Contudo, as tecnologias de AP estão mais avançadas e difundidas entre os cultivos agrícolas de cereais e grãos (ZAMYKAL e EVERINGHAM, 2009). Em contraposição, a lacuna oportuniza o desenvolvimento e aprimoramento contínuo das tecnologias da AP aplicadas à cana-de-açúcar.

Na produção da cana-de-açúcar, o aumento na eficiência da adubação nitrogenada é um dos desafios da agricultura (abrange setores de pesquisa, desenvolvimento de tecnologias, extensão e produção agrícola). Neste cenário, a aplicação localizada, alinhada aos conceitos das boas práticas de manejo, contribui com suprimento do nutriente de acordo com a exigência das plantas, sem exceder a capacidade de suporte do solo aos nutrientes (SAEYS et al., 2008). Dentre as estratégias para a aplicação localizada de fertilizantes, o local de deposição pode facilitar o acesso das raízes aos nutrientes e reduzir perdas do insumo (STEWART, 2006).

Entretanto, o manejo localizado pode envolver diferentes etapas do processo de produção agrícola, como: a definição de objetivos (aumento da disponibilidade do N mineral no solo), a proposição de estratégias (incorporação do fertilizante no solo, uso de fontes nitrogenadas com baixo potencial de emissão NH_3, ou ainda aplicação de inibidores de volatilização de NH_3), o levantamento de informações (identificação da variabilidade espacial por meio de análises de teor de N foliar, índices de vegetação e histórico de produtividade), a interpretação dos dados (*hardware*, *software*, instrumentos de medição, análises, mapas de prescrição), o emprego de máquinas e equipamentos (operação com taxa variável, instrumentos de monitoramento, dispositivos para aplicação localizada), e a busca por inovações tecnológicas com capacidade de superação de práticas convencionais (REETZ e FIXEN, 2016).

2.3.1 Identificação da variabilidade espacial para o manejo localizado

Nos últimos anos, estudos têm sido realizados para acessar a variabilidade espacial, como suporte à recomendação da adubação nitrogenada, empregada por equipamentos de aplicação com taxa variável. Contudo, transformações do N mineral no sistema solo-planta (conversão do amônio para o nitrato) e rotas dinâmicas (imobilização, mineralização, lixiviação, desnitrificação, volatilização) causam complexidade na avaliação sobre a disponibilidade do nutriente no solo para as plantas, por sua vez, também dificultam a recomendação da taxa de aplicação.

No entanto, a deficiência na disponibilidade do nutriente no solo pode produzir alteração no nível de intensidade de verde das folhas; considerando o princípio, índices de vegetação são alternativas para avaliar o estado nutricional das plantas em relação ao N mineral. Em geral, os índices de vegetação da cana-de-açúcar vêm sendo correlacionados ao estado nutricional ou produção de biomassa (AMARAL e MOLIN, 2011, 2014; MIPHOKASAP et al., 2012; PORTZ et al., 2012; AMARAL et al., 2015; ROSA et al., 2015). Entre os índices de vegetação, são comumente empregados: o NDVI (*normalized difference vegetation índex*), CI (*chlorophyll index*) e ISR (*inverse of the simple ratio*).

Essencialmente, a maior fração de N foliar está contida nas moléculas de clorofila (pigmentos fotossintéticos), desse modo, a intensidade da pigmentação é relacionada com a concentração de N foliar. A partir da relação, a estimativa da clorofila tem sido observada por meio de sensores, como o SPAD 502 (Minolta Corp, Ramsey, NJ-USA, Figura 4). O instrumento possui um emissor de luz LED (comprimento de onda na banda do vermelho). A luz emitida é absorvida ou transmitida por reflectância. A intensidade da interação é mensurada por um sensor fotodiodo de silício. Teoricamente é possível converter o valor mensurado em informações sobre o conteúdo de clorofila, ou então, acessar a condição nutricional relacionada ao N foliar, sendo suporte para avaliar a variabilidade espacial e orientar as práticas da adubação nitrogenada (FRANCIS e PIEKIELEK, 2016).

Mesmo assim, os índices de vegetação não eximem avaliações como o teor de N-foliar; aliás, tais verificações podem contribuir na calibração e interpretação de informações extraídas a partir dos sensores, os quais viabilizam levantamento de um número maior de informações georreferênciadas através da lavoura.

Figura 4 – Medidor de índice de clorofila aplicado na folha de cana-de-açúcar

Uma das alternativas para acessar índices de vegetação da cana-de-açúcar é o emprego de sensores embarcados nas máquinas agrícolas. Entre as vantagens do monitoramento "*on-the-go*" está o maior nível de detalhamento das informações através da lavoura, sendo assim, contribui para melhorar o nível de resolução na caracterização da variabilidade espacial. Além disso, a tecnologia pode ser combinada com os equipamentos de adubação com taxa variável. Em monitoramento realizado com o sensor de dossel N-Sensor ALS (Yara Internacional ASA, Duelmen, Germany) em lavoura de cana-de-açúcar, Portz et al., (2012) descreve que o índice de vegetação identificou a variabilidade espacial de biomassa e detectou diferenças na absorção do N pelas plantas no crescimento inicial (altura de caule igual a 0,2 a 0,6 m), quando a eficiência no uso do N fertilizante pelas plantas é maior (FRANCO et al., 2011; VIEIRA-MEGDA et al., 2015).

2.3.2 Tecnologias de aplicação do fertilizante

A operação de adubação com taxa variável geralmente é conduzida com o fertilizante aplicado em superfície (paralelo às linhas, ou em área total). A prática pode favorecer perdas do N fertilizante para o meio ambiente, ou mesmo, o emprego de taxa de aplicação mais elevada (sobretaxa). A aplicação em superfície é comumente empregada na adubação nitrogenada em lavouras pré-estabelecidas, como cultivos perenes (fruticultura, cafeicultura), semi-perenes (cana-de-açúcar, pastagem) e cultivos anuais (milho, sorgo, trigo, feijão, arroz, e.g.).

Na operação, um distribuidor centrífugo de fertilizante sólido granulado é utilizado para aplicação em área total. Nos últimos anos, o equipamento tem sido relacionado à tecnologia de aplicação a taxa variável. Essencialmente, a aplicação à taxa variável está associada a maior eficácia da adubação; contudo, erros podem prejudicar os resultados (VIRK et al., 2013), tais como, variações na alimentação mássica dos discos centrífugos (FULTON et al., 2001), segregação dos nutrientes (N-P-K) no reservatório causado pela vibração da máquina (VIRK et al., 2013), características dinâmicas durante a transição de taxas de aplicação (FULTON et al., 2005), calibração não adequada (FULTON et al., 2001, 2005, 2013; VIRK et al., 2013) e variações no padrão de sobreposição entre as faixas de distribuição (VIRK et al., 2013).

Na aplicação realizada pelo distribuidor centrífugo, ocorre uma maior concentração do produto próximo ao centro geométrico da máquina. Para alcançar um padrão de uniformidade entre as passadas, um nível de sobreposição das faixas de aplicação é realizado. Mesmo assim, a uniformidade de distribuição não é exata, quando comparada à recomendação. Em avaliação da uniformidade da aplicação, Virk et al. (2013) observaram coeficiente de variação (c.v.) significativo (c.v. ~26%). Contudo, o emprego de formulações N-P-K pode resultar em c.v.(s) superiores a 30%, devido a desuniformidade entre os produtos, como variações na densidade, formato dos grânulos e características higroscópicas (FULTON et al., 2001; VIRK et al., 2013; CAMPBELL et al., 2015).

A aplicação incorporada de fertilizantes utilizando taxa variável está geralmente associada à etapa de implantação das lavouras, junto à operação de semeadura ou plantio. Em geral, a taxa de distribuição do fertilizante sólido granulado nas linhas é determinada por um mecanismo dosador (rosca helicoidal, e.g.) instalado na base do reservatório. No sistema convencional, a taxa de aplicação constante é determinada pelo acionamento do mecanismo dosador, relacionado à velocidade de deslocamento da máquina, através de transmissões mecânicas síncronas (rodas dentadas ou engrenagens). Em contraposição, na aplicação com taxa variável, a atuação na velocidade de acionamento do mecanismo dosador é função da recomendação.

Na aplicação de fertilizante incorporado, além de menor exposição aos fatores de perdas para o meio ambiente, a operação está associada a maior qualidade, expressa pela maior uniformidade de aplicação (~8% ≤ c.v. ≤ ~15%, segundo Ning et al., 2015). Em síntese, a operação com taxa variável, utilizando abordagem de controle contínuo em malha fechada, possui o objetivo de reduzir o erro da aplicação em relação à recomendação prescrita, mesmo sob distúrbios no processo (variações na carga, velocidade, e.g.). A característica contribui para melhorar a qualidade da operação (REYES et al., 2015), favorecendo a aplicação localizada.

De forma geral, a manutenção dos parâmetros de controle em configuração padrão também pode contribuir para reduzir a exatidão da aplicação (VIRK et al., 2013), devido à influência das condições de operação, como características físicas do produto (granulometria, densidade, teor de umidade) e velocidade de deslocamento. Além disso, resultados ambíguos podem ser alcançados quando a recomendação (descrita no mapa de prescrição, e.g.) não está adequada a real necessidade da lavoura (FULTON et al., 2013).

2.4 Fertilizantes líquidos: fontes, aplicação, dispositivos e características

Nas áreas de cana-soca é comum a aplicação de vinhaça, um bioefertilizante líquido, subproduto da destilação do etanol. Em geral, a vinhaça possui uma concentração de potássio suficiente para o suprimento da taxa de aplicação exigida pela cana-de-açúcar. O produto também fornece macro e micronutrientes, como o N mineral, porém, a quantidade é insuficiente para as plantas, portanto, a operação não substitui a adubação nitrogenada (CANTARELLA e ROSSETTO, 2010). O fornecimento do N mineral pode ser alcançado pela aplicação da aquamônia (concentração de 0,18 kg L^{-1} de N), um fertilizante líquido produzido por meio da hidratação da amônia anidra (80% de N). Entretanto, a fonte possui alto índice de perdas por emissão de NH_3 quando o fertilizante é aplicado na superfície, sendo assim, a aplicação incorporada na camada superficial do solo é uma estratégia para reduzir as perdas (BOARETTO et al., 1991).

O emprego do adubo líquido uran (32% de N) também é uma alternativa; em comparação entre as aplicações utilizando uran e ureia, as perdas por volatilização foram menores quando utilizado o fertilizante líquido (17% v.s. 54%) (LARA CABEZAS et al., 2000). A característica é fundamentada na menor concentração amídica presente no uran (16% de $N\text{-}NH_2$). A composição também fornece a forma nítrica (8% de $N\text{-}NO_3^-$) e amoniacal (8% de $N\text{-}NH_4^+$); dentre as quais, as plantas de cana-de-açúcar possuem preferência pela absorção do NH_4 (ROBINSON et al., 2011).

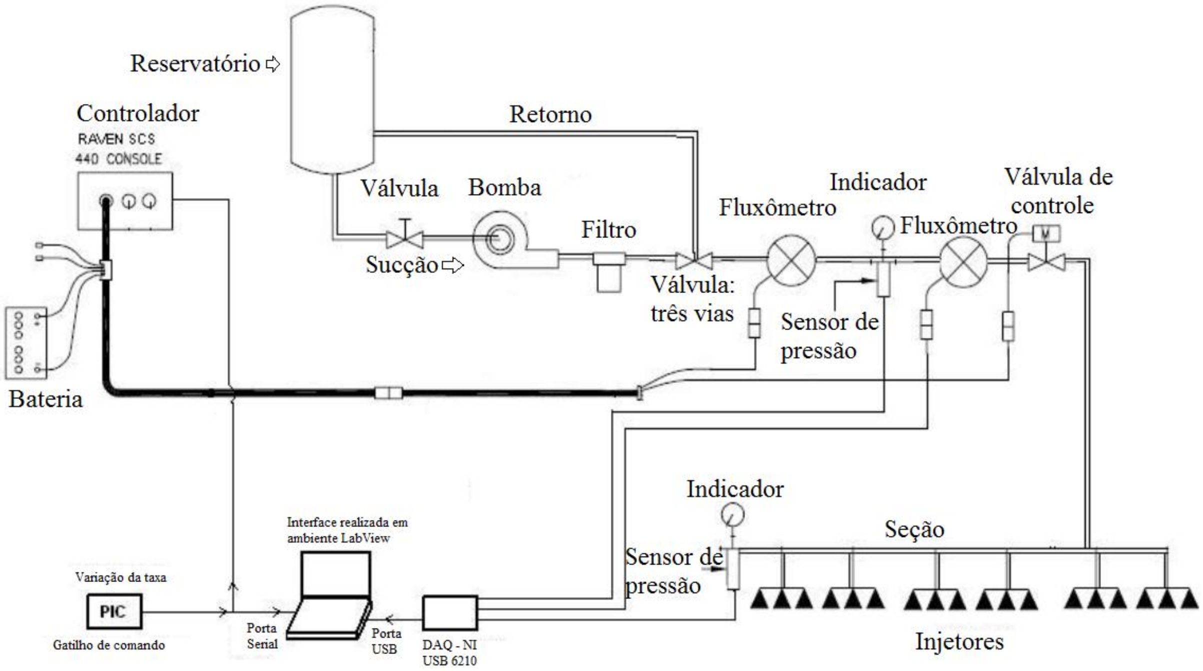
Nos últimos anos, estudos em áreas de cana-de-açúcar têm sido conduzidos com o fertilizante Ajifer-8 (7,5% de N, 7% de S, 14% de carbono orgânico), um líquido organomineral produzido por processo de fermentação microbiológica de subprodutos da indústria alimentícia (COSTA et al., 2003; MARIANO et al., 2015; MARIANO et al., 2016). Em avaliação realizada em área de cana-de-açúcar utilizando diferentes fertilizantes nitrogenados, Costa et al. (2003) revelaram que o emprego do Ajifer produziu menores perdas por emissão de NH_3 (9%), quando comparado à ureia (36%) ou uran (15%); além disso, a aplicação da ureia resultou em nível menor de produtividade, associada às perdas. Entretanto, geralmente os fertilizantes líquidos possuem menor concentração de nutrientes, quando comparado aos fertilizantes sólidos granulados.

As principais especificações dos fertilizantes líquidos são referentes à concentração do nutriente, densidade, viscosidade e tamanho das partículas. Entre as vantagens no uso dos adubos líquidos, estão: melhor controle da uniformidade de aplicação, menor segregação de nutrientes, versatilidade das formulações N-P-K (permite mistura de micronutrientes na calda de aplicação) e menor consumo de energia na produção; em contraposição, entre as desvantagens, são apontadas: a necessidade de agitação durante a aplicação de fluidos com partículas em suspensão, riscos de acidentes em operação com amônia anidra e entupimento dos injetores causado pela precipitação de partículas (KORNDÖRFER et al., 1995).

Para a aplicação de adubos líquidos, em geral, os componentes hidráulicos fundamentais são o reservatório, tubulações (sucção, aplicação e retorno), bomba hidráulica (centrífuga, pistões, peristáltica, e.g.), filtro, manômetro, fluxômetro, válvulas (globo, solenoides proporcional, *on-off*, e.g.), e injetores (Figura 5). Na operação é comum o emprego de equipamentos desenvolvidos para aplicação em superfície. Tais sistemas possuem configuração similar às tecnologias para a pulverização de defensivos agrícolas (Figura 5), porém, com diferenças nas características do produto de aplicação (viscosidade, partículas em suspensão, densidade), vazão, pressão e jato de aplicação (Figura 6b,c). Nos equipamentos com aplicação a taxa variável, o fluxo de saída mensurado pelo fluxômetro é comparado com a vazão exigida (determinada em função da recomendação da taxa de adubação); o resultado fundamenta o controle de potência no nível de abertura ou fechamento da válvula.

Aos sistemas com adubação incorporada no solo, as diferenças são associadas ao mecanismo de aplicação. Entre as alternativas é possível o emprego de um dispositivo sulcador, com injeção do fertilizante líquido em posição posterior a ferramenta. Princípio semelhante também é utilizado para acessar a subsuperfície do solo em áreas com camada de resíduos vegetais, por meio do conjunto: disco de corte, sulcador e injetor de fertilizante (Figura 6d). Em geral, os equipamentos desenvolvidos para aplicação incorporada são associados aos produtos com maior potencial de emissão de NH_3 e odores, como os biofertilizantes produzidos a partir de dejetos animais e aquamônia (MOSELEY et al., 1998; MCLAUGHLIN e CAMPBELL, 2004; MCLAUGHLIN et al., 2006; NYORD et al., 2008; ROCHETTE et al., 2009).

Figura 5 – Exemplo de diagrama de sistema de aplicação de taxa variável de adubo líquido



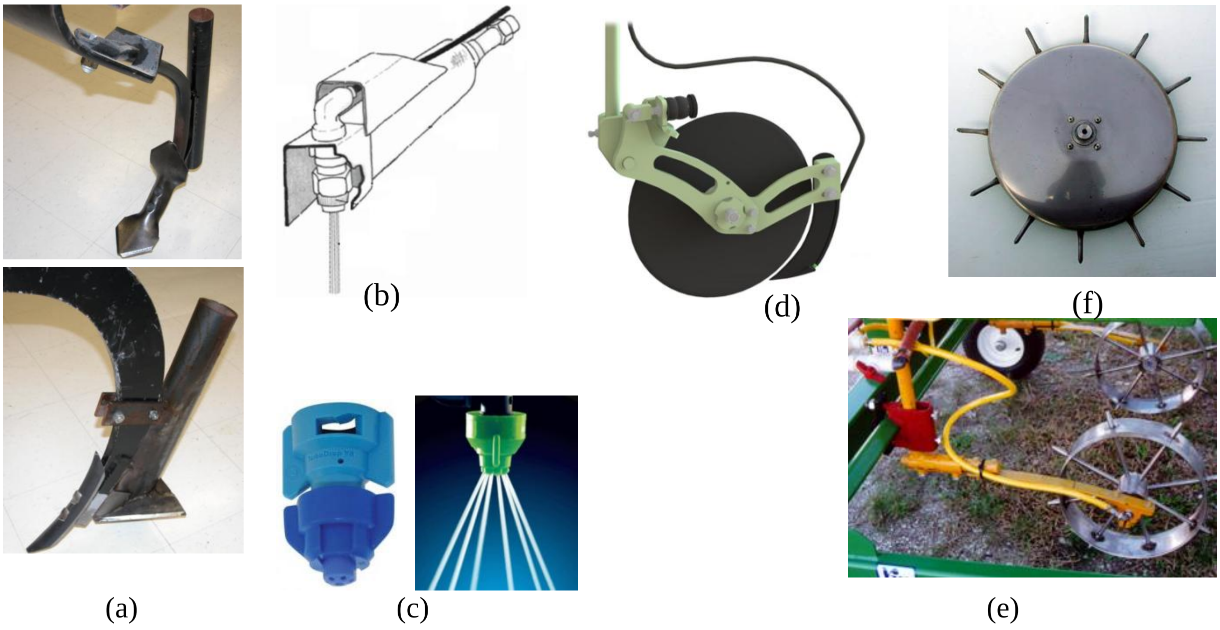
Fonte: Bennur e Taylor (2010).

De acordo com Womac e Tompkins (1990), a melhoria do processo de adubação pode ser alcançada, quando (i) o fertilizante é aplicado diretamente no solo com mínima mobilização e (ii) profundidade controlada (70 a 100 mm, e.g.). A especificação pode ser obtida em processo de puncionamento e injeção do adubo líquido em profundidade. Na década de 1980, o princípio da tecnologia foi primeiramente desenvolvido para adubação em lavouras de milho (Figura 6e, f), visando os benefícios da adubação incorporada e redução nos danos ao sistema radicular de lavouras pré-estabelecidas (BAKER et al., 1989). Além disso, a estratégia tem sido proposta para aplicação em lavouras de arroz inundado, nas quais, a lâmina superficial de água e a sensibilidade do sistema radicular das plantas dificultam o processo convencional de incorporação contínua do fertilizante (BAUTISTA et al., 2001). Nos últimos anos, o princípio da tecnologia também tem sido destacado em outros estudos sobre a aplicação localizada de fertilizantes (NYORD et al., 2008; CHUNFENG e XIU, 2015; LIU et al., 2015).

O conceito da operação mecanizada de puncionamento no solo em áreas de cana-soca foi introduzido em estudo prévio, descrito em SILVA (2013). A viabilidade do processo alternativo de aplicação em subsuperfície com mínima mobilização (solo, palha e raízes) foi alcançada através do desenvolvimento de sistema mecânico puncionador. Entretanto, na primeira etapa realizada entre os anos de 2011 a 2013, o projeto foi centrado na concepção do processo de perfuração mecanizada da camada superficial do solo, sem considerações sobre a injeção do fertilizante líquido.

Entre os sistemas desenvolvidos para injetar adubo líquido em profundidade, Niemoeller et al. (2011) avaliaram um sistema que utiliza jato de alta pressão (~40 MPa). A operação de injeção do fluido no solo foi caracterizada em três etapas. Primeiramente, a pressão do jato produz o rompimento da superfície do solo, na sequência, o rompimento do solo ocorre a partir dos espaços “vazios” (macroporos), no último estágio, a pressão do jato reduz a força dos mecanismos de ligação do solo, causando o progresso da injeção na camada superficial. Em avaliação de sistema similar (Figura 6b), Nyord et al. (2008) observaram profundidade de injeção menor que 20 mm, sendo considerada insuficiente para alcançar os benefícios associados à adubação incorporada. A menor profundidade de perfuração do jato foi atribuída à absorção da energia cinética pelos resíduos vegetais na cobertura, além da “baixa” pressão do jato (1 a 4,5 MPa).

Figura 6 – Dispositivos para aplicação de adubo líquido. a. Sulcadores para adubação incorporada (MCLAUGHLIN et al., 2006). b. Injetor utilizado na aplicação de jato pressurizado (NYORD et al., 2008). c. Injetor utilizado na aplicação em superfície (HYPRO, 2016). d. Disco utilizado no corte de palha, combinado com sulcador (ORTHMAN, 2016). e. Aplicação de adubo líquido por meio de puncionamento e injeção de fertilizante (KENNCO, 2016). f. dispositivo injetor “spoke wheel” (LIQUIJET, 2016)



(b) (d) (f)

(a) (c) (e)

Em comum aos equipamentos de aplicação de fertilizante líquido, a pressão e vazão são parâmetros fundamentais dos sistemas hidráulicos; desde o projeto, dimensionamento, especificação, monitoramento e controle. Nos circuitos hidráulicos, a análise da pressão pode indicar sobrecargas (entupimentos de injetores, obstrução das tubulações) e vazamentos (caracterizado pela queda de pressão). Além disso, o monitoramento da pressão e vazão pode contribuir na qualidade da operação de adubação. Nos equipamentos que possuem múltiplos injetores por barra (Figura 5), a perda de carga ao longo da seção pode influenciar na uniformidade aplicação entre os injetores. No entanto, a aplicação de medidores de vazão em cada injetor dificulta o monitoramento do processo. Neste contexto, a vazão através dos injetores pode ser monitorada pelo diferencial de pressão através da barra de seção (aplicação de dois manômetros, o primeiro em posição anterior a aplicação, e o segundo em extremidade da seção, Figura 5); assim, um aumento no diferencial de pressão significa um acréscimo na variação na vazão entre os injetores.

A vazão fluídica também pode ser avaliada por instrumentos com o princípio de Venturi, placa de orifício, rotâmetro, turbina, magnéticos indutivos e ultrassônicos. Em equipamentos de aplicação de adubo líquido é comum o emprego de instrumento com microturbina, no qual, o fluxo de saída é proporcional à frequência de rotação (ANGLUND e AYERS, 2003). Em função da vazão, o desempenho dos sistemas pode ser avaliado pelas características estáticas (MUNACK et al., 2001; YANG, 2001; ANGLUND e AYERS, 2003; SAEYS et al., 2008; BENNUR e TAYLOR, 2010; SHARDA et al., 2016), como: o erro de exatidão (diferença percentual entre a dose exigida e a dose aplicada); a faixa de dosagem (valores de mínima e máxima capacidade de aplicação); e a precisão dos injetores (faixa de tolerância do erro e coeficiente de variação).

Em síntese, o processo de adubação utilizando fertilizante líquido é influenciado principalmente pela fonte nitrogenada (uran, ureia, aquamônia, biofertilizante líquido, e.g.), sistema mecânico-hidráulico aplicado ao método de adubação (superfície, incorporado, injeção) e qualidade da operação (uniformidade de aplicação e desvio em relação à dosagem recomendada pela orientação agronômica). Tais questões, junto à determinação da dosagem espacialmente apropriada às plantas, são fundamentais para implementação de processo para aplicação localizada alinhada aos princípios das boas práticas de manejo da adubação em cana-soca.

2.5 CONSIDERAÇÕES GERAIS

O uso racional dos fertilizantes nitrogenados em lavouras de cana-de-açúcar possui benefícios na eficácia da adubação (*nitrogen use efficiency*) e conservação do meio ambiente. Para tanto, a “agricultura de precisão” pode contribuir com o manejo localizado, considerando a variabilidade espacial em relação à exigência nutricional das lavouras de cana-de-açúcar. Contudo, para implementar a aplicação localizada de fertilizante nitrogenado, fundamentada nas boas práticas de manejo, o processo deve contemplar princípios como a deposição do fertilizante em local que facilite o acesso das raízes ao nutriente e propicie a redução de perdas para o meio ambiente. Tal condição pode ser alcançada quando o fertilizante é aplicado na camada subsuperficial do solo, próximo às raízes da cana-de-açúcar. Neste contexto, o uso de fertilizante líquido nitrogenado permite além da aplicação do método convencional de incorporação contínua, o emprego de estratégias alternativas para acesso da subsuperfície do solo, como no processo de injeção de jato fluídico em operação de puncionamento no solo.

2.6 REFERÊNCIAS

AMARAL, L. R.; MOLIN, J. P. Sensor óptico no auxílio à recomendação de adubação nitrogenada em cana-de-açúcar. **Pesquisa Agropecuaria Brasileira**, v. 46, n. 1, p. 1633–1642, 2011.

AMARAL, L. R.; MOLIN, J. P. The effectiveness of three vegetation indices obtained from a canopy sensor in identifying sugarcane response to nitrogen. **Agronomy Journal**, v. 106, n. 1, p. 273–280, 2014.

AMARAL, L. R.; MOLIN, J. P.; PORTZ, G.; FINAZZI, F. B.; CORTINOVE, L. Comparison of crop canopy reflectance sensors used to identify sugarcane biomass and nitrogen status. **Precision Agriculture**, v. 16, n. 1, p. 15–28, 2015.

ANGLUND, E. A.; AYERS, P. D. Field evaluation of response times for a variable rate (pressure–based and injection) liquid chemical applicator. **Applied Engineering in Agriculture**, v. 19, n. 3, p. 273–282, 2003.

BAKER, J. L.; COLVIN, T. S.; MARLEY, S. J.; DAWELBEIT, M. A point-injector applicator to improve fertilizer management. **Appl. Eng. Agric**, v. 5, p. 334–338, 1989.

BAUTISTA, E. U.; KOIKE, M.; SUMINISTRADO, D. C. Mechanical deep placement of nitrogen in wetland rice. **Journal of Agricultural Engineering Research**, v. 78, n. 4, p. 333–346, 2001.

BENNUR, P. J.; TAYLOR, R. K. Evaluating the response time of a rate controller used with a sensor-based, variable rate application system. **Applied Engineering in Agriculture**, v. 26, n. 6, p. 1069–1075, 2010.

BOARETTO, A. E.; CRUZ, A. P.; LUZ, P. H. C. **Adubo líquido: produção e uso no Brasil**. 1st ed. Campinas: Fundação Cargil, 1991.

CAMPBELL, C. M.; FULTON, J. P.; WOOD, C. W.; MCDONALD, T. P.; ZECH, W. C. Utilizing nutrient over mass distribution patterns for assessment of Poultry litter spreaders. **Transactions of the ASAE**, v. 53, n. 3, p. 659–666, 2015.

CANTARELLA, H.; ROSSETTO, R. Fertilizers for sugarcane. In: L. A. B. Cortez (Ed.); **Sugarcane bioethanol R&D for productivity and Sustainability**. First ed., p.405–422, 2010. São Paulo: Blucher & Fapesp.

CHEN, B.; LIU, E.; TIAN, Q.; YAN, C.; ZHANG, Y. Soil nitrogen dynamics and crop residues. A review. **Agronomy for Sustainable Development**, v. 34, n. 2, p. 429–442, 2014.

CHIEN, S. H.; PROCHNOW, L. I.; CANTARELLA, H. **Chapter 8 Recent Developments of Fertilizer Production and Use to Improve Nutrient Efficiency and Minimize Environmental Impacts**. 1st ed. Elsevier Inc., 2009.

CHUNFENG, Z.; XIU, W. Development and experiments on the injection system of the self-propelled liquid fertilizer machine. The 5th annual IEEE international conference on cyber technology in automation, control and intelligent systems. **Anais...** . p.1650–1654, 2015. Shenyang, China.

CONAB. Monitoring the Brazilian Safra - Sugarcane. Disponível em: <http://www.conab.gov.br/OlalaCMS/uploads/arquivos/15_12_17_09_03_29_boletim_cana_portugues_-_3o_lev_-_15-16.pdf>. Acesso em: 1/1/2016.

COSTA, M. C. G.; VITTI, G. C.; CANTARELLA, H. N-NH3 losses from nitrogen sources applied over unburned sugarcane straw. **Revista Brasileira de Ciência do Solo**, v. 27, n. 4, p. 631–637, 2003.

CTC. census of sugarcane variety and yield. Disponível em: <http://www.ctcanavieira.com.br/downloads/Censo2012.pdf>. Acesso em: 13/7/2016.

FAO. Food and agriculture organization of the united nations: Statics division. Disponível em: <http://faostat3.fao.org/>. Acesso em: 1/1/2016.

FORTES, C.; TRIVELIN, P. C. O.; VITTI, A. C. Long-term decomposition of sugarcane harvest residues in Sao Paulo state, Brazil. **Biomass and Bioenergy**, v. 42, p. 189–198, 2012. Elsevier Ltd.

FRANCIS, D. D.; PIEKIELEK, W. P. **Site-specific management Guidelines: assessing crop nitrogen needs with chlorophyll meters**. 1st ed. Peachtree Corners, GA-USA: IPNI-International Plant Nutrition Institute, 2016.

FRANCO, H. C. J.; OTTO, R.; FARONI, C. E.; et al. Nitrogen in sugarcane derived from fertilizer under Brazilian field conditions. **Field Crops Research**, v. 121, n. 1, p. 29–41, 2011.

FRANCO, H. C. J.; TRIVELIN, P. C. O.; FARONI, C. E.; VITTI, A. C.; OTTO, R. Stalk yield and technological attributes of planted cane as related to nitrogen fertilization relacionados com a adubação nitrogenada. **Scientia Agricola**, v. 67, n. 5, p. 579–590, 2010.

FULTON, J. P.; SHEARER, S. A; HIGGINS, S. F.; DARR, M. J.; STOMBAUGH, T. S. Rate response assessment from various granular VRT applicators. **Transactions of the Asae**, v. 48, n. 6, p. 2095–2103, 2005.

FULTON, J. P.; SHEARER, S. A.; CHABRA, G.; HIGGINS, S. F. Performance assessment and model development of a variable-rate, spinner-disc fertilizer applicator. **Transactions of the ASAE**, v. 44, n. 5, p. 1071–1081, 2001.

FULTON, J. P.; SHEARER, S. A.; HIGGINS, S. F.; MCDONALD, T. P. A method to generate and use as-applied surfaces to evaluate variable-rate fertilizer applications. **Precision Agriculture**, v. 14, p. 184–200, 2013.

HYPRO. Liquid fertilizer nozzles. Disponível em: <http://www.hypro-eu.com/en-gb/Our+Products/Spray+Nozzles/Liquid+Fertiliser+Spraying/>. Acesso em: 23/8/2016.

IFA. **International fertilizer industry association: Mineral fertilizer use and the environment**. 2000.

JAT, M. L.; BIJAY-SINGH; GERARD, B. **Nutrient Management and Use Efficiency in Wheat Systems of South Asia**. 1st ed. Elsevier Inc., 2014.

KENNCO. Liquid fertilizer injection wheel. Disponível em:

<http://www.kenncomfg.com/products/fertilizer-applicators>. Acesso em: 23/8/2016.

KORNDÖRFER, G. H.; ANDERSON, D. L.; MUNDIM, V. C.; SIMÕES, M. S. Produção de adubos fluidos para cana-de-açúcar. **Revista STAB**, v. 14, n. 2, p. 25–29, 1995.

LARA CABEZAS, W. A. R.; TRIVELIN, P. C. O.; KONDÖRFER, G. H.; PEREIRA, S. Nitrogen Balance of solid and liquid nitrogen sources on side-dressed no-till corn system at triângulo mineiro (MG). **R. Bras. Ci. Solo Bras**, v. 24, p. 363–376, 2000.

LIQUIJET. Fertilizer applicator: Spike wheel. Disponível em: <http://www.spikewheel.com/spikewheel.htm>. Acesso em: 23/8/2016.

LIU, T. Q.; FAN, D. J.; ZHANG, X. X.; et al. Deep placement of nitrogen fertilizers reduces ammonia volatilization and increases nitrogen utilization efficiency in no-tillage paddy fields in central China. **Field Crops Research**, v. 184, p. 80–90, 2015.

MARIANO, E.; LEITE, J. M.; MEGDA, M. X. V; TORRES-DORANTE, L.; TRIVELIN, P. C. O. Influence of nitrogen form supply on soil mineral nitrogen dynamics, nitrogen uptake, and productivity of sugarcane. **Agronomy Journal**, v. 107, p. 641–650, 2015.

MARIANO, E.; LEITE, J. M.; VIEIRA-MEGDA, M. X.; et al. Biomass and nutrient content by sugarcane as affected by fertilizer nitrogen sources. **Crop science**, v. 56, n. May-June, p. 1234–1244, 2016.

MCLAUGHLIN, N. B.; CAMPBELL, A. J. Draft-speed-depth relationships for four liquid manure injectors in a fine sandy loam soil. , v. 46, p. 1–5, 2004.

MCLAUGHLIN, N. B.; LI, Y. X.; BITTMAN, S.; et al. Draft requirements for contrasting liquid manure injection equipment. **Canadian Biosystems Engeering**, v. 48, p. 29–37, 2006.

MEENA, V. S.; VERMA, J. P.; MEENA, S. K. Towards the current scenario of nutrient use efficiency in crop species. **Journal of Cleaner Production**, v. 102, n. MAY, p. 556–557, 2015.

MIPHOKASAP, P.; HONDA, K.; VAIPHASA, C.; SOURIS, M.; NAGAI, M. Estimating canopy nitrogen concentration in sugarcane using field imaging spectroscopy. **Remote Sensing**, v. 4, p. 1651–1670, 2012.

MOSELEY, P. J.; MISSELBROOK, T. H.; PAIN, B. F.; EARL, R.; GODWIN, R. J. The effect of injector tine design on odour and ammonia emissions following injection of bio-solids into arable cropping. **Journal of Agricultural Engineering Research**, v. 71, n. 4, p. 385–394, 1998.

MUNACK, A.; BUNING, E.; SPECKMANN, H. A high-performance control system for spreading liquid manure. **Control Engineering Practice**, v. 9, p. 387–391, 2001.

NIEMOELLER, B.; HARMS, H. H.; LANG, T. Injection of liquids into the soil with a high-pressure jet. **Agricultural Engineering International: CIGR Journal**, v. 13, n. 2, p. 1–15, 2011.

NING, S.; TAOSHENG, X.; LIANGTU, S.; RUJING, W.; YUANYUAN, W. Variable rate fertilization system with adjustable active feed-roll length. **International Journal of**

Agriculture & Biological Engineering, v. 8, n. 4, p. 19–26, 2015.

NYORD, T.; SØGAARD, H. T.; HANSEN, M. N.; JENSEN, L. S. Injection methods to reduce ammonia emission from volatile liquid fertilisers applied to growing crops. **Biosystems Engineering**, v. 100, n. 2, p. 235–244, 2008.

OLIVEIRA, E. C. A.; GAVA, G. J. C.; TRIVELIN, P. C. O.; OTTO, R.; FRANCO, H. C. J. Determining a critical nitrogen dilution curve for sugarcane. **Journal of Plant Nutrition and Soil Science**, v. 176, n. 5, p. 712–723, 2013.

ORTHMAN. Liquid fertilizer applicator. Disponível em: <http://www.orthman.com/our-products.aspx?itemid=2049&prodid=10880&pagetitle=Liquid+Fertilizer+Applicator>. Acesso em: 23/8/2016.

OTTO, R.; CASTRO, S. A. Q.; MARIANO, E.; et al. Nitrogen Use Efficiency for Sugarcane-Biofuel Production: What Is Next? **BioEnergy Research**, v. 1, p. 1–18, 2016.

OTTO, R.; COUTINHO, H.; FRANCO, J.; et al. The Role of Nitrogen Fertilizers in Sugarcane Root Biomass under Field Conditions. **Agricultural Sciences**, v. 5, p. 1527–1538, 2014.

PORTZ, G.; MOLIN, J. P.; JASPER, J. Active crop sensor to detect variability of nitrogen supply and biomass on sugarcane fields. **Precision Agriculture**, v. 13, n. 1, p. 33–44, 2012.

REETZ, H. F.; FIXEN, P. E. **Site-specific management Guidelines: strategic approach to site-specific systems**. 1st ed. Peachtree Corners, GA-USA: IPNI-International Plant Nutrition Institute, 2016.

REYES, J. F.; ESQUIVEL, W.; CIFUENTES, D.; ORTEGA, R. Field testing of an automatic control system for variable rate fertilizer application. **Computers and Electronics in Agriculture**, v. 113, p. 260–265, 2015.

ROBINSON, N.; BRACKIN, R.; VINALL, K.; et al. Nitrate paradigm does not hold up for sugarcane. **PloS one**, v. 6, n. 4, p. e19045, 2011.

ROCHETTE, P. .; ANGERS, D. A. .; CHANTIGNY, M. H. .; et al. Reducing ammonia volatilization in a no-till soil by incorporating urea and pig slurry in shallow bands. **Nutrient Cycling in Agroecosystems**, v. 84, p. 71–80, 2009.

ROSA, H. J. A.; AMARAL, L. R. DO; MOLIN, J. P.; CANTARELLA, H. Sugarcane response to nitrogen rates, measured by a canopy reflectance sensor. **Pesquisa Agropecuaria Brasileira**, v. 50, n. 1, p. 840–848, 2015.

SAEYS, W.; DEBLANDER, J.; RAMON, H.; ANTHONIS, J. High-performance flow control for site-specific application of liquid manure. **Biosystems Engineering**, v. 99, n. 1, p. 22–34, 2008.

SHARDA, A.; FULTON, J. P.; TAYLOR, R. K. Performance of variable-orifice nozzles for Liquid fertilizer applications. **Applied Engineering in Agriculture**, v. 32, n. 3, p. 347–352, 2016.

SILVA, M. J. **Processo de aplicação de fluidos em profundidade com mínima mobilização do solo**. 82 p. Dissertação (Mestrado em Engenharia Agrícola) – Universidade Estadual de Campinas “UNICAMP”, Campinas. 2013.

STEWART, M. Conserving resources and building productivity. **Best Management Practices for Fertilizer**, 2006. IPNI-International Plant Nutrition Institute. Disponível em: <http://www.ipni.net/ppiweb/ppinews.nsf/0/AFFACB3FAA07E205852571170058CA2E/$FILE/SCGP BMPs.pdf>. .

VIEIRA-MEGDA, M. X.; MARIANO, E.; LEITE, J. M.; et al. Contribution of fertilizer nitrogen to the total nitrogen extracted by sugarcane under Brazilian field conditions. **Nutrient Cycling in Agroecosystems**, v. 101, p. 241–257, 2015.

VIRK, S. S.; MULLENIX, D. K.; SHARDA, A.; et al. Case study: distribution uniformity of a blended fertilizer applied using a variable-rate spinner-disc spreader. **Applied Engineering in Agriculture**, v. 29, n. 5, p. 627–636, 2013.

VITTI, A. C.; TRIVELIN, P. C. O.; GAVA, G. J. C.; et al. Sugar cane yield related to the residual nitrogen from fertilization and the root system. **Pesquisa Agropecuaria Brasileira**, v. 42, n. 2, p. 249–256, 2007.

WOMAC, A. R.; TOMPKINS, F. D. Probe-type injector for fluid fertilizers. **Agricultural Engineering**, v. 6, n. March, p. 149–154, 1990.

YANG, C. A variable rate applicator for controlling rates of two liquid fertilizers. **Applied Engineering in Agriculture**, v. 17, n. 3, p. 409–417, 2001.

ZAMYKAL, D.; EVERINGHAM, Y. L. Quantifying variability is only half the story - a review. In: E. Lichtfouse (Ed.); **Sugarcane and Precision Agriculture**. 1st ed., p.189–218, 2009. Dordrecht: Springer Netherlands.

CAPÍTULO III

3 LIQUID FERTILIZER APPLICATION TO RATOON CANE USING A SOIL PUNCHING METHOD

SILVA, M. J.; FRANCO, H. C. J.; MAGALHÃES, P. S. G. Liquid fertilizer application to ratoon cane using a soil punching method. **Soil & Tillage Research**, 165, p. 279–285. 2017. doi:10.1016/j.still.2016.08.020

ABSTRACT - Sugarcane is a semi-perennial crop that is cultivated for five or six harvest cycles before replanting. Following annual mechanized harvest, nitrogen (N) fertilizer is commonly applied during the ratoon cane sprouting phase through furrows along the side of plant rows (subsurface application) or banded on the surface. With subsurface application, mechanical operations are hampered by the trash coverage that remains after harvest; furthermore, opening furrows can partially damage roots. However, with soil surface application, nutrient uptake efficiency is decreased as a result of microbial immobilization and losses through ammonia volatilization and runoff. Thus, to achieve subsurface application for ratoon cane with minimal mobilization of the system (soil, straw and roots), this work aimed to (i) develop and evaluate a mechanical prototype that enables a soil punching process in ratoon cane and (ii) evaluate the cane yield using the soil punching method for liquid N fertilizer injection compared to liquid N fertilizer applied alongside of plant rows on the surface and subsurface (through furrows). To evaluate the punching mechanism, we performed a kinematic simulation (puncher tip displacement and injection time interval), tests in a soil bin and ratoon cane field. Based on prototype operations, the average distance between applications was 300 mm, with an average depth up to 90 mm, which was similar to the design requirements. Regarding results of liquid N fertilization methods in a ratoon cane field, we found that the incorporation treatments (soil punching and subsurface application through furrows) achieved slightly better cane yield (98-96 Mg ha^{-1}) when compared to the surface application (91 Mg ha^{-1}) and control treatment (75 Mg ha^{-1}). In general, the soil punching was considered as a promising alternative method for supplying liquid fertilizer at the subsurface using low-energy power (approximately 745 W) with minimal environmental impact.

keywords – precision agriculture, sugarcane, fertilizer application, deep placement, prototype design

3.1 INTRODUCTION

Sugarcane is the most promising source for ethanol and sugar production. Currently, Brazil is the largest sugarcane producer, with 688 million Mg cultivated on 9.8 million hectares (IBGE, 2015). Recently, the harvesting model of burning (to facilitate mechanical or manual harvest) has been replaced by mechanical green cane harvesting due to several environmental advantages, such as soil moisture maintenance, nutrient recycling, weed reduction (MARCHI et al., 2005), legal issues (GESP, 2007) and lower labour intensive. However, fertilizer incorporation into the soil is hampered by the significant amount of trash coverage (mainly, dry leaves and tops) left on the soil surface after harvest (CANTARELLA et al., 2008; VIEIRA-MEGDA et al., 2015). In São Paulo (the largest cane-producing state in Brazil), studies performed after cane harvest have reported trash amounts ranging from 10 up to 20 Mg ha^{-1} (VITTI et al., 2007; FORTES et al., 2012)

During sprouting and growth, which occurs after the annual cane harvest, nitrogen (N) is required in greater amount. In general, N is the most difficult nutrient to manage in sugarcane fertilization because of interactions with soil organic matter (SOM) and potential losses in the soil-plant system (CANTARELLA and ROSSETTO, 2010; FRANCO et al., 2010; THORBURN et al., 2011). In Brazil, the most common methods for N fertilization in ratoon cane utilize granular sources applied along the side of plant rows through furrows (subsurface application) or banded on the surface. However, N fertilizer applied on the surface without incorporation may increase N loss due to ammonia (NH_3) volatilization (RODRIGUES and KIEHL, 1986; CABEZAS et aL., 2000; PRASERTSAK et al., 2002), especially when urea, uran, aqua ammonia or anhydrous ammonia is used (losses can be up to ~40%, Costa et al., 2003). This process is mainly caused by an enzyme present in the sugarcane straw (urease activity). The fertilizer incorporation into the subsurface can reduce volatilization (especially when urea is used), though fertilizer incorporation by means of furrows may have low efficiency and high costs (MARIANO et al., 2012).

In general, surface application has advantages such as effective capacity for the field operation (hectares per hour); however, losses to the environment are more likely, contributing to less effective fertilizer uptake by the crop. On the other hand, site-specific management and incorporation of fertilizer into the subsurface can contribute to reducing the environmental impact, and supplying fertilizer near the roots to facilitate uptake. Within this context, liquid fertilizer injection into the subsurface represents an alternative strategy due to some favourable advantages for site-specific management, such as better control of application uniformity and the required dose, lower nutrient segregation (BOARETTO et al., 1991; KORNDÖRFER et al., 1995; PIO et al., 2008).

Liquid injection can be achieved by means of a punching process through the straw layer and soil subsurface using a probe, with minimal mobilization (soil and straw) without damage to the ratoon cane roots. Some mechanical equipment with a similar approach for liquid fertilizer injection can be found in Baker et al. (1989), Womac and Tompkins (1990), Chen (2002), Johann et al. (2006), Lang et al., (2011); Liu et al., (2011b); Nyord et al., (2008) and Wang et al. (2011) and Niemoeller et al. (2011). However, such equipment was developed to assist liquid fertilizer injection by considering the intrinsic characteristics of the crops in those studies (maize and rice).

In recent years, studies aimed at improving ratoon cane fertilization have mainly focused on evaluations of N fertilizer rates (VITTI et al., 2007A; CANTARELLA et al., 2008; FRANCO et al., 2010; FRANCO et al., 2011; MARIANO et al., 2012; OTTO et al., 2014) and N sources (COSTA et al., 2003; VITTI et al., 2007b; CANTARELLA et al., 2008; NASCIMENTO et al., 2013; VIEIRA-MEGDA et al., 2015). In contrast, studies about N fertilizer application methods are less common (PRASERTSAK et al., 2002; VITTI et al., 2007), even though decisions about the application method are crucial to fertilizer uptake efficiency. Fertilization improvements can be reasoned with regard to reducing loss to the environment in combination with greater uptake. Thus, application method can contribute to site-specific management when combined with other techniques, such as variable rate application, timing (application during the appropriate plant growth stage, i.e., when the fertilizer is most crucial) and splitting application (more applications throughout the crop cycle).

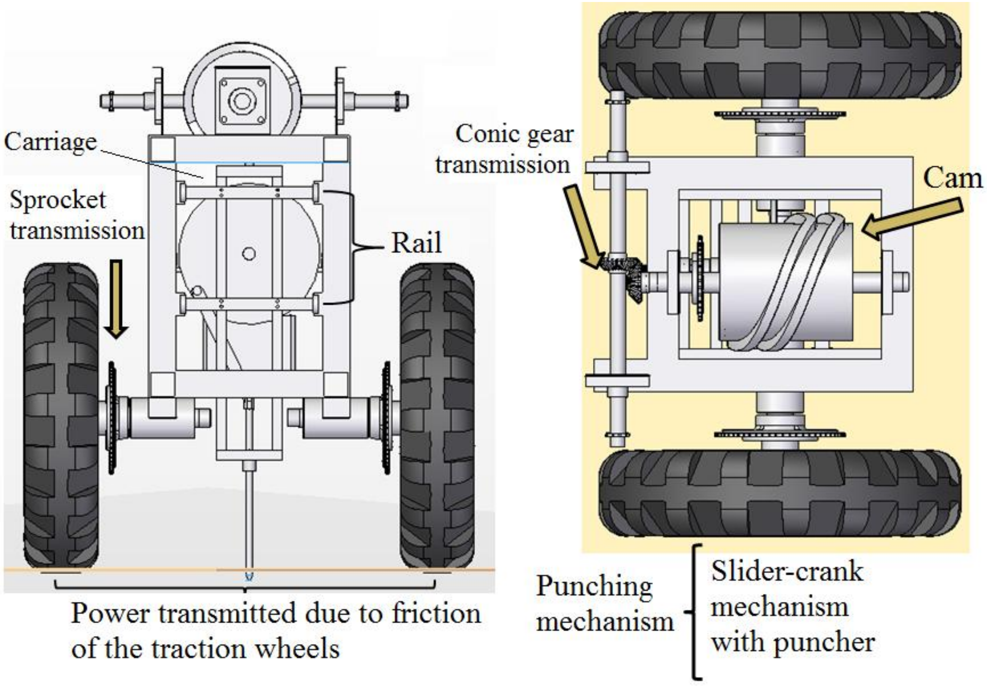
Liquid fertilizer application at the subsurface by means of minimal mobilization (soil, straw layer, roots) can be an alternative to supply fertilizer near the cane roots, contributing to loss reductions and fertilizer uptake increases. In an effort to achieve subsurface application with minimal mobilization, this work aimed to (i) develop and evaluate a mechanical prototype that enables a soil punching process in ratoon cane and (ii) evaluate the cane yield using the soil punching method for liquid N fertilizer injection compared to liquid N fertilizer applied alongside of plant rows on the surface and subsurface (through furrows).

3.2 MATERIAL AND METHODS

3.2.1 Working principle

For prototype design, the requirements were subsurface application without tillage, through vertical soil punching (100 mm deep) with equidistant points of application (300 mm apart). The major components of the proposed mechanical system for vertical soil punching included a rotating drum cam, carriage, spline shaft, and slider-crank mechanism with a puncher (Figure 7). The rotating drum cam was designed to drive the carriage along alternative movements in a longitudinal direction at the same forward speed. The slider-crank mechanism, which drives the punching mechanism for soil penetration was assembled on the carriage. The traction wheels were used to provide mechanical power, with synchronism conducted by a power transmission (sprockets, gears and spline shaft). Essentially, the working principle consists of punching mechanism synchronism related to the forward speed.

Figure 7 – Layout of the prototype



During soil punching, the longitudinal movement of the carriage cancels out the relative velocity opposing the forward speed, and the slider-crank drives the puncher tip vertically into the soil. In summary, the main kinematic characteristics for a punching cycle are as follows: (i) zero linear displacement during vertical soil punching; (ii) twofold linear velocity when the puncher tip is driven above the ground to the next soil punch. The period of cycle (T [s]) was determined according to the distance between equidistant soil punching points (s [m]) relative to the forward speed ($\dot{x}$ [m s^{-1}]), enabling calculation of the mechanism's angular velocity ($\dot{\omega}$ [rad s^{-1}]). To assist in the design, construction and comprehension of the soil punching mechanism, we performed a kinematic analysis by means of the Newton-Euler method. The characteristics verified in this analysis were the displacement of puncher tip and the injection time. For this, we carried out the simulation analysis using Matlab R2010a (The Mathworks, Inc. Natick, MA). Following construction and evaluations, we registered the product (Patent BR 102013018213 - Magalhães and Silva, 2013).

3.2.2 Evaluation methodology

3.2.3 Mechanical process of soil punching

First tests were conducted in a soil bin, where soil is free of organic material and stones, providing homogeneous soil conditions. This soil was originated from an arable Oxisol soil layer located in southern Brazil. According to the USDA textural triangle, it was classified as sandy clay loam (Table 1). Currently, approximately 60% of sugarcane in the South-Central Region of Brazil is planted in this soil type (MAGALHÃES et al., 2012). In summary, the soil bin is 12 m long, 2 m wide and 1 m deep, being composed of a common carriage to support prototypes, soil processing equipment, a hydrostatic power transmission unit and instrumentation access. The soil processing equipment consisted of a frame to carry the levelling blade, roller for soil compaction and a water sprayer for manipulating the soil moisture, which was held constant at 13% to within 1% during the tests. The soil layer prepared for tests were approximately 200 mm (methodology described in Magalhães et al., 2007).

Table 1 – Soil physical properties

Soil type	Oxisols
Soil texture	Sandy clay loan
Maximum dry bulk density (kg m^{-3}) @ 14.5±0.12% (w/w)	1720
Clay <0.002 mm (g kg^{-1})	332.5±2.4
Sand 2 – 0.2 mm (g kg^{-1})	377.0±1.6
Sand 0.2 – 0.053 mm (g kg^{-1})	180.0±2.9
Silt 0.053 – 0.002 mm (g kg^{-1})	110.5±2.1
Cohesion (kPa)	216.2±0.7
Internal frictional angle (degree)	54.7±1.1

Three tests were performed at the soil bin with a forward speed of 0.7 m s^{-1} (mechanism angular velocity 14 rad s^{-1}). Based on these tests, we estimated the power required for the soil punching mechanism as a function of reaction force measured using a load cell (Vincere do Brasil, model ST 2500 N, Campinas, Brazil) attached in the puncher axis. Data acquisition was performed using "Spider Module" (HBM Inc., Spider8®, Darmstadt, Germany) at a sampling frequency of 100 Hz. The computer interface with the data acquisition system (DAQ) was performed with Catman Easy (HBM Inc., version 3.3.5 ®, Darmstadt, Germany). The penetration resistance was measured using an electronic penetrometer (PLG5200-SoloTrack, Falker©, São Geraldo, Brazil) according to the recommendations of ASABE (2009). After each test, the minimal soil disturbance of the soil punching was evaluated by measuring depths and distances using a calliper and a tape measure, respectively.

In addition, the soil punching operation was tested in a ratoon cane field (Figure 8) located at College of Agriculture Engineering of the University of Campinas (22 ° 48’ 57” S, 47 ° 3’ 33” W). According to EMBRAPA (2006), the local soil is classified as a Red Latosol (Hapludox). For evaluation, two tests were performed using a forward speed of 0.8 m s^{-1} (16 rad s^{-1} mechanism angular velocity) along 20 m. After each test, we measured depths and distances using a calliper and a tape measure. For both evaluations, the results were analysed using descriptive statistics (e.g., averages, standard deviation, maximum and minimal values).

Figure 8 – Prototype constructed

3.2.4 Liquid nitrogen applied in the ratoon cane field: the soil punching method

To evaluate the effect of the soil punching method on the sugar cane yield, an experiment was performed at the first ratoon cane cycle (RB855156 variety), 10 days after mechanical green harvest in a commercial field (Iracema mill: 22.75º S and 47.43º W - Iracemapolis-São Paulo, Brazil). The soil was classified as Rhodic Eutrudox according to Soil Taxonomy (Soil Survey Staff, 2010) with a clay texture (52% of clay, 37.25% of sand and 10.72% of silt) according to the USDA texture triangle. Liquid fertilizer was applied in the fall season (May 2014), which is characterized by lower temperatures and rainfall. N fertilization was supplied by ammonium nitrate mixed with water (concentration of 0.21 kg L^{-1} N) at a rate of 100 kg ha^{-1} of N, an average agronomic recommendation applied to ratoon cane in Sao Paulo State (RAIJ et al., 1997; PRADO and PANCELLI, 2006). This N source exhibits low losses regard to ammonia volatilization (less than 3% according to Vitti et al., 2007b and Nascimento et al., 2013), a characteristic favourable for comparing the real effect of the application method on the stalk yield.

The experiment was conducted with six treatments randomly distributed among four blocks (24 plots). The treatments were as follows: surface application (1-SA); continuous incorporated application (2-CA); control (without fertilizer, 3-Ct); and soil punching applications distanced every 150 mm (4-PA150), 300 mm (5-PA300), and 450 mm (6-PA450). Each plot was 10 m wide (seven cane rows with an inter-row spacing of 1.5 m) and 15 m long.

To carry out the continuous application method (2-CA), a narrow furrow was dug (~100 mm deep) approximately 200 mm away from a row, and liquid fertilizer was uniformly sprinkled in the furrow; next, the furrow was filled and covered using soil and trash. For surface application (1-SA), liquid fertilizer was applied in a ~50 mm-wide band along the cane row. For soil punching treatments (PA), the drillings were performed parallel to the cane row (~200 mm away), at 100 mm deep, and liquid fertilizer was then injected into the holes (15 mm diameter), which were filled with soil. The liquid volume (D [mL $injection^{-1}$]) was determined according to the agronomic recommendation (T_x [kg ha^{-1} of N]) converted to a volumetric application rate (V [L ha^{-1}]). This conversion was also performed in accordance with the nutrient concentration (C [kg L^{-1}]), distance between applications (s [m]) and inter-row spacing (e [m]), as follows:

$$V = \frac{T_x}{C} \quad \rightarrow D = \frac{(e).(s).(V)}{10^4} * 10^3 \tag{1}$$

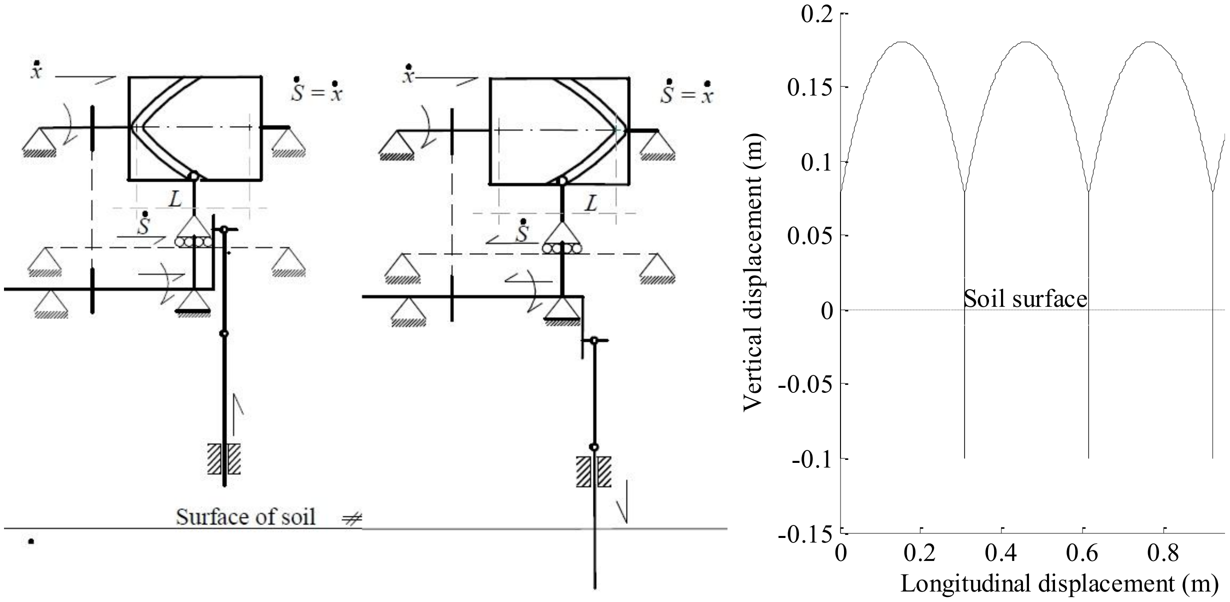
To measure the stalk cane yield, at approximately one year after N fertilization (May 2015), the sugarcane was harvested using a mechanical green harvester accompanied with a cane truck-loading instrument with load cells. We measured the cane mass in the three centre rows of plots. The results were analysed by Matlab using multi-comparison of means with Tukey’s test at 5% significance. Also, the results were analysed using descriptive statistics.

3.3 RESULTS AND DISCUSSION

3.3.1 Kinematic characteristics of soil punching

Kinematic simulation analysis was essential for designing and predicting operational characteristics. This analysis examined the displacement of the puncher tip during soil punching (Figure 9). First, the puncher tip movement was represented above the ground, when drum cam drives the carriage in the same direction of forward speed. This interval reflects the distance between applications (300 mm), an average distance between ratoons. In the next phase, the drum cam drives the carriage in the direction opposite to the forward speed; during this stage, the relative longitudinal movement related to soil is cancelled to perform the vertical soil punching (up to 100 mm). The vertical movement helps protect against dragging and consequently permanent deformation of the puncher.

Figure 9 – Representation of the puncher displacement

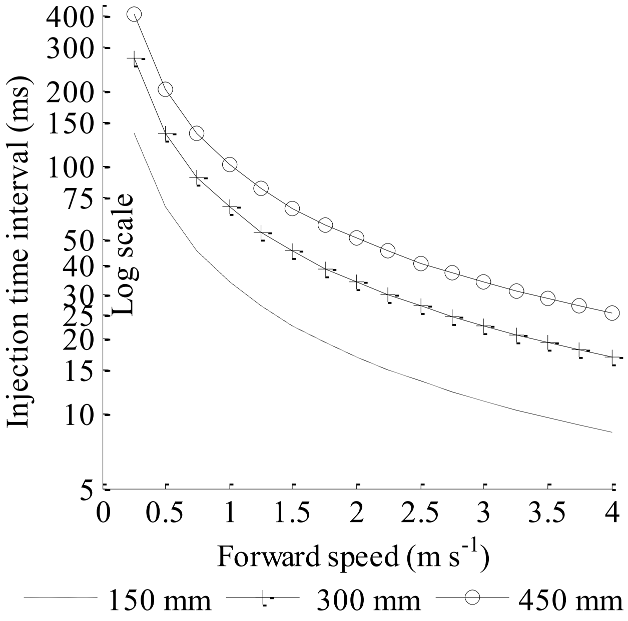


(a) (b)

Regarding the soil punching process, knowledge about injection time is essential for determining the flow and pressure in the hydraulic system. Injection time was defined as an interval where the soil is perforated between 50 and 100 mm. This range depth was considered sufficient to decrease losses due to ammonia volatilization (RODRIGUES and KIEHL, 1986; PRASERTSAK et al., 2002). In addition, sugarcane active roots are more concentrated close to the surface at a depth of ~100 mm (AZEVEDO et al., 2011; SOUSA et al., 2013; OTTO et al., 2014) and near the cane row (OTTO et al., 2009).

Based on simulation, it was observed that available injection time is influenced by the distance between applications and forward speed. Also, the simulation indicated that available injection time decreases on a logarithmic scale according to the increase in forward speed, requiring a greater capacity of the hydraulic-mechanical system for liquid fertilizer injection (Figure 10). However, the average liquid fertilizer flow as a function of the forward speed was considered low (3 to 12 L min^{-1}) due to the small dose applied per cycle (5 to 20 mL) of soil punching.

Figure 10 – Simulation of the injection time



3.3.2 Evaluation of the mechanical process of soil punching

For evaluation performed in the sugarcane field, average distance between applications was 320 mm, with an average depth of 60 mm (Table 2). This distance was greater than that specified (300 mm), largely due to a loss of traction on wheels, which led to a reduction in synchronization. Furthermore, the shallower depth with respect to the specification (100 mm) was attributed to irregularities on the surface caused by previous mechanization and the straw layer (average thickness 46 mm). Regarding the soil bin evaluation, the results were similar to those specified; particularly due to better control the soil conditions, including the soil surface uniformity and penetration resistance. Overall, the process caused minimal soil mobilization, only at the points of application, whereby perforations were performed according to the puncher format (soil structure deformation).

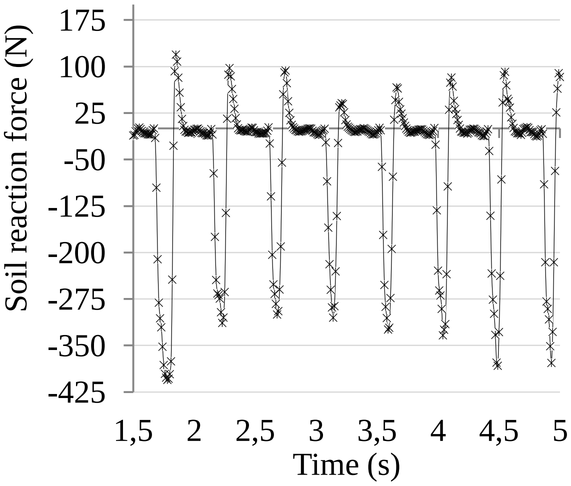
Table 2 – Evaluation of the mechanism

	Soil bin			Field cane area	
Distance (mm)	302	310	306	330	312
$\bar{S}$ (mm)	0.7	1.2	0.9	4.3	9
c.v. (%)	2.2	3.8	2.9	4.3	9
Depth (mm)	92	95	96	63	54
$\bar{S}$ (mm)	6.1	6.4	5.5	11	14
c.v. (%)	6.7	6.7	5.8	17	25

$\bar{S}$ – Standard deviation; c.v. – coefficient of variation.

During the soil punching, penetration soil resistance represents the principal load. For the soil bin tests, the maximum compressive force was 350 N (Figure 11). The compressive reaction force was proportional to the soil punching depth; it was also influenced by the variations in penetration resistance. In addition, a normal traction force (maximum load of 75 N) was caused by the relative movement into the soil (Figure 11). In general, reaction force was primarily influenced by the physical properties, including soil compaction, which can be evaluated via penetration resistance. The average soil resistance in soil bin tests were approximately 1.5 MPa. However, penetration resistance in the ratoon cane fields generally achieve higher values. At depth range established for liquid fertilizer injection (50 to 100 mm deep), Roque et al. (2010) reported an average resistance of 1.9 MPa (17% moisture) and Braunack et al. (2006) reported 1.2 to 2.0 MPa. Further, penetration resistance in ratoon cane fields can be much higher due to machinery traffic, soil moisture, and soil physical characteristics. These approach can be confirmed by the results of Souza et al. (2014), who observed a penetration resistance of 5 MPa (17% soil moisture) in the topsoil of a ratoon cane field.

Figure 11 – Soil reaction force

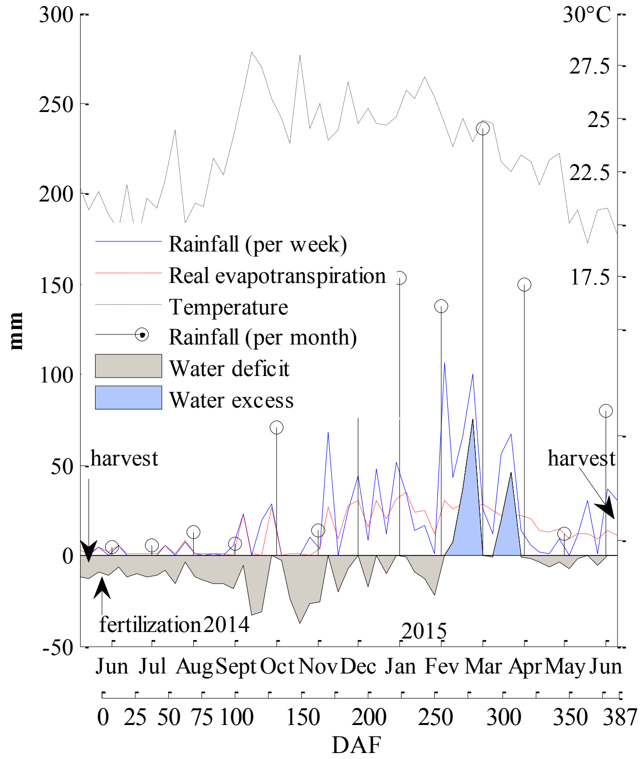


In the soil punching process, reaction force can be used as a reference for sizing and specifications of the mechanical system, such as the probe injector (inner and outer diameter). Considering the interactions between the soil and probe, a smaller outer diameter facilitates the soil punching process (smaller resistance to penetration); however, it also increases the slenderness ratio, which increases the rod's susceptibility to permanent deformation caused by the bending moment generated on axial compression. In addition, the measured strength was used to estimate the power required for soil punching. Thus, considering the forward velocity (0.7 m s^{-1}) and angular velocity of the punching mechanism (13.6 rad s^{-1}), the maximum power required for soil punching was estimated at 743 W; this demand was considered low, because agricultural tractors generally provide greater power in the drawbar, hydraulic oil system, and power take off (PTO).

3.3.3 N fertilization in a ratoon cane field: the soil punching method

After harvest, ratoon canes require approximately one year to complete the crop cycle (sprouting, growth, and maturation), and during this period, weather-related conditions have an influence on growth and consequently on the stalk cane yield. Optimal sugarcane growth occurs at a temperature range of 22 to 30°C and a water demand of ~1400 mm per year (EMBRAPA, 2015). During the N fertilization experiment (2014/2015 season, Figure 12), the local rainfall totalled 941 mm (52% concentrated in summer); this precipitation was considered insufficient because it was less than the total required by sugarcane (30% lower). Furthermore, a critical situation occurred after N fertilization during sprouting and growth, producing a soil water deficit and low evapotranspiration (near to zero). In general, these conditions were not favourable for sugarcane.

Figure 12 – Annual water balance



Fonte: CIIAGRO (2015)

The cane harvesting was performed at one year after N fertilization (May 2015). The results revealing that strategies for N fertilizer application can modify the sugarcane yield. In general, best results were obtained with fertilizer-incorporation treatments (Table 3). Furthermore, when N fertilizer was drilled into the soil (PA300, PA150 and CA), an increase in yield (96 to 98 Mg ha^{-1}) was observed relative to surface application (91 Mg ha^{-1}) and control treatment (75 Mg ha^{-1}). This effectiveness of subsurface application compared to surface application was also observed in research conducted by Prasertsak et al. (2002) in a 1st ratoon cane field located in Queensland (AUS) using ^{15}N-labelled urea under favourable rainfall conditions (50 mm accumulated up to 12 days after fertilization and 3770 mm accumulated over the cycle). Towards the end of the cane cycle (334 days after fertilization), the authors measured the total N-fertilizer in the trash-soil-plant system and found that N recovery was higher to incorporated application (54.4% of the applied N) when compared to surface application (40.9% of the applied N). This difference was attributed to losses (ammonia volatilization, runoff, leaching and denitrification).

Table 3 – Evaluation of sugarcane stalk yield

	Cane stalk yield (Mg ha^{-1})				
Treatments	Average	max	min	S	cv (%)
PA300	98 a	124	71	14	14
PA150	96 a	124	67	19	20
CA	96 a	120	71	15	15
SA	91 ab	111	67	14	16
PA450	87 ab	102	62	12	13
Ct	75 b	93	44	12	16

Values followed by the same letter within a column (treatments) do not differ according to the Tukey test at $p < 0.05$; least significant difference (LSD) equals 21 Mg ha^{-1}; and the F value was 2.97.

In our study, the PA450 treatment (distanced each 450 mm) achieved a lower cane yield (87 Mg ha^{-1}) when compared to PA300 and PA150 treatment. The greater distance between applications was attributed as a limiting factor for supplying nutrient. Considering this, applications at 150 mm intervals (PA150) was favour for fertilizer distribution; nonetheless, applications distanced at 300 mm (PA300) resulted in an equivalent cane yield. A similar approach to the fertilizer application in a rice paddy field was evaluated by Liu et al. (2015) using a semi-automatic device to “the point deep placement of N fertilizer” (soil punching). Based on results, the authors also confirmed some advantages to the application method (NH_3 volatilization decreased by 20–45%, mean floodwater pH decreased by 2–4%, mean floodwater NH_4^+-N concentration decreased by 29–98% and grain yield increased by 5–11%) when compared to the application on surface (broadcasting). In addition, authors highlighted an importance of developing fertilizer application machines to overcome this difficulty of incorporated fertilizers using “the point deep placement method”.

3.4 CONCLUSIONS

The mechanical system described here for soil punching liquid fertilizer in the subsurface is a promising alternative to existing surface application, with minimal mobilization of the soil-plant system (soil, roots and straw). In general, the results of soil punching tests were considered satisfactory because of depths and distances of applications were comprised in requirements of the operation (vertical soil punching with subsurface application distanced each 300 mm). However, the depths achieved in soil bin tests (average of 92 to 96 mm) were greater than those achieved in the cane field tests (average of 54 to 63 mm) due to micro-relief variations at the soil surface and straw layer thickness (approximately 46 mm). Based on evaluation analysis, we conclude that the key parameters for soil punching are as follows: soil penetration resistance, injection time according to the forward speed, application depth influenced by soil micro-relief and distance between applications influenced by synchronism of the mechanism velocity related to the forward speed.

Overall, fertilizer application improvement can be based on reducing losses to the environment combined with greater fertilizer uptake. Considering this, we confirm that soil punch application or continuous incorporated application attained better results with regard to stalk cane yield (96-98 Mg ha^{-1}) when compared to surface application (91 Mg ha^{-1}) or control treatment (75 Mg ha^{-1}). In addition, about the cane yield results, it was possible to observe that small distances between applications (represented by treatments PA150 and PA300) were more favourable for N fertilizer uptake when compared to a large distance (PA450).

3.5 REFERENCES

ASABE. **Standard - Procedures for Using and Reporting Data Obtained with the Soil Cone Penetrometer. ASAE EP542 FEB1999 (R2009)**. St. Joseph, Mich., 2009.

AZEVEDO, M. C. B. DE; CHOPART, J. L.; MEDINA, C. D. C. Sugarcane root length density and distribution from root intersection counting on a trench-profile. **Scientia Agricola**, v. 68, n. February, p. 94–101, 2011.

BAKER, J. L.; COLVIN, T. S.; MARLEY, S. J.; DAWELBEIT, M. A point-injector applicator to improve fertilizer management. **Appl. Eng. Agric**, v. 5, p. 334–338, 1989.

BOARETTO, A. E.; CRUZ, A. P.; LUZ, P. H. C. **Adubo líquido: produção e uso no Brasil**. 1st ed. Campinas: Fundação Cargil, 1991.

BRAUNACK, M. V.; ARVIDSSON, J.; HÅKANSSON, I. Effect of harvest traffic position on soil conditions and sugarcane (Saccharum officinarum) response to environmental conditions in Queensland, Australia. **Soil and Tillage Research**, v. 89, n. 1, p. 103–121, 2006.

CANTARELLA, H.; ROSSETTO, R. Fertilizers for sugarcane. In: L. A. B. Cortez (Ed.); **Sugarcane bioethanol R&D for productivity and Sustainability**. First ed., p.405–422, 2010. São Paulo: Blucher & Fapesp.

CANTARELLA, H.; TRIVELIN, P. C. O.; CONTIN, T. L. M.; et al. Ammonia volatilisation from urease inhibitor-treated urea applied to sugarcane trash blankets. **Scientia Agricola**, v. 65, n. August, p. 397–401, 2008.

CHEN, Y. . Liquid manure injection tool adapted to different soil conditions. **Transactions of the ASAE**, v. 45, n. 6, p. 1729–1736, 2002.

CIIAGRO. Integrated Center of agrometeorological information: water balance. Disponível em: <http://www.ciiagro.sp.gov.br/ciiagroonline/Listagens/BH/LBalancoHidricoLocal.asp>. Acesso em: 1/1/2015.

COSTA, M. C. G.; VITTI, G. C.; CANTARELLA, H. N-NH3 losses from nitrogen sources applied over unburned sugarcane straw. **Revista Brasileira de Ciência do Solo**, v. 27, n. 4, p. 631–637, 2003.

EMBRAPA. Empresa Brasileira de Pesquisa Agropecuária **- Centro Nacional de Pesquisa de Solos Sistema Brasileiro de classificação de solos**. 2nd ed. Rio de Janeiro, 2006.

EMBRAPA. **Brazilian agricultural research corporation**: Embrapa's technological information agency. Disponível em: <http://www.agencia.cnptia.embrapa.br/gestor/cana-de-acucar/arvore/CONTAG01_10_711200516716.html>. Acesso em: 6/1/2015.

FORTES, C.; TRIVELIN, P. C. O.; VITTI, A. C. Long-term decomposition of sugarcane harvest residues in Sao Paulo state, Brazil. **Biomass and Bioenergy**, v. 42, p. 189–198, 2012. Elsevier Ltd.

FRANCO, H. C. J.; OTTO, R.; FARONI, C. E.; et al. Nitrogen in sugarcane derived from fertilizer under Brazilian field conditions. **Field Crops Research**, v. 121, n. 1, p. 29–41, 2011.

FRANCO, H. C. J.; TRIVELIN, P. C. O.; FARONI, C. E.; VITTI, A. C.; OTTO, R. Stalk yield and technological attributes of planted cane as related to nitrogen fertilization. **Scientia Agricola**, v. 67, n. 5, p. 579–590, 2010.

GESP - SECRETARIA DO ESTADO DO MEIO AMBIENTE. **Protocolo Agroambiental**. São Paulo, 2007.

IBGE. **Instituto Brasileiro de Geografia e Estatística** - Levantamento sistemático da produção agrícola. Confronto das Safras de 2014 e das Estimativas para 2015 – Brasil. Disponível em: <http://www.ibge.gov.br/home/estatistica/indicadores/agropecuaria/lspa/lspa_201504_5.shtm>. Acesso em: 26/5/2015.

JOHANN, A. L.; RUSSO, E.; CAPPELLI, N. L.; UMEZU, C. K. Development and evaluation of a low cost servo-valve for liquid inputs application. **Engenharia Agrícola**, v. 26, n. 1, p. 142–150, 2006.

KORNDÖRFER, G. H.; ANDERSON, D. L.; MUNDIM, V. C.; SIMÕES, M. S. Produção de adubos fluidos para cana-de-açúcar. **Revista STAB**, v. 14, n. 2, p. 25–29, 1995.

LANG, C.; WANG, J.; SHI, Y.; XI, X. Design and Development Control System for Deep-Fertilization Variable Liquid Fertilizer Applicator. **2011 Second International Conference on Digital Manufacturing & Automation**, p. 369–372, 2011. Ieee.

LARA CABEZAS, W. A. R.; TRIVELIN, P. C. O.; KONDÖRFER, G. H.; PEREIRA, S. Nitrogen Balance of solid and liquid nitrogen sources on side-dressed no-till corn system at triângulo mineiro (MG). **R. Bras. Ci. Solo Bras**, v. 24, p. 363–376, 2000.

LIU, T. Q.; FAN, D. J.; ZHANG, X. X.; et al. Deep placement of nitrogen fertilizers reduces ammonia volatilization and increases nitrogen utilization efficiency in no-tillage paddy fields in central China. **Field Crops Research**, v. 184, p. 80–90, 2015.

LIU, Y.; WANG, J. J.; WANG, J. J.; GE, Y. Optimal Design and Analysis on Pricking Hole Mechanism with Planetary Elliptic Gears for Deep-Fertilization Liquid Fertilizer Applicator. **2011 Second International Conference on Digital Manufacturing & Automation**, p. 809–812, 2011. Ieee.

MAGALHÃES, P. S. G.; BIANCHINI, A.; BRAUNBECK, O. A. Simulated and Experimental Analyses of a Toothed Rolling Coulter for Cutting Crop Residues. **Biosystems Engineering**, v. 96, p. 193–200, 2007.

MAGALHÃES, P. S. G.; NOGUEIRA, L. A. H.; CANTARELLA, H.; et al. Agro-industrial technological paths. In: M. K. Poppe; L. A. B. Cortez (Eds.); **Sustainability of Sugarcane bioenergy**. First ed., v. 1, p.27–71, 2012. Brasilia, DF: Center of Strategic Studies and Management (CGEE).

MAGALHÃES, P. S. G.; SILVA, M. J. Equipamento com princípio de puncionamento para aplicação localizada de adubo líquido em profundidade. Patent BR 1020130182133. 2013.

MARCHI, A. S.; ROCHA, A. A. S. P. D. E. DA; SILVA, J. E. A. R. DA. Unburned cane harvesting with trash recovery routes. In: S. J. Hassuani; M. R. L. Verde Leal; I. C. I. de C. Macedo (Eds.); **Biomass power generation, Sugar cane bagasse and trash**. p.65–69, 2005. Piracicaba, SP: PNUD Brasil.

MARIANO, E.; TRIVELIN, P. C. O.; VIEIRA, M. X.; et al. Ammonia losses estimated by an open collector from urea applied to sugarcane straw. **Revista Brasileira de Ciência do Solo**, v. 36, n. 1, p. 411–419, 2012.

NASCIMENTO, C. A. C. DO; VITTI, G. C.; FARIA, L. D. A.; LUZ, P. H. D. C.; MENDES, F. L. Ammonia volatilization from coated urea forms. **Revista Brasileira de Ciência do Solo**, v. 37, n. 1, p. 1057–1063, 2013.

NIEMOELLER, B.; HARMS, H. H.; LANG, T. Injection of liquids into the soil with a high-pressure jet. **Agricultural Engineering International: CIGR Journal**, v. 13, n. 2, p. 1–15, 2011.

NYORD, T.; SØGAARD, H. T.; HANSEN, M. N.; JENSEN, L. S. Injection methods to reduce ammonia emission from volatile liquid fertilisers applied to growing crops. **Biosystems Engineering**, v. 100, n. 2, p. 235–244, 2008.

OTTO, R.; COUTINHO, H.; FRANCO, J.; et al. The Role of Nitrogen Fertilizers in Sugarcane Root Biomass under Field Conditions. **Agricultural Sciences**, v. 5, p. 1527–1538, 2014.

OTTO, R.; FRANCO, H. C. .; FARONI, C. E.; VITTI, A. C.; TRIVELIN, P. C. O. Fitomassa de raízes e da parte aérea da cana-de-açúcar relacionada à adubação nitrogenada de plantio. **Pesquisa Agropecuaria Brasileira**, v. 44, n. 1, p. 398–405, 2009.

PIO, L. C.; ABDALLA, S. R. S.; PROCHNOW, L. Panorama atual do setor de fertilizantes fluidos e foliares: equipamentos e tecnologia de aplicação para fertilizantes fluidos. **International Plant Nutrition Institute**, v. 123, p. 15–16, 2008.

PRADO, R. M.; PANCELLI, M. A. Nutrição nitrogenada em soqueiras e a qualidade tecnológica da cana-de-Açúcar. **STAB**, v. 25, n. 2, p. 60–63, 2006.

PRASERTSAK, P.; FRENEY, J. R.; DENMEAD, O. T.; SAFFIGNA, P. G.; PROVE, B. G. Effect of fertilizer placement on nitrogen loss from sugarcane in tropical Queensland. **Nutrient Cycling in Agroecosystems**, v. 62, n. 3, p. 229–239, 2002.

RAIJ, B. VAN.; CANTARELLA, H.; QUAGGIO, J. A.; A. M. C. FURLANI. **Recomendações de adubação e calagem para o Estado de São Paulo. Campinas**. Campinas: Instituto Agronômico; Fundação IAC., 1997.

RODRIGUES, M. B.; KIEHL, J. C. Volatilização de amônia após emprego da ureia em diferentes doses e modos de aplicação. **Rev. Bras. Ciência do Solo**, v. 10, p. 37–43, 1986.

ROQUE, A. A. O.; SOUZA, Z, M.; BARBOSA, R. S.; SOUZA, G. S. Controle de tráfego agrícola e atributos físicos do solo em área cultivada com cana - de - açúcar. **Pesquisa Agropecuaria Brasileira**, v. 45, n. 7, p. 744–750, 2010.

SOIL SURVEY STAFF. **Keys to Soil Taxonomy**. 11th ed. Washington: USDA- Natural Resources Conservation Service, 2010.

SOUSA, A. C. M.; MATSURA, E. E.; ELAIUY, M. L. C.; et al. Root system distribution of sugarcane irrigated with domestic sewage effluent application by subsurface drip system. **Engenharia Agrícola**, v. 33, n. 4, p. 647–657, 2013.

SOUZA, G. S.; SOUZA, Z. M.; SILVA, R. B.; BARBOSA, R. S.; ARAÚJO, F. S. Effects of traffic control on the soil physical quality and the cultivation of sugarcane. **R. Bras. Ci. Solo Bras**, v. 38, p. 135–146, 2014.

THORBURN, P. J. J.; BIGGS, J. S. S.; WEBSTER, A. J. J.; BIGGS, I. M. M. An improved way to determine nitrogen fertiliser requirements of sugarcane crops to meet global environmental challenges. **Plant and Soil**, v. 339, n. 1, p. 51–67, 2011.

VIEIRA-MEGDA, M. X.; MARIANO, E.; LEITE, J. M.; et al. Contribution of fertilizer nitrogen to the total nitrogen extracted by sugarcane under Brazilian field conditions. **Nutrient Cycling in Agroecosystems**, v. 101, p. 241–257, 2015.

VITTI, A. C.; TRIVELIN, P. C. O.; GAVA, G. J. C.; FRANCO, H. C. J.; et al. Produtividade da cana-de-açúcar relacionada à localização de adubos nitrogenados aplicados sobre os resíduos culturais em canavial sem queima. **R. Bras. Ci. Solo Bras**, v. 26, n. 4, p. 491–498, 2007.

VITTI, A. C.; TRIVELIN, P. C. O.; GAVA, G. J. C.; PENATTI, C. P.; et al. Produtividade da cana-de-açúcar relacionada ao nitrogênio residual da adubação e do sistema radicular. **Pesquisa Agropecuária Brasileira**, v. 42, n. 2, p. 249–256, 2007.

WANG, J.; JU, J.; WANG, J. Experimental study on pricking hole performances of deep application liquid fertilizer device. 2011 Fourth international conference on intelligent computation technology and automation. **Anais...** . p.71–76, 2011. Ieee. Disponível em: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5750837>. Acesso em: 30/7/2012.

WOMAC, A. R.; TOMPKINS, F. D. Probe-type injector for fluid fertilizers. **Agricultural Engineering**, v. 6, n. March, p. 149–154, 1990.

CAPÍTULO IV

4 A LIQUID INJECTION DOSING SYSTEM FOR SITE-SPECIFIC FERTILIZER MANAGEMENT

ABSTRACT - Based on the Best Management Practices (BMPs) for nitrogen fertilization, 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 fertilizer recovery efficiency compared to the deep placement of fertilizer. We have worked to implement site-specific fertilizer management that encompasses a mechanized soil punching process combined with liquid fertilizer injection, which causes minimal mobilization of the soil subsurface (i.e., roots, soil or straw) and harmonizes with conservative tillage practices. Our objective was to design a hydraulic injection system to enable site-specific management according to the BMPs, as applied to mechanized soil punching to implement deep fertilizer placement. For this, we developed a injection dosing system (conceptual design, laboratory evaluations and analyses) to perform liquid injection synchronized with soil punching and variable rate application. In general, the applications were satisfactory because (i) the liquid injection was synchronized 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) we varied the application rate in a representative range (5.0 up to 18 mL cycle^{-1}), which demonstrated a good potential for the deep placement fertilizer as a function of the local agronomic recommendations. Both conditions were aligned with the BMPs.

keywords – precision agriculture, sugarcane, deep placement of fertilizer, variable rate application

Nomenclature

A_o	*Injector orifice area (m^2)*
A_p	*Circular piston area (m^2)*
C_f	*Flow coefficient (dimensionless)*
D	*Dosage (mL cycle^{-1})*
$\frac{dh_p}{dt}$	*injector piston velocity (m s^{-1})*
g	*acceleration from gravity (9.81 m s^{-2})*
h	*Head across the orifice (mH$_2$O)*
H	*Hydraulic power (W)*
h_p	*Piston displacement amplitude (mm)*
Q_i	*Injector output flow (m^{3}s^{-1})*
$\bar{Q}$	*Average output flow (L min^{-1})*
S_{dist}	*Soil punching distance (m cycle^{-1})*
T	*Soil punching period (s)*
$\dot{x}$	*Forward speed (m s^{-1})*

Greek letters

ΔP_I	*Differential pressure through injection line (Pa)*
ΔP_{IO}	*Pressure drop across injector orifices (Pa)*
ΔP_{O_V}	*Differential pressure needs to opening valve (Pa)*
ΔP_V	*Pressure drop across valves and pipeline (Pa)*
η_v	*Volumetric efficiency (%)*
ρ	*Fluid density (kg m^{-3})*
ω	*Angular velocity (rad s^{-1})*

4.1 INTRODUCTION

Rational fertilizer management is essential in agriculture for environmental conservation coupled with better fertilizer 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 et al., 2009). Nitrogen fertilization plays a key role in this context because the application of N fertilizer to the surface results in NH_3 volatilization losses of up to 50% depending on the N source. Especially Urea, the most commonly applied fertilizer, results in very high N losses. However, N losses can be significantly reduced using proper management strategies that include incorporation of the fertilizer into soil (SOMMER et al., 2004). Even though, the most common top dressing fertilization methods are broadcasting or side dressing, both of which are associated with less labor and cost compared to the deep placement of fertilizer (BAUTISTA et al., 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-fertilizer rates on corn, sugarcane, rice, wheat crops (Amaral et al., 2015; Cilia et al., 2014; Portz et al., 2012; Quebrajo et al., 2015). Nitrogen fertilizer applied to the soil surface at variable rates, and without considering appropriate fertilizer placement, losses to the environment may occur and not result in a better nitrogen recovery efficiency, so such practices may be responsible for the over-application of fertilizer. 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 (IPNI mission’s, 2016). Thus, we believe that an appropriate process for site-specific fertilizer management must be aligned with BMPs principles.

Nitrogen fertilizer is currently commonly applied to ratoon cane during the initial sprouting stage after the mechanical green harvest. After surface application, in addition to N-fertilizer losses to the environment, a significant amount of crop residue remains after the harvest (up to 20 Mg ha^{-1}, according to Fortes et al., 2012) and it may produce a mulching layer that impedes fertilizer contact with the soil subsurface. On the other hand, incorporation of N fertilizer applied to ratoon cane can significantly reduce NH_3 losses and promote a better nitrogen recovery efficiency (PRASERTSAK et al., 2002). However, deep placement of fertilizer 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 we perceived a technology gap, we have proposed a strategy for site-specific management that uses a mechanized soil punching process to provide nutrients near to the plant roots using liquid fertilizer injection, with minimal disturbance of the roots, soil or straw, that harmonizes with conservative tillage practices. To accomplish this, we designed a soil punching mechanism that enables liquid fertilizer injection (SILVA et al., 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 fertilizer on corn, sorghum, rice, and wheat crops. Analogous to nitrogen fertilizer management in sugarcane, a nitrogen fertilizer top dressing in wetland rice is commonly applied by broadcasting or side dressing. Such fertilizer management practices have been associated with N-fertilizer 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 favor continuous drilling for the deep placement of fertilizer due to problems with clogging, difficulty of incorporation and partial damage to the roots. In this context, by using a semi-automatic process to point deep placement of N fertilizer 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 deep placement of fertilizer by liquid injection (NYORD et al., 2008; NIEMOELLER et al., 2011; XI et al., 2011; WANG, J. et al., 2011; LIU et al., 2011; CHUNFENG; XIU, 2015). However, we perceived 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 deep placement of fertilizer are generally applied at sowing stage. However, based on the Best Management Practices (BMPs) recommended by IPNI, we believe that site-specific management of nitrogen fertilization must take into account the most appropriate placement of fertilizer 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 mechanized soil punching for deep placement. This study encompassed the conceptual design, laboratory evaluation and analyses of the injection system.

4.2 MATERIAL AND METHODS

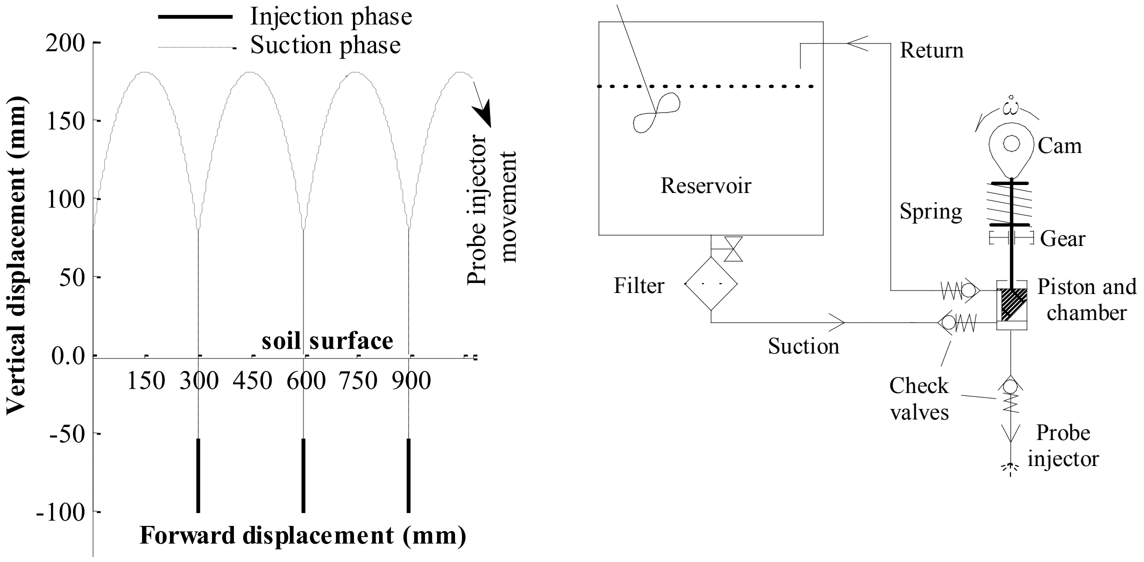
4.2.1 Hydraulic injection system descriptions

For the point deep placement of liquid fertilizer, the hydraulic system must synchronize the liquid injection with the displacement of the probe injector into soil (Figure 13a). Additionally, liquid injection must be performed according to required fertilizer rate (i.e., the application rate must be variable). To meet these specifications, we designed a injection dosing system based on a reciprocating piston pump. The proposed hydraulic system was composed of a reservoir, an injection dosing pump and an injector (Figure 13b). 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 synchronized 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, Figure 13a). 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 to 2π rad), probe injector displacement above the ground mainly occurs between 0 to $3\pi/2$ 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 ($3\pi/2$ to 2π rad), when the soil is perforated at the application depth (greater than 50 mm deep, as recommended at Prasertsak et al., 2002), liquid injection was implemented by the positive movement of the piston. In addition, the synchronicity was sustained by the cam shaft velocity (ω – rad s^{-1}), determined as a function of the soil punching equipment speed ($\dot{x}$ – m s^{-1}), punching cycle (T - s) and soil punching distance (S_{dist} – m $cycle^{-1}$), using Eq 1:

$$\omega = \frac{2\pi}{T} \therefore \quad T = \frac{S_{dist}}{\dot{x}} \quad \rightarrow \omega = \frac{2\pi\dot{x}}{S_{dist}} \qquad 1$$

Figure 13 – Injection system for point deep placement of liquid fertilizer. a. Probe injector movement that enabled the liquid injection into the soil (SILVA et al., 2017). b. Hydraulic injection system based on soil punching process

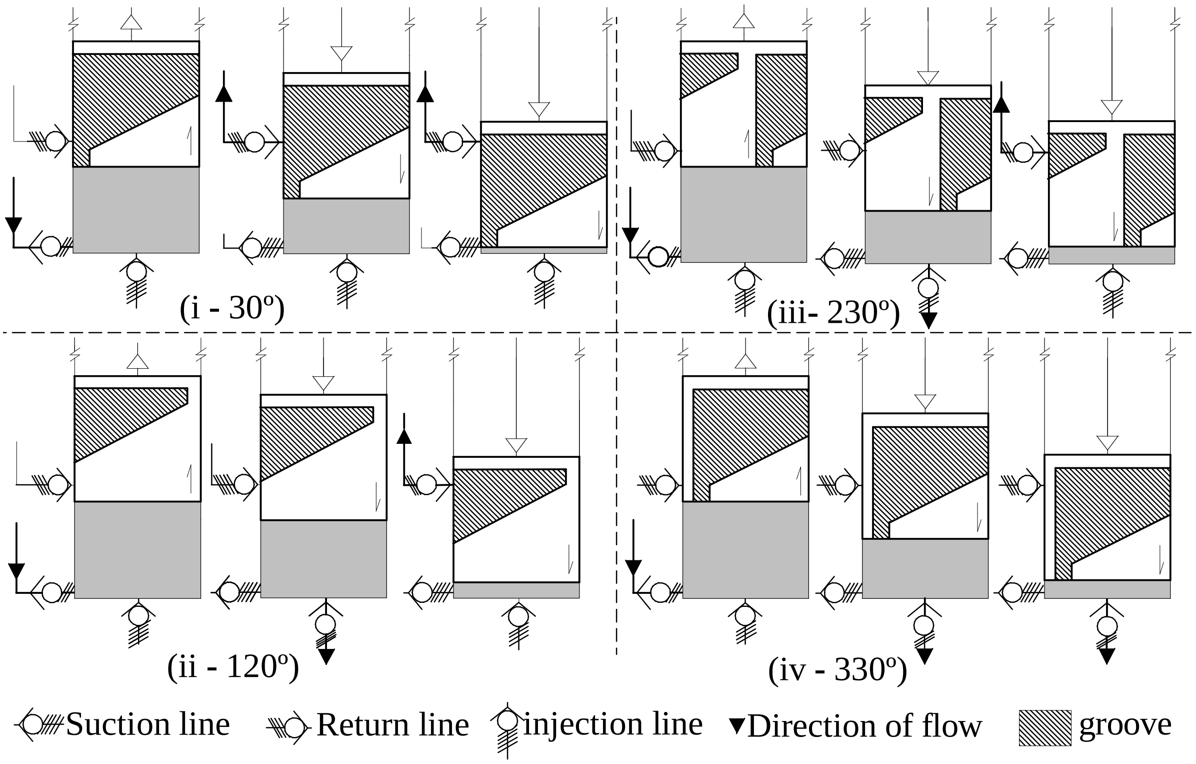


(a) (b)

Liquid injection at the required rate was controlled using the piston pump return line. For this, we designed an injection piston with a groove (Figure 14) that allowed the fluid to communicate with the hydraulic return line according to the radial position of the piston, which was between 0 to 360°. To sustain the injection dosing (i.e., the working principle), the differences in resistance achieved by the check valves were essential to unidirectional flow through the suction, injection and return lines (Swagelok valve, models: B-8C2-1/3 and B-8C2-25, Solon-OH, USA). While, the check valve of injection line was specified to opening with 1.72 bar, in the suction and return lines were specified valves of 0.03 bar, an opening pressure 57 times smaller.

According to the radial position of the piston, output flow may occur only on direction of return line, due to lower flow resistance (Figure 14(i)). Or then, the output flow is first conducted to the injector (Figure 14(ii)), and when occurs fluid communication with hydraulic return through groove area, the output flow is deviated to the reservoir. In another radial position (Figure 14(iii)), a larger volume is applied in the injection line. Or else, the maximum applied volume in injection line, on the radial position where liquid has not contact with hydraulic return line (Figure 14(iv)).

Figure 14 – Working principle that allowed the variable rate dosage as a function of radial position of the piston

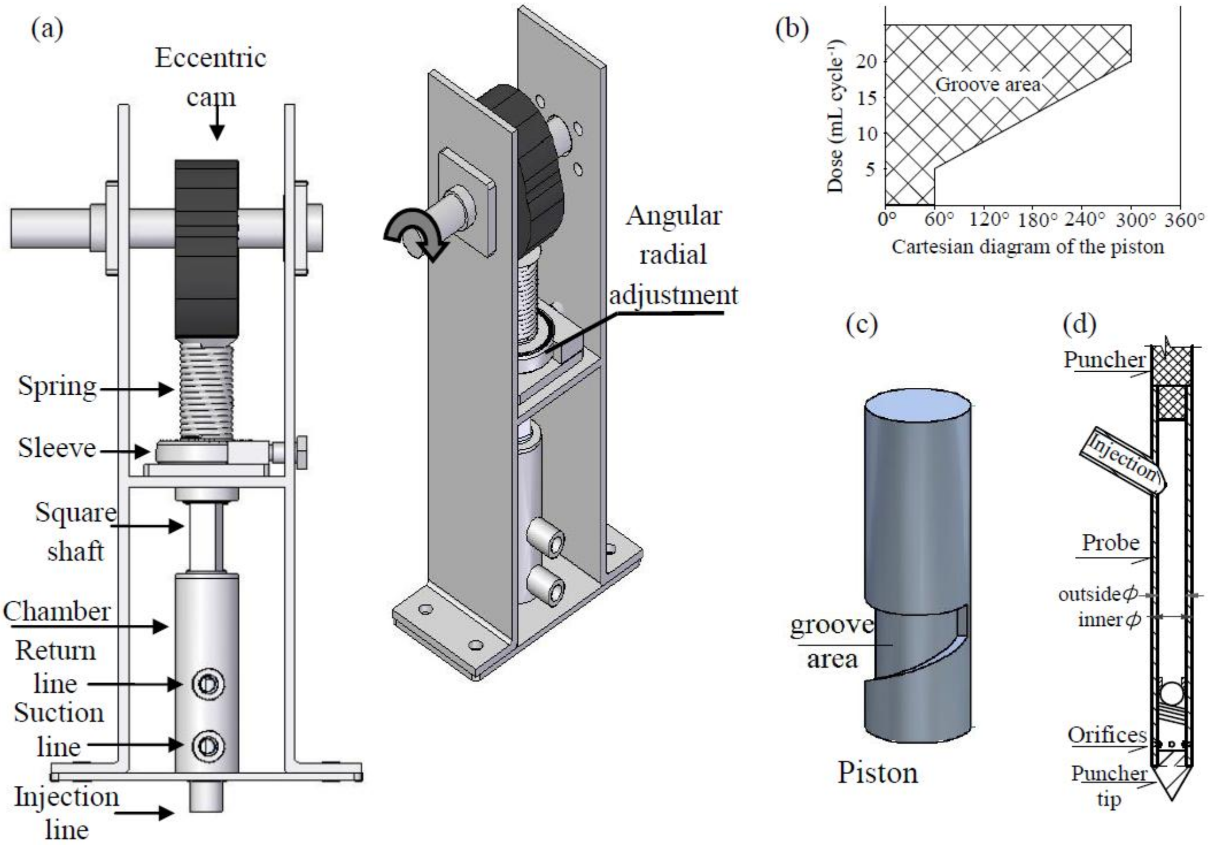


Our design of the liquid injection dosing system (Figure 15) took into account the (i) N concentration of the liquid urea ammonium nitrate (0.416 kg L^{-1}), (ii) N fertilizer range of 50 to 180 kg ha^{-1}, and (iii) soil punching distance equal to 0.15 to 0.3 m $cycle^{-1}$ (S_{dist}) and inter-row spacing of 1.5 m (i.e., the usual row spacing) . From these parameters (Eq. 2), the application range was determined at a 5 to 20 mL $cycle^{-1}$, which was essential for the sizing and proper specifications, such as the piston, groove area and chamber.

$$\mathrm{D\ (mL\ cycle^{-1})} = \frac{\mathrm{rate(kg\ ha^{-1}) * interrow\ (m) * S_{dist}\ (m\ cycle^{-1}) * 10^{3}(mL\ L^{-1})}}{\mathrm{concentration(kg\ L^{-1}) * 10^{4}(m^{2}\ ha^{-1})}} \qquad 2$$

The piston that we designed was assembled in a shaft with a square section that had reciprocating motion (Figure 15a) through a sleeve, in which a radial angular adjustment was performed using degree scaling with regards to the return line. In addition, the probe for injection of the liquid into the soil was manufactured using a stainless steel tube (ϕ15.86 mm on the outside diameter) to produce minimal soil disturbance. Six orifices (ϕ2 mm) were drilled near the injector tip to provide the liquid to the maximum depth (Figure 15d). Following construction and evaluations, we registered the product (Patent BR 10 2016 028809 6 - Magalhães and Silva, 2016).

Figure 15 – Hydraulic injection elements. a. Layout designed to the piston pump. b. Diagram designed to adjust the applied volume, according to the radial angular position of the piston. c. Piston with groove area. d. Probe injector



4.2.2 Hydraulic injection system: pressure and output flow

Along the injection timing, differential pressure (ΔP_I, Eq. 3) was mainly influenced by the opening pressure of check valve (ΔP_{O_V}), pressure drop across the valve and pipelines (ΔP_V) and pressure drop across the injector orifices (ΔP_{IO}). The pressure drop and output flow across the injector orifices was aligned with steady-state orifice equation (Eq. 4), attributed to the orifices area (A_o), instantaneous flow (Q_i) and coefficient of flow (C_f) considered equals to 0.6, a common value applied to orifice plates, venture pipes and nozzles, (NBR ISO 51167). However, average output flow ($\bar{Q}$) is different of instantaneous flow (Q_i) that has a cyclical characteristic. The average output flow or instantaneous flow is extreme relevant for sizing and specifications of hydraulic elements (reservoir volume, valves capacity, filter and pipeline sizing, e.g.); also, output flow monitoring may assist on control and analysis. The following equations were used to calculate instantaneous flow (Q_i - $m^3\ s^{-1}$), average output flow ($\bar{Q}$ - $L\ min^{-1}$) and estimate hydraulic power (H - W):

$$\Delta P_I = \Delta P_{O\_V} + \Delta P_V + \Delta P_{IO} \qquad 3$$

$$Q_i = C_f . A_o \sqrt{\frac{2.\Delta P_{IO}}{\rho}} \qquad 4$$

$$Q_t = A_p . \left(\frac{dh_p}{dt}\right) \rightarrow Q_i = \frac{(Q_t).(\eta_v)}{100} \qquad 5$$

$$H = (Q_i).(\Delta P_I) \quad \text{or} \quad H = \frac{(\Delta P_I).(A_p).(\eta_v)}{100}.\left(\frac{dh_p}{dt}\right) \qquad 6$$

$$\overline{Q} = \frac{60.(D).(\dot{x})}{1000.(S_{dist})} \quad \text{or} \quad \overline{Q} = \frac{60.(D)(\dot{\omega})}{2\pi} \qquad 7$$

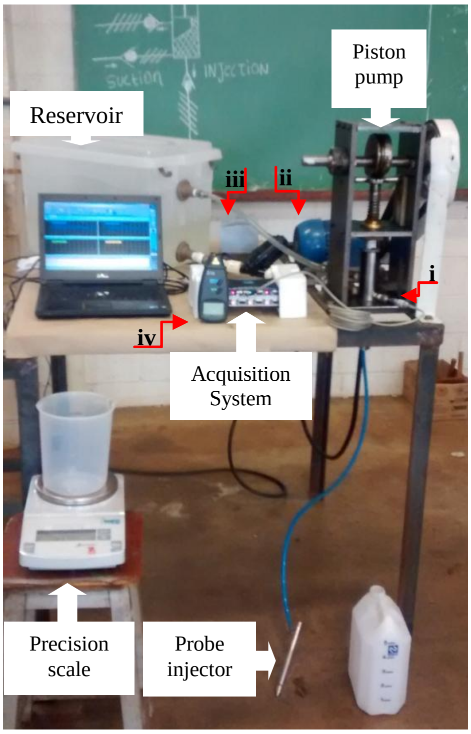
4.2.3 Experimental setup descriptions

To facilitate the analysis of the hydraulic injection system, we performed experimental assemblies and evaluations at the laboratory bench (Figure 16). A three-phase electric motor (WEG electric motors, Jaragua do Sul - Brazil) with 1.1 kW (1,720 rev min^{-1}) was used to drive the piston pump, and a frequency inverter (WEG electric motors, model CFW-08) was used to change the operating conditions of the electric motor velocity. The angular velocity was measured around the eccentric cam shaft using a digital photo-tachometer (Minipa, MDT-2238A model, São Paulo, Brazil).

The evaluations were carried with water, which has a similar viscosity to liquid fertilizer. A volumetric receiver was used to measure the volume, and the time was recorded to determine the average output flow. In sequence, the liquid volume was correlated to the mass measured with a precision scale (Ohaus Corporation, model ARD110, resolution 0.01g, Parsippany, United States). Along the tests, the fluid pressure in the piston pump was measured using an absolute pressure transducer (HBM, Inc., P8AP-20 model, Darmstadt, Germany - measuring span 20 bar, accuracy class 0.3). For data acquisition was used the QuantumX device (HBM, Inc., model MX840A, Darmstadt, Germany) and the Catman Easy on computer interface (HBM, Inc., Version 3.4.1, Darmstadt, Germany), under sampling rate of 300 Hz considered enough to observe pressure behavior across the cycle.

The effectiveness on variable rate application was evaluated through variation of the piston radial angle related to hydraulic return, using increments of 5º (0° to 360°). On evaluations, the piston pump velocity was carried with 10.47 and 20.95 rad s^{-1} (100 and 200 rev min^{-1}). In addition, on the radial positions of 120º, 170º, 230º and 270º, besides evaluations under 10.47 and 20.95 rad s^{-1}, these positions were also evaluated as a function of a larger range of velocity (6.5 to 30 rad s^{-1}), through increments of 1 rad s^{-1} and four replications per stage, to enable calculus of means and coefficient of variation (c.v.). On operating conditions, we took into account the applied dosage (Eq. 7), fluid pressure peaks, injection timing (through observation of the pressure peak width) and hydraulic power (Eq. 6).

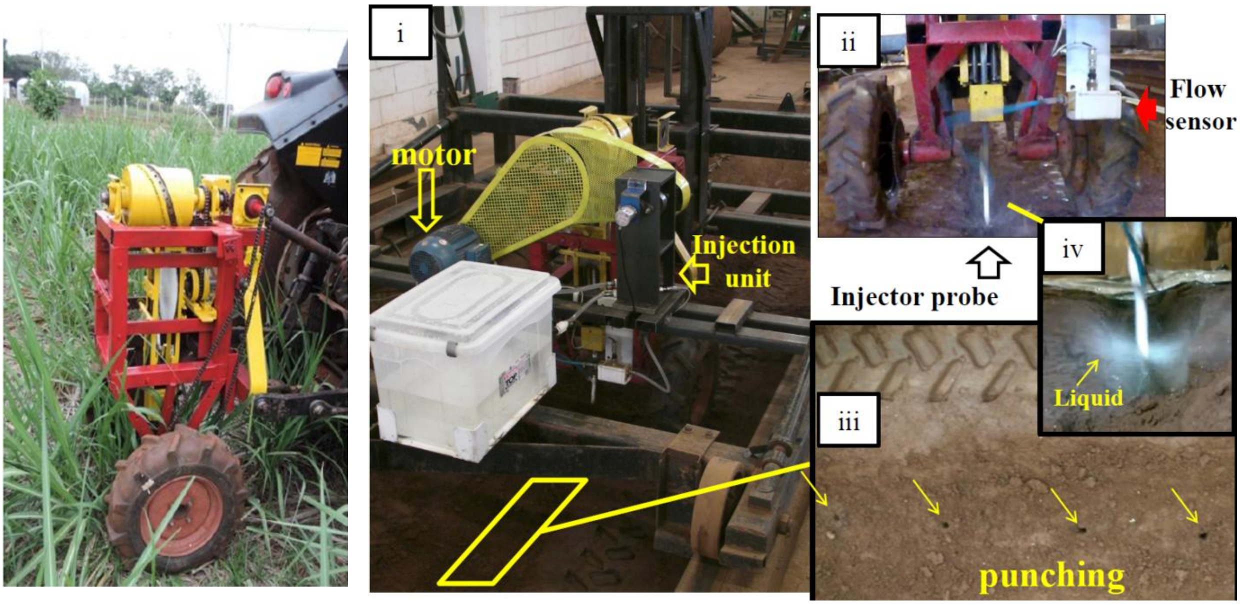
Figure 16 – Experimental setup on laboratory bench; (i) pressure transducer, (ii) electric motor, (iii) frequency inverter and (iv) photo-tachometer



Next, experiments were conducted in a laboratory soil bin (Figure 17b) to provide desirable laboratory conditions to have greater control over some aspects of the soil punching process (e.g., the soil penetration resistance, the soil moisture, the soil micro-relief and a stone-free soil) and to have access to technical laboratory support, instrumentation and electrical networks. The soil bin is 12 m long, 2 m wide and 1 m deep and included a common carriage to support the prototype and soil processing equipment (BIANCHINI and MAGALHÃES, 2008). The system was driven by a hydrostatic power transmission unit with a maximum forward speed of approximately 1.0 m s^{-1} due to limitations imposed by the soil bin dimensions and operator safety. An average penetration resistance of 1.95 MPa (max 3.0 MPa and c.v. 45%) and a soil moisture content of approximately 16.5 db% (max 18 db% and c.v. 5.3%) were maintained.

The hydraulic injection system was coupled with the soil punching equipment. This assembly was used to facilitate analysis of the liquid injection during the soil punching process. The system was driven by a three-phase electric motor (WEG electric motors, Jaragua do Sul - Brazil) with an output power of 3.7 kW (1715 rev min^{-1}) controlled by a frequency inverter. The synchrony of the soil punching and fluid injection was sustained by mechanical transmission via sprockets and chains.

Figure 17 – Experimental setup. a. Soil punching equipment presented at Silva et al. (2017). b. (i) Experimental deployment was performed to apply liquid during the soil punching process; (ii) the injector probe was attached at the punching mechanism; (iii) soil punching applications; (iv) stationary test



(a) (b)

The piston pump shaft velocity was recorded by a tachogenerator sensor (Hohner Electronics Ltd., model TH55R6000, Artur Nogueira - Brazil), while the pressure in the piston pump and instantaneous output flow were measured using an absolute pressure transducer (HBM, Inc., P8AP-20 model, Darmstadt, Germany) and a microturbine sensor (Flo-tech, FSC-375 model, Milwaukee, United States) installed in intermediate part of the injection pipeline. A QuantumX device (HBM, Inc., model MX840A, Darmstadt, Germany) was used for data acquisition and Catman Easy as the computer interface (HBM, Inc., Version 3.4.1, Darmstadt, Germany). Signal post-processing was performed in MATLAB (MathWorks, Version R2012a, Natick, MA, USA).

For evaluation, the radial angle of the piston was maintained at a constant position (270º, to hold the applied dosage near a constant value) and the forward speed ranged from 0.6 to 1.0 m s^{-1} (equivalent to 12.5 to 20.5 rad s^{-1} on the piston pump shaft, Eq.1). Each soil bin test comprised 15 to 17 punching cycles. Measurements were made at approximately 5.0 m (i.e., in the central part of soil bin) of the applied doses, output flow peaks and pressure peaks. After the operation ceased, we measured the application depth and soil punching distance with a caliper and a tape measure, respectively. Along with soil bin evaluations, we performed some stationary tests (i.e., without loading of the soil drill, Figure 17b – iv) to investigate the effects of the soil on the fluid resistance across the orifices. For this, the system (piston pump shaft and soil punching mechanism) was evaluated from 11 - 18.5 rad s^{-1} (similar to the soil bin scaling).

The experimental data were analyzed using control charts of the average ($\bar{X}$) and standard deviation (S). According to Montgomery (2009), when the sample size is moderately large (n >12) or the sample size (n) is variable, the equations 9 and 10 are more appropriate to calculate the upper control limit (UCL), lower control limit (LCL) and Center line (CL), where A_3, B_4 and B_3 are constants (Montgomery, 2009) and m represents the number of samples, $\bar{X}_i$ is the subgroup average and $\bar{\bar{X}}$ is the weighted average (Eq. 8), S_i is the subgroup standard deviation and $\bar{S}$ is the weighted standard deviation (Eq. 8).

$$\bar{\bar{X}} = \frac{1}{m}\left(\sum_{i=1}^{n} \bar{X}_i\right) \text{ and } \bar{S} = \frac{1}{m}\left(\sum_{i=1}^{n} S_i\right) \qquad 8$$

$$\text{Average limits: } UCL = \bar{\bar{X}} + A_3.(\bar{S});\ CL = \bar{\bar{X}};\ \ LCL = \bar{\bar{X}} - A_3.(\bar{S}) \qquad 9$$

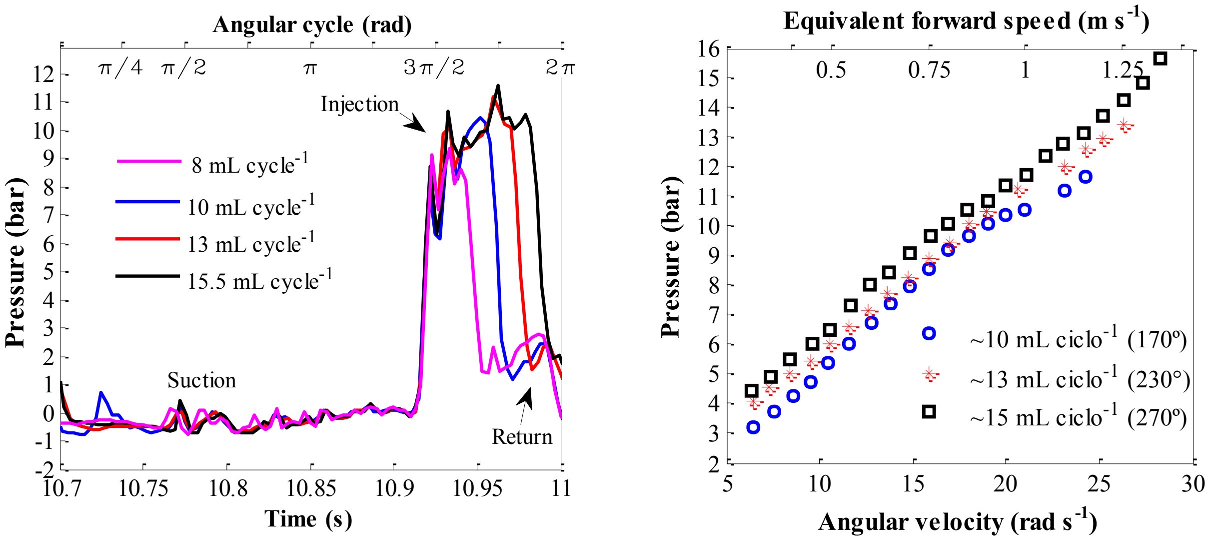
$$\text{Standard deviation limits: } UCL = B_4.(\bar{S});\ CL = \bar{S};\ \ LCL = B_3.(\bar{S}) \qquad 10$$

4.3 RESULTS AND DISCUSSION

4.3.1 Hydraulic pressure in the injection metering pump

Along operating cycle, the pressure characteristics were similar to the design specifications (Figure 18a), where, suction was carried around 0 to $3\pi/2$ rad followed by injection phase up to 2π rad. The pressure peaks achieved on fluid injection (or values near to the maximum pressure) were associated with resistance caused by the hydraulic elements, such as, the opening pressure of check valve (~1.75 bar), flow resistance across the injector orifices (~6.25 bar) or fluid inertia (~2.5 bar). According to the evaluated dosage scaling (10, 13, and 15.5 mL $cycle^{-1}$, Figure 18a), we observed an increase on injection timing (40, 50 and 60 ms) and pressure peaks (10.45, 11.2 and 11.6 bar), besides reduction on fluid return timing.

Figure 18 – Hydraulic pressure in the injection metering pump. a. Pressure measurements at one operating cycle, in which angular velocity was 20.95 rad s^{-1} (200 rev min^{-1}). b. Maximum pressure values observed during the injection timing



(a) (b)

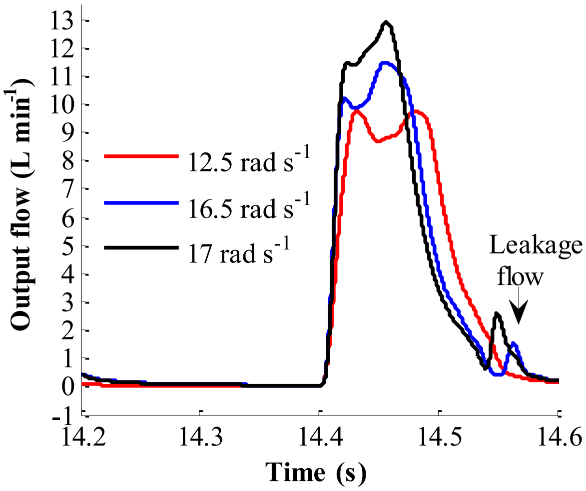
In general, the pressure behavior along the cycles was analogous to that shown in Figure 18a, even, when it was changed the drive angular velocity. Thus, it was extracted the maximum pressure values from evaluations with angular velocity scaling (6.5 to 27 rad s^{-1}). Figure 18b shows the results, where we observed an approximately linear straight line to the evaluated range, with higher pressure levels proportional to the applied dosage and angular velocity. Therefore, the higher pressure (15 bar) was found at highest conditions for angular velocity (27 rad s^{-1}) and dosage (15 mL cycle^{-1}). However, this cannot be considered a general characteristic, because pressure levels fundamentally depends of loading source (resistance level to the flowing), as shown by Zhang et al. (2012) through evaluation of axial piston pump under different loads.

The flow resistance across the orifices of injector was considered the most significant contribution on pressure peaks, measured at the injection metering piston pump. Based on the steady orifice equation (Eq. 4), the differential pressure was associated mainly with fluid velocity (or output flow level), thus, confirming the results shown in Figure 18b. However, the velocity effect on pressure can produce changes on discharge flow efficiency, as demonstrated by Knutson and Van de Ven (2016) on analysis performed with output flow through the check valves in a hydraulic piston pump. In general, discharge coefficient is assumed as a constant value of 0.6 (NBR-ISO-5167, 1994); but, it can achieve significantly lower indexes (0.3-0.5, Knutson and Van de Ven, 2016).

4.3.2 Instantaneous output flow through the injection line

Increments on piston pump velocity (12.5, 16.5 and 17 rad s^{-1}, Figure 19) caused reduction on the injection timing (90, 80, 70 ms) and increased the flow rate peaks (10, 11.5 and 13 L min^{-1}). From results, we also observed a partial leakage flow across the injection line during flow return to the reservoir, associated with pressure level during the flow communication with return line (Figure 18a). This transition phase was characterized by abrupt dropped on pressure and output flow (Figure 18a and Figure 19). The condition favors emergence of water hammer phenomenon upon the check valve (KARNEY and SIMPSON, 2007; XU et al., 2011; MENG et al., 2012; KALIATKA et al., 2014), which produce changes on pressure due to the steam appearing (cavitation) followed by steam collapsing (KALIATKA et al., 2014). To prevent against the water hammer consequences, Xu et al. (2011) suggest applying a contra-push check valve.

Figure 19 – Instantaneous output flow through hydraulic injection line

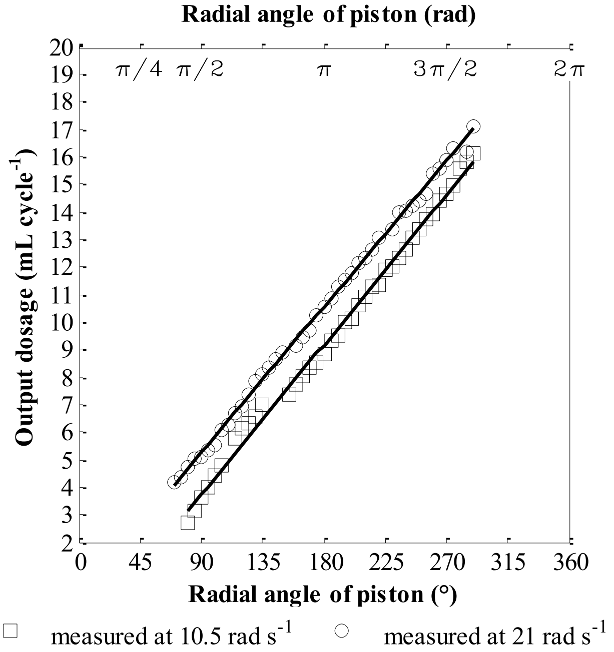


4.3.3 Variable rate application system

When the piston pump was driven at 21 rad s^{-1}, the injected doses were greater than at 10.5 rad s^{-1} because of the effect of the velocity on the pressure (Figure 20). The increased pressure on the check valve may have induced some flow through the injection line during the return to the reservoir. Additionally, the velocity differences (10.5 v.s. 21 rad s^{-1}) were associated with the volumetric efficiency of the liquid suction. In general, the volumetric efficiency of a piston pump can be as high as 90-92% (XU et al., 2016; ZUTI et al., 2016), higher than for other types of pumps (i.e., centrifugal pumps), but the piston pump efficiency can oscillate with the operating pressure (XU et al., 2016).

During liquid fertilizer application, the forward speed of the equipment is commonly maintained approximately constant (near an operating point) to reduce the pressure and output flow variations through the injectors. For this reason, the injection dosing pump was driven at constant velocity (10.5 and 21 rad s^{-1}), while the liquid injection dose was linearly increased from 4 to 17 ml $cycle^{-1}$ from 60º to 300° (i.e., the radial positions of the piston, Figure 20). This characteristic allows the variable application rate, allowing the provision of nutrients according to agronomic recommendations, which is a BMPs for fertilizer stewardship (FILLERY and KHIMASHIA, 2016) and a pre-requisite for site-specific management.

Figure 20 – Dosage as a function of the radial angle of piston



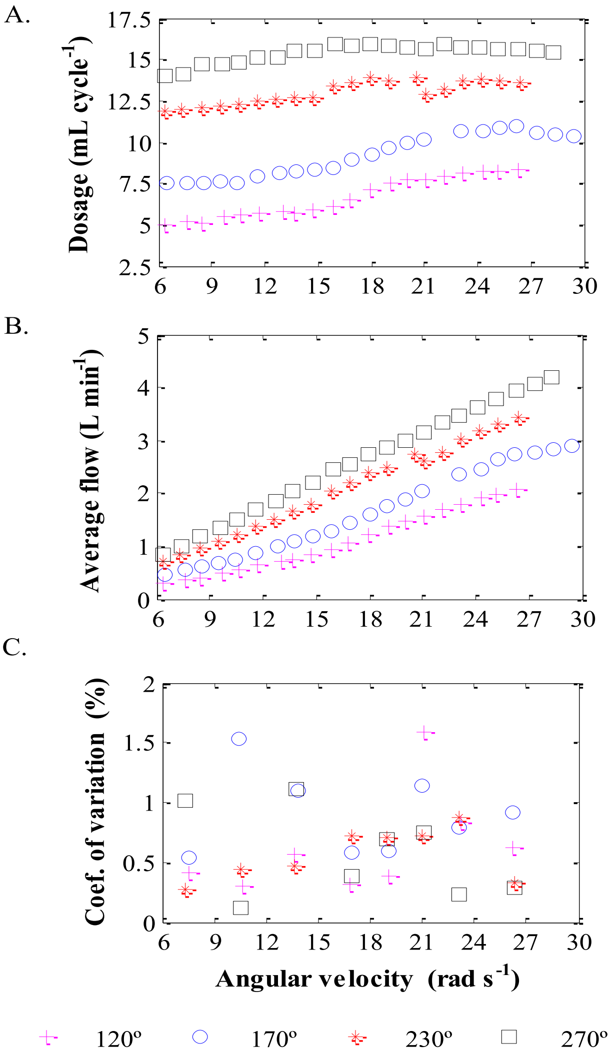
In conventional hydraulic systems used for liquid fertilizer application on the soil surface or incorporated into the soil, the variable flow rate is implemented by the actuation of a servo valve (YANG, 2001; JOHANN et al., 2006; BENNUR and TAYLOR, 2010; YAMIN et al., 2016). This component in hydraulic circuit is positioned after the three-way directional valve, which is connected with pump, reservoir and injection. On the other hand, our proposed injection dosing system does not require valves to achieve a variable flow rate because the working principle has been simplified by the piston pump, which is responsible for the liquid injection and dosage control.

4.3.4 Metering injection system under different angular velocities on piston pump

In theory, a constant radial angle of the piston should result similar injected dose, even with different angular velocities of the piston pump. However, slight variations were observed when the position was fixed at 120°; the doses ranged from 5 to 8 mL cycle^{-1} at the velocities tested (6 to 27 rad s^{-1}, Figure 21a). The results were associated with the opening and closing of the check valves (i.e., the transient phase) when the hydraulic pressure increased. The effects of these valves on piston pumps have been highlighted in recent studies (WANG et al., 2015; XU et al., 2015; PEI et al., 2016), mainly because they effect the flow through the hydraulic lines. However, we realized that dosage changes in a narrow range were quite small (less than 0.2 mL cycle^{-1}, between 23 to 27 rad s^{-1}, e.g.). Thus, the best precision for liquid injection was near the operating point.

For the radial angle positions evaluated, we observed a proportional increase of the flow rate proportional to the angular velocity of piston pump (Figure 21b). Furthermore, the injection dosage varied only slightly (c.v.(s) less than 2%, Figure 21c), which we thought was a desirable operational characteristic. From the perspective of fertilizer application, an advantage of a liquid product is the greater uniformity of the output flow rate compared to the granular fertilizer sources (KORNDÖRFER et al., 1995). In an evaluation of commercial equipment, Sharda et al. (2016) also reported little variation (~7%) for the soil surface application of liquid fertilizer.

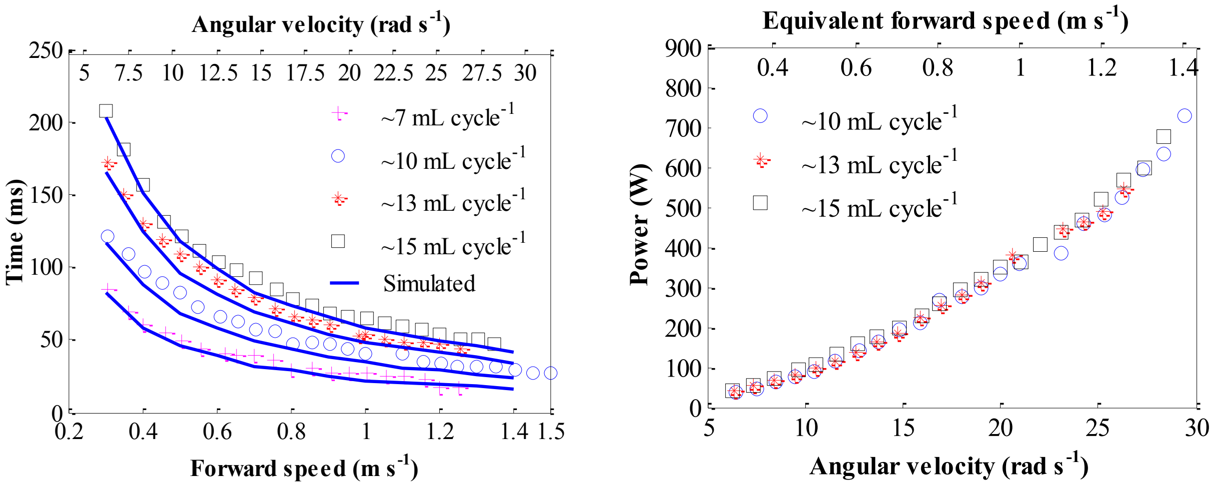
Figure 21 – Metering injection pump under increments of angular velocity



Overall characteristics of the hydraulic system

On evaluations, hydraulic injection timing was included between 205 to 15 ms; in general, we observed a non-linear reduction according to velocity, in which, how much smallest the injection timing, it was demanded higher hydraulic power. In contrast with other evaluations (output flow, injection timing, and pressure), we did not observe significant hydraulic power differences with regards to the evaluated doses. The hydraulic power showed an exponential curve according to increasing velocity, inversely proportional to the injection timing, where curve trend to zero (Figure 22a). Along operating cycle, the highest hydraulic power demand was included on injection phase, due to output flow and pressure values (Figure 22b). Even though, hydraulic power was considered lower (750 W, when considered 1.4 m s^{-1}). Based on results, we perceived that injection timing and hydraulic power were mainly influenced by the operating velocity, hydraulic pump elements (cam, piston and chamber dimensions, e.g.), operating characteristics (soil punching distance and dosage level, e.g.) and hydraulic pressure.

Figure 22 – Operating characteristics of the hydraulic injection system. a. Injection timing, considering soil punching distance of 300 mm. b. Required power during liquid injection



(a) (b)

In general, the proposed hydraulic injection system showed some similar characteristics applied on common injection system, with regards to the composed elements (piston pump, camshaft, injector nozzle, in-line injection, e.g.) and working principle (output flow and pressure peaks, synchronized operation, injection timing, e.g.).. However, the liquid fertilizer is not self-lubricating, mainly because it is based at water. While, the proposed injection system can reach flow rate peaks above 13 L min^{-1} (Figure 19), flow rate peaks in fuel injection is made around 0.7 up to 3 L min^{-1} (CATANIA and FERRARI, 2011; HWANG et al., 2016; QIU et al., 2016). Other difference is related to the pressure amplitude values. In the system, operating pressure for liquid injection is significantly lower (reached up to 15 bar, Figure 18b), when, it is compared to the pressure reached in a common injection systems (350-900 bar, shown by Kegl et al., 2008; Hwang et al., 2016; Nazemi and Shahbakhti, 2016; Qiu et al., 2016). Other differences are related to the angular velocity of piston pump (fuel injection pump is driven with above than 1000 rev min^{-1}, Catania and Ferrari, 2011) and smaller injection timing (around 1.1 - 4 ms, According to Hwang et al., 2016; Qiu et al., 2016). These contrasts helps to confirm the needs of the design of hydraulic system to meet specific characteristics for liquid fertilizer injection synchronized with the soil punching process.

4.3.5 Liquid injection combined to mechanized soil punching process

Statistical control quality analysis established the weighted average dosage at 17.5 mL cycle^{-1} (Figure 23). In general, the average doses ranged between the lower and upper limits (15.7 and 19.2 mL cycle^{-1}, respectively). However, some average values were closer to the limits and some average standard deviation values exceeded the control limits. Such deviations near the central average were mainly attributed to changes in the test velocity (0.6 to 1 m s^{-1}) and discontinuous loading during a cycle, especially during liquid injection and soil punching because of an increase in power and the demand for torque. Additionally, variations of soil penetration resistance could have produced load changes across cycles. To overcome this problem, a flywheel may provide shock absorptions from discontinuous loading, as well as balancing the angular velocity and reducing torsional vibration (SONG et al., 2014).

Figure 23 – Shewhart control chart

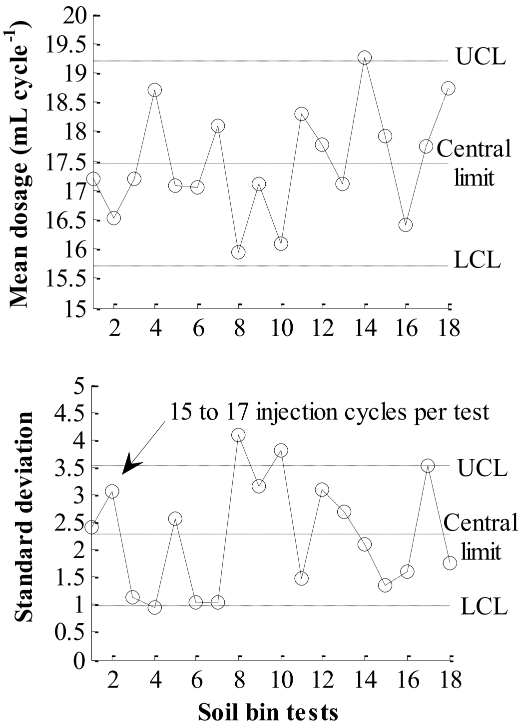
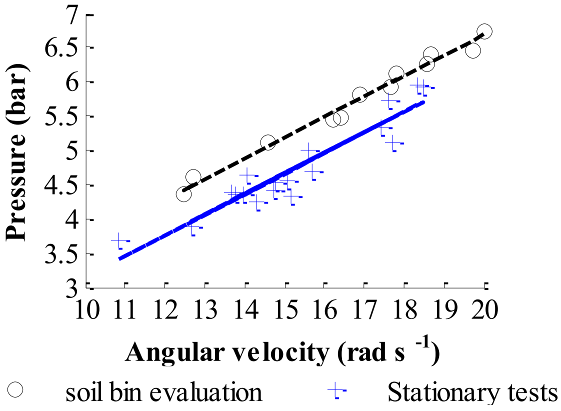


Figure 24 shows the maximum hydraulic pressure values from the soil punching evaluation compared to the stationary tests (without loading of soil drilling). In general, we achieved a similar straight line slope. However, higher pressures were measured for liquid injection combined with the soil punching process. The differences were approximately 0.5 bar in a range of approximately 10 - 20 rad s^{-1}. These higher pressures were attributed to the partial obstruction of the injection orifices caused by the soil particles. Even so, we did not observe problems with clogging, as previously described by Bautista et al. (2001) for liquid injection into the soil. Injector clogging can decrease the quality of the operation due to its effects on the uniformity of the application. Thus, this increase in hydraulic pressure was considered advantageous because an output flow interruption just occur if pressure demand exceeds the available motor power in the piston pump system.

Figure 24 – Pressure measured along the soil punching evaluations with regards to the off-load tests



The highest forward speed in the soil punching tests was approximately 1.0 m s^{-1}. Table 4 shows the results for this speed, in which the equivalent angular velocity was ~20.5 rad s^{-1}. The lowest average angular velocity (19.6 rad s^{-1}, Test 4) produced a greater soil punching distance (mean 355 mm). Similarly, a higher variation (i.e., the c.v.) of the soil punching distance (13%), angular velocity (8.6%) and pressure (8.1%) was observed. On the other hand, in Test 3, less variation of the angular velocity (c.v. 6.9%, mean 20 rad s^{-1}), soil punching distance (c.v. 4%, mean 332 mm), output flow peaks (c.v. 3.3%, mean 13.4 L min^{-1}) and dosage (c.v. 5.5%, mean 16.4 mL $cycle^{-1}$) occurred.

Table 4 – Liquid injection combined to mechanized soil punching process

Soil bin tests	**Ang. Vel. (rad s^{-1})**		**Press. peaks (bar)**		**O. flow peaks (L min^{-1})**		**Dosage (mL $cycle^{-1}$)**		**Depth (mm)**		**Distance (mm)**	
N°	mean*	c.v.	mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.
Test 1	20.5	8.0	6.9	5.9	14.4	3.4	18.4	7.5	79	10	339	5
Test 2	20.0	7.9	6.7	4.8	14.4	7.7	17.9	11	85	7	330	5
Test 3	20.0	6.9	7.2	5.9	13.4	3.3	16.4	5.5	83	9	332	4
Test 4	19.6	8.6	6.9	8.1	14.7	6.8	18.6	8.9	94	6	355	13

c.v. – coefficient of variation (%).

Because a lower variation was achieved for the dosage across the cycles (5.5 to 11%, Table 4), we believe that the proposed system has the potential for more precise applications. The results favor a precision agriculture approach in which application uniformity is usually approximately 8.0 to 15%, as previously demonstrated for the site-specific management of fertilizer with drilling machines (NING et al., 2015; REYES et al., 2015). If fertilizer broadcasting is used instead of deep placement, beyond the losses to environment, it is common to observe variations (c.v.) higher than 20% on application. However, if N-P-K formulations are applied, c.v.s as high as 30 - 35% have been observed (FULTON et al., 2001; VIRK et al., 2013; CAMPBELL et al., 2015).

Silva et al. (2017) suggested that N fertilizer placement in ratoon cane required improvement, and we think that our proposed liquid injection system has the potential to overcome difficulties in the N fertilizer application in ratoon cane. In a recent comparison of placement methods for liquid fertilizer injection in ratoon cane, Silva et al. (2017) demonstrated that point deep placement was more effective (i.e., resulted in a higher cane stalk yield) than placement on surface (98 Mg ha^{-1} v.s. 91 Mg ha^{-1}). The result was associated with the higher availability of mineral N for plant uptake, when liquid fertilizer was applied near the roots with minimal soil disturbance.

4.4 CONCLUSIONS

To provide liquid fertilizer at the soil subsurface near plant roots with minimal soil disturbance, we developed a injection dosing system based on reciprocating piston pump, in which (i) the liquid injection was synchronized with soil punching controlled by an eccentric cam and (ii) a variable rate of application was achieved with a piston designed with a grooved area that allowed fluid communication with the hydraulic return to the reservoir. In the system, the working principle was guaranteed by the fast opening/closure of check valves, used on direction of flow through suction, injection and return lines.

Based on design of injection system, the doses are similar when the radial angle of piston is maintained in a constant position. However, we observed slight changes on the applied dosage according to the changes on velocity, as well as, on the output flow and pressure. The condition was attributed to the transient time that occurs amid on the injection interval, when flow is deviated to hydraulic return. In this period, we observed an abrupt reduction on the output flow and pressure that caused a water hammer emergence. In general, the pressure overshoot on injection line produced a partial flow (leakage) through the check valve. To reduce this effect on the applied dosage, a presented strategy was performing applications on narrow velocity range, around an operating point.

On analysis, we observed a higher power demand during the soil punching, when the liquid is injected. In period, hydraulic pressure was mainly attributed to the flow resistance across the injection orifices, opening valve pressure, pressure drop across the injection line (valve, pipeline and injector) and soil influence as partial obstruction of injection orifices (but, without clogging). Even though, the power demand for liquid injection was considered low, mainly because of pressure levels (below than 15 bar) and maximum flow values (less than 14 L min^{-1}). Further, based on application uniformity (c.v. less than 2% in the bench tests, and c.v. around 11% in the soil punching tests) and statistical control quality, we realized that proposed systems have a potential to improve quality and precision of fertilizer application.

In general, the operations were satisfactory, because (i) the liquid injection was synchronized in the soil punching interval, with fluid incorporated into the soil at depth greater than 50 mm, condition considered the most adequate for deep placement, with potential to assist on reduction of nutrient losses combined to nutrients uptake. In addition, (ii) the applied dosage as a function of the radial angle of the piston was performed between a representative range (5.0 up to 18 mL cycle^{-1}), showing a favorable potential to variable fertilizer application according to required rate. Both conditions recommended to better management practices for fertilizer application.

4.5 REFERENCES

AMARAL, L. R.; MOLIN, J. P.; PORTZ, G.; FINAZZI, F. B.; CORTINOVE, L. Comparison of crop canopy reflectance sensors used to identify sugarcane biomass and nitrogen status. **Precision Agriculture**, v. 16, n. 1, p. 15–28, 2015.

BAUTISTA, E. U.; KOIKE, M.; SUMINISTRADO, D. C. Mechanical deep placement of nitrogen in wetland rice. **Journal of Agricultural Engineering Research**, v. 78, n. 4, p. 333–346, 2001.

BAUTISTA, E. U.; SUMINISTRADO, D. C.; KOIKE, M. Mechanical deep placement of fertilizer in puddled soils: evaluation of nitrogen losses and yield of transpanted and direct-seeded rice. **Journal of Japanese Society of Agricultural Machinery**, v. 62, n. 1, 2000.

BENNUR, P. J.; TAYLOR, R. K. Evaluating the response time of a rate controller used with a sensor-based, variable rate application system. **Applied Engineering in Agriculture**, v. 26, n. 6, p. 1069–1075, 2010.

BIANCHINI, A.; MAGALHÃES, P. S. G. Evaluation of coulters for cutting sugar cane residue in a soil bin. **Biosystems Engineering**, v. 100, n. 3, p. 370–375, 2008.

CAMPBELL, C. M.; FULTON, J. P.; WOOD, C. W.; MCDONALD, T. P.; ZECH, W. C. Utilizing nutrient over mass distribution patterns for assessment of Poultry litter spreaders. **Transactions of the ASAE**, v. 53, n. 3, p. 659–666, 2015.

CATANIA, A. E.; FERRARI, A. Experimental Analysis, Modeling, and Control of Volumetric Radial-Piston Pumps. **Journal of Fluids Engineering**, v. 133, n. 8, p. 081103, 2011. Disponível em: <http://fluidsengineering.asmedigitalcollection.asme.org/article.aspx?articleid=1438842>. Acesso em: 9/3/2014.

CHUNFENG, Z.; XIU, W. Development and experiments on the injection system of the self-propelled liquid fertilizer machine. The 5th annual IEEE international conference on cyber technology in automation, control and intelligent systems. **Anais...** . p.1650–1654, 2015. Shenyang, China.

CILIA, C.; PANIGADA, C.; ROSSINI, M.; et al. Nitrogen status assessment for variable rate fertilization in maize through hyperspectral imagery. **Remote Sensing**, v. 6, n. 7, p. 6549–6565, 2014.

FILLERY, I. R. P.; KHIMASHIA, N. Procedure to estimate ammonia loss after N fertiliser application to moist soil. **Soil Research**, v. 54, p. 1–10, 2016.

FORTES, C.; TRIVELIN, P. C. O.; VITTI, A. C. Long-term decomposition of sugarcane harvest residues in Sao Paulo state, Brazil. **Biomass and Bioenergy**, v. 42, p. 189–198, 2012. Elsevier Ltd.

FULTON, J. P.; SHEARER, S. A.; CHABRA, G.; HIGGINS, S. F. Performance assessment and model development of a variable-rate, spinner-disc fertilizer applicator. **Transactions of the ASAE**, v. 44, n. 5, p. 1071–1081, 2001.

HWANG, J.; BAE, C.; GUPTA, T. Application of waste cooking oil (WCO) biodiesel in a compression ignition engine. **Fuel**, v. 176, p. 20–31, 2016. Elsevier Ltd.

JOHANN, A. L.; RUSSO, E.; CAPPELLI, N. L.; UMEZU, C. K. Development and evaluation of a low cost servo-valve for liquid inputs application. **Engenharia Agrícola**, v. 26, n. 1, p. 142–150, 2006.

KALIATKA, A.; VAIŠNORAS, M.; VALINČIUS, M. Modelling of valve induced water hammer phenomena in a district heating system. **Computers and Fluids**, v. 94, p. 30–36, 2014.

KARNEY, B. W.; SIMPSON, A. R. In-line check valves for water hammer control. **Journal of Hydraulic Research**, v. 45, n. March 2015, p. 547–554, 2007.

KEGL, B.; KEGL, M.; PEHAN, S. Optimization of a fuel injection system for diesel and biodiesel usage. **Energy & Fuels**, v. 22, p. 1046–1054, 2008.

KNUTSON, A. L.; VEN, J. D. VAN DE. Modelling and experimental validation of the displacement of a check valve in a hydraulic piston pump. **International Journal of Fluid Power**, v. 9776, n. April, p. 1–11, 2016.

KORNDÖRFER, G. H.; ANDERSON, D. L.; MUNDIM, V. C.; SIMÕES, M. S. Produção de adubos fluidos para cana-de-açúcar. **Revista STAB**, v. 14, n. 2, p. 25–29, 1995.

LIU, T. Q.; FAN, D. J.; ZHANG, X. X.; et al. Deep placement of nitrogen fertilizers reduces ammonia volatilization and increases nitrogen utilization efficiency in no-tillage paddy fields in central China. **Field Crops Research**, v. 184, p. 80–90, 2015.

LIU, Y.; WANG, J. J.; WANG, J. J.; GE, Y. Optimal Design and Analysis on Pricking Hole Mechanism with Planetary Elliptic Gears for Deep-Fertilization Liquid Fertilizer Applicator. **2011 Second International Conference on Digital Manufacturing & Automation**, p. 809–812, 2011. Ieee.

MAGALHÃES, P. S. G.; SILVA, M. J. Sistema hidráulico dosador injetor de fluidos (Hydraulic dosing-injector system). Patent BR 10 2016 028809 6, 2016. Brazil

MENG, H. B.; LIU, Y.; LI, Y. Experiment on Water Hammer Protection Performances of the Shuttle Check Valve in Multi-Pump Parallel Connection System. **Applied Mechanics and Materials**, v. 192, p. 37–41, 2012.

MONTGOMERY, D. **Introduction to statistical quality control**. 2009.

NAZEMI, M.; SHAHBAKHTI, M. Modeling and analysis of fuel injection parameters for combustion and performance of an RCCI engine. **Applied Energy**, v. 165, p. 135–150, 2016. Elsevier Ltd.

NIEMOELLER, B.; HARMS, H. H.; LANG, T. Injection of liquids into the soil with a high-pressure jet. **Agricultural Engineering International: CIGR Journal**, v. 13, n. 2, p. 1–15, 2011.

NING, S.; TAOSHENG, X.; LIANGTU, S.; RUJING, W.; YUANYUAN, W. Variable rate fertilization system with adjustable active feed-roll length. **International Journal of Agriculture & Biological Engineering**, v. 8, n. 4, p. 19–26, 2015.

NYORD, T.; SØGAARD, H. T.; HANSEN, M. N.; JENSEN, L. S. Injection methods to reduce ammonia emission from volatile liquid fertilisers applied to growing crops. **Biosystems Engineering**, v. 100, n. 2, p. 235–244, 2008.

PEI, J.; HE, C.; MIAORONG, L.; HUANG, X.; SHEN, K. The valve motion characteristics of a reciprocating pump. **Mechanical Systems and Signal Processing**, v. 66-67, p. 657–664, 2016.

PORTZ, G.; MOLIN, J. P.; JASPER, J. Active crop sensor to detect variability of nitrogen supply and biomass on sugarcane fields. **Precision Agriculture**, v. 13, n. 1, p. 33–44, 2012.

PRASERTSAK, P.; FRENEY, J. R.; DENMEAD, O. T.; SAFFIGNA, P. G.; PROVE, B. G. Effect of fertilizer placement on nitrogen loss from sugarcane in tropical Queensland. **Nutrient Cycling in Agroecosystems**, v. 62, n. 3, p. 229–239, 2002.

QIU, T.; SONG, X.; LEI, Y.; et al. Effect of back pressure on nozzle inner flow in fuel injector. **Fuel**, v. 173, p. 79–89, 2016.

QUEBRAJO, L.; PÉREZ-RUIZ, M.; RODRIGUEZ-LIZANA, A.; AGÜERA, J. An approach to precise nitrogen management using hand-held crop sensor measurements and winter wheat yield mapping in a mediterranean environment. **Sensors (Switzerland)**, v. 15, n. 3, p. 5504–5517, 2015.

REYES, J. F.; ESQUIVEL, W.; CIFUENTES, D.; ORTEGA, R. Field testing of an automatic control system for variable rate fertilizer application. **Computers and Electronics in Agriculture**, v. 113, p. 260–265, 2015.

SHARDA, A.; FULTON, J. P.; TAYLOR, R. K. Performance of variable-orifice nozzles for Liquid fertilizer applications. **Applied Engineering in Agriculture**, v. 32, n. 3, p. 347–352, 2016.

SILVA, M. J.; FRANCO, H. C. J.; MAGALHÃES, P. S. G. Liquid fertilizer application to ratoon cane using a soil punching method. **Soil & Tillage Research**, v. 165, p. 279–285, 2017.

SNYDER, C. S.; BRUULSEMA, T. W.; JENSEN, T. L.; FIXEN, P. E. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. **Agriculture, Ecosystems and Environment**, v. 133, n. August, p. 247–266, 2009.

SOMMER, S. G.; SCHJOERRING, J. K.; DENMEAD, O. T. Ammonia emission from mineral fertilizers and fertilized crops. **Advances in Agronomy**, v. 82, p. 557–622, 2004.

SONG, L. Q.; ZENG, L. P.; ZHANG, S. P.; ZHOU, J. D.; NIU, H. E. Design and analysis of a dual mass flywheel with continuously variable stiffness based on compensation principle. **Mechanism and Machine Theory**, v. 79, n. 174, p. 124–140, 2014.

VIRK, S. S.; MULLENIX, D. K.; SHARDA, A.; et al. Case study: distribution uniformity of a blended fertilizer applied using a variable-rate spinner-disc spreader. **Applied Engineering in Agriculture**, v. 29, n. 5, p. 627–636, 2013.

WANG, G.; ZHONG, L.; HE, X.; et al. Dynamic behavior of reciprocating plunger pump discharge valve based on fluid structure interaction and experimental analysis. **PLoS ONE**, v. 10, n. 10, p. 1–20, 2015.

WANG, J.; JU, J.; WANG, J. Experimental Study on Pricking Hole Performances of Deep Application Liquid Fertilizer Device. **Fourth International Conference on Intelligent Computation Technology and Automation**, p. 71–76, 2011.

XI, X.; WANG, J.; LANG, C. Module design for parameter optimization of pricking hole mechanism of deep-fertilization liquid fertilizer applicator. 2011 International Conference on Computer Distributed Control and Intelligent Environmental Monitoring. **Anais...** . p.480–482, 2011. Ieee. Disponível em: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5747861>. Acesso em: 30/7/2012.

XU, B.; HU, M.; ZHANG, J.; SU, Q. Characteristics of volumetric losses and efficiency of axial piston pump with respect to displacement conditions *. **Applied Physics & Engineering: Zhejiang Univ-Sci**, v. 17, n. 3, p. 186–201, 2016.

XU, B.; SUN, Y.; ZHANG, J.; SUN, T.; MAO, Z. A new design method for the transition region of the valve plate for an axial piston pump. **Applied Physics & Engineering: Zhejiang Univ-Sci**, v. 16, n. 3, p. 229–240, 2015. Disponível em: <http://link.springer.com/10.1631/jzus.A1400266>. .

XU, H.; GUANG, Z. M.; QI, Y. Y. Hydrodynamic characterization and optimization of Contra-push check valve by numerical simulation. **Annals of Nuclear Energy**, v. 38, n. 6, p. 1427–1437, 2011.

YAMIN, M.; SMAIL, W. I. W.; KASSIM, M. S. M.; AZIZ, S. A.; SHAMSHIRI, R. VRT liquid fertilizer applicator for soil nutrient management. **Jurnal Teknologi**, v. 2, p. 73–78, 2016.

YANG, C. A variable rate applicator for controlling rates of two liquid fertilizers. **Applied Engineering in Agriculture**, v. 17, n. 3, p. 409–417, 2001.

ZHANG, X.; QUAN, L.; YANG, Y.; WANG, C.; YAO, L. Output characteristics of a series three-port axial piston pump. **Chinese Journal of Mechanical Engineering**, v. 25, n. 3, p. 498–505, 2012.

ZUTI, Z.; SHUPING, C.; XIAOHUI, L.; YUQUAN, Z.; WEIJIE, S. Design and Research on the New Type Water Hydraulic Axis Piston Pump. Journal of Pressure Vessel Technology, v. 138, n. 3, p. 031203, 2016.

CAPÍTULO V

5 NITROGEN FERTILIZER PLACEMENT METHODS FOR SITE-SPECIFIC MANAGEMENT IN SUGARCANE RATOON

ABSTRACT – N fertilizer placement on the surface is a common method used in brazilian sugarcane fields. The practice under green cane trash blanket (GCTB) systems may favor losses to the environment and mineral N immobilization. Deep-band placement of N fertilizer may provide a higher mineral N availability with improvement of nitrogen use efficiency (NUE). However, the crop residue layer left on the soil surface may promote difficulties for continuous incorporation of fertilizer. Alternatively, we have worked to develop a point deep placement method for site-specific management by means of a mechanized soil punching process, which is used to access the soil subsurface to inject liquid nitrogen fertilizer near the roots with minimal disturbance of the roots, soil and crop residues. Considering the GCTB system, this work aimed to find better N fertilizer placement practices for site-specific management using liquid fertilizer. Therefore, we performed a comparative analysis applying these placement methods in a ratoon sugarcane field. In general, N mineral availability was associated with the chlorophyll index, leaf N, cane stalk yield and sugarcane quality. Based on these results, higher mineral N availability and better results of crop production (e.g. cane stalk yield) were observed for the deep placement methods. In addition, the soil punching method was considered equivalent to the common continuous deep placement method. These findings contribute to improving management practices (BMPs) in the GCTB system, providing support to improve the mechanized process of liquid fertilizer application.

Keywords: nitrogen fertilization, liquid fertilizer, deep placement, *Saccharum spp*.

5.1 INTRODUCTION

Sugarcane production in Brazil is essential to supply the sugar demand (domestic and export markets) and diversification of the national energy matrix as a renewable source (ethanol and electricity). Currently, Brazil is the world's largest sugarcane producer. In 2015, the annual millable stalk production was 660 million Mg, produced on 9.0 million hectares, an average of 73 Mg ha^{-1} (CONAB, 2015). These numbers indicate Brazil as responsible for approximately 40% of the world sugarcane production; however, the yield average is lower than other countries such as Colombia (86 Mg ha^{-1}), Australia (82 Mg ha^{-1}), and Honduras (84 Mg ha^{-1}). Moreover, since 2008, when cane yield average peaked at 80 Mg ha^{-1}, we have observed a decrease in the brazilian sugarcane yield, combined with continuous expansion of the cultivated areas (FAO, 2016).

In general, changes in harvesting may assist to explain this scenario. In previous practice, the sugarcane fields were burnt to ease manual or mechanized harvesting, but along the last years, this model has been replaced by mechanized green cane harvesting, mainly because of the agro-environmental protocol signed in 2007. In the brazilian center-south region, where sugarcane fields are more representative, the green cane harvesting represents approximately 85% of the total area (CTC, 2012). The green cane trash blanketing (GCTB) system has several advantages for the environment (local air quality), agronomic (soil moisture maintenance, nutrient recycling, weed reduction) and social and human health (less labour intensive). However, the significant amount of crop residue on the surface that remains after the harvest (up to 20 Mg ha^{-1}, Fortes et al., 2012) have also produced changes in N fertilization.

Before the GCTB model, deep N placement was commonly practiced in sugarcane fields to prevent N losses to the environment (MARIANO, E. et al., 2016). Today, N fertilizers are frequently applied on the surface because of difficulty accessing the soil subsurface through the residue layer (~100 mm, Leal et al., 2013). However, the N fertilizer placement in the surface of crop residues may increase the N losses by ammonia (NH_3) volatilization (PRASERTSAK et al., 2002; COSTA et al., 2003; SOMMER et al., 2004; NASCIMENTO et al., 2013; DATTAMUDI et al., 2016). Especeally, when urea fertilizer is used, one of the most relevant sources in brazilian ratoon cane fields, the N losses via NH_3 volatilization can reach up to 40% due to urease activity in the crop residues (COSTA et al., 2003). Alternatively, we have observed the use of N fertilizer sources with low NH_3 volatilization, such as ammonium nitrate (NH_3 emission equals 3 to 5%, Vitti et al., 2007).

Nevertheless, microbial immobilization and losses via denitrification may also limit the effectiveness (Basanta et al., 2003; Fortes et al., 2013; Franco et al., 2011; Vieira-Megda et al., 2015). In an attempt to reduce the impact of placement on the surface, the fertilizer has been applied “below of the crop residues”. The working principle is realized by insufflations of fertilizer across the residue layer.

Under the described conditions, perceptions of the lower effectiveness of N fertilization in GCTB systems may lead farmers to adopt greater N fertilizer rates. Before the practice, an empirical and widely adopted recommendation was 1.0 kg N per expected sugarcane stalk Mg (100 kg ha^{-1} N to achieve a cane yield of 100 Mg ha^{-1}, e.g.); but now, to maintain the expected yield indexes, this empirical factor has been replaced by 1.2 kg N per millable stalk Mg (OTTO et al., 2016). Nowadays, the N fertilizer rate applied on ratoon cane fields in São Paulo state is approximately 100 to 120 kg ha^{-1}. Higher N fertilizer rates may increase the stalk yield; even so, there is not a linear correlation, especially when the applied rates are higher than 150-180 kg ha^{-1} (FORTES, C. et al., 2013; VALE et al., 2013; CASTRO et al., 2014; LOFTON; TUBAÑA, 2015; SILVA et al., 2015). Moreover, this empirical practice does not seem to be the most proper technical management from economic or environmental perspectives.

To improve nitrogen use efficiency (NUE) under GCTB systems, Otto et al. (2016) suggested some strategies to optimize plant uptake and reduce losses. Among the management practices, the authors highlighted placement methods for mineral N availability (NH_4^+ and NO_3^-). In general, NUE is influenced by the interactions between fertilizer and soil (leaching, denitrification, immobilization and volatilization), N fertilizer rate, N source, placement, fertilizer application timing, plant N demand and uptake (DORDAS, 2015). Among these, deep placement under conservative agriculture tillage may improve the soil mineral N availability for plant uptake, consequently impacting the NUE (DORDAS, 2015). According to recommendations of the International Plant Nutrition Institute, the best management practices (BMPs) for nutrient stewardship encourage applying the right product (source), at the right rate, at the right time, and using the most appropriate placement (IPNI mission’s, 2016). In this context, precision agriculture may contribute with machinery technologies to support site-specific management of the BMPs.

In GCTB systems, one strategy to access the soil subsurface for deep N fertilizer placement involves crop residue cutting. For this, a rolling disc (toothed, notched or smooth) followed by a shank is used for continuous incorporation. However, the cutting process may introduce a greater amount of trash into the furrow, when the coulter pushes straw against the ground without cutting it (BIANCHINI and MAGALHÃES, 2008). This condition may decrease the effectiveness of N fertilizer incorporation, especially in dried soils, because the soil clods do not favor complete fertilizer incorporation. Alternatively, we have worked to develop a site-specific management method that encompasses a mechanized soil punching process and liquid fertilizer injection to provide nutrients near the roots of plants using a minimal disturbance of soil, roots and crop residues (SILVA et al., 2017). By means of point deep placement, we propose to overcome the current difficulties in the conventional incorporation of fertilizers into the soil (as well as crop residue cutting and soil mobilization), as well as reduce the partial damage to the root systems used in nutrient uptake.

For point deep placement under GCTB systems, Silva and Magalhães (2014) proposed soil punching with applications distanced every 300 mm (the average distance between ratoons) and fluid incorporation at a depth higher than 50 mm to attempt to reach an appropriate mineral N availability for plant uptake. For this, a prototype was designed to enable liquid fertilizer injection synchronized with mechanized soil punching. The advantages included a low power demand for soil punching and liquid fertilizer injection (less than 3.5 kW); on the other hand, variations in soil micro relief and soil penetration resistance can interfere in the operation quality (SILVA et al., 2017).

Here, we extend the point deep placement method to the sugarcane field, to search answers such as which length represents a proper distance between application points. In addition, the experiment covered the common placement methods for N fertilization in ratoon cane (surface, continuous incorporation into the soil, application below the crop residues). This work aimed to find better N fertilizer placement practices for site-specific management using liquid fertilizer under the GCTB system. In order to the objective, we performed a comparative analysis related to the (i) soil mineral N availability, (ii) crop measures (chlorophyll index, leaf N), and (iii) sugarcane product (cane stalk yield and sugarcane quality).

5.2 MATERIAL AND METHODS

5.2.1 Experimental field descriptions

The placement methods for nitrogen fertilization were evaluated in a first ratoon crop, supported by the Iracema Sugar Mill (São Martinho Group), located at Iracemápolis county (São Paulo state, Brazil: 22.75º S and 47.43º W). The soil site was classified as Rhodic Eutrudox (Soil Survey Staff, 2010), analogous to Latossolo Vermelho distroférrico (EMBRAPA, 2006b). According to the USDA texture triangle, the soil was classified as clay (clay 49 to 57%, sand 36 to 38% and silt 6 to 14%). The selected experimental area was planted with sugarcane cultivar RB855156. This choice was based on positive results for N fertilization rates over the cane stalk yield (SILVA et al., 2015). RB855156 is associated with early maturation, good budding and tillering at the ratoon stage, easy husking of the dry leaves and disease resistance against rust, mosaic, red leaf streaks, and leaf scald, e.g. (MATSUOKA et al., 1995).

On May 15, 2014, the plant cane was mechanically harvested without burning, and the crop residues (dry leaves and tops) were left on the surface (approximately 10 Mg ha^{-1} of dry mass). Ten days after harvest, soil samples were taken at different layers (up to 1 m deep). Each sample was homogenised using four replication points, collected parallel to the sugarcane rows (~300 mm beside). The laboratory methodology for chemical analysis (Table 5) was performed according to Raij et al. (2001).

Table 5 – Soil chemical parameters before N fertilization (May 2014)

Depth	P	Mg	Ca	K	Al	H+Al	CEC*	BS	pH	V	TOC	SOM
m	mg dm^{-3}	------------------mmol$_c$ dcm^{-3}						--------------------	CaCl$_2$	%	---g dcm^{-3}---	
0.0 - 0.2	65	23	37	2.4	0	42	105.1	63.1	5.3	60	19	32
0.2 - 0.4	12	14	37	0.4	0	28	80.2	52.2	5.4	65	12	20
0.4 - 0.6	30	14	27	0.6	5	45	87.4	42.4	4.8	49	12	20
0.0 - 0.1	40	29	40	1.4	0	40	110.4	70.4	5.4	64	21	37
0.1 - 0.2	39	19	29	0.8	2	38	86.8	48.8	5	56	13	23
0.6 - 1.0	8	12	38	0.5	0	20	70.5	50.5	5.5	72	8	13

*Cation exchange capacity (CEC), bases sum (BS), base saturation (V), Total organic carbon (TOC), Soil organic matter (SOM).

5.2.2 Experiment design and treatments

The N fertilization was performed after the mechanical green harvesting, before the beginning of ratoon cane sprouting. We used ammonium nitrate mixed with water (concentration of 0.21 kg L^{-1} N). The N fertilizer rate was 100 kg ha^{-1}, which is commonly applied to ratoon crops in Sao Paulo state, Brazil. This N source has low losses associated with NH_3 volatilization, even when it is applied on the surface of the crop residues (VITTI et al., 2007). This characteristic helps to compare the real effect of the placement method on the mineral soil availability, crop nutritional status and stalk yield.

In order to evaluate the N fertilizer placement, we took into account common methods employed for ratoon cane in Brazil, as well as the alternatives for site-specific management. The treatments were: surface placement at one side (i) or at both sides of the cane rows (ii), placement below the crop residues at one side (iii), deep placement by continuous incorporation at one side (iv) or at both sides of the cane rows (v), point deep placement (at one side) by punching application distanced every 150 mm (vi – pa150), 300 mm (vii – pa300) and 450 mm (viii – pa450), and control treatment without fertilizer (ix). The nine treatments were randomly allocated inside four blocks (randomized block design). Each plot was established with seven cane rows (10.5 m wide) that were 15 m long (157.5 m^2). This arrangement was considered enough to minimize soil variability effects on the comparison analyses.

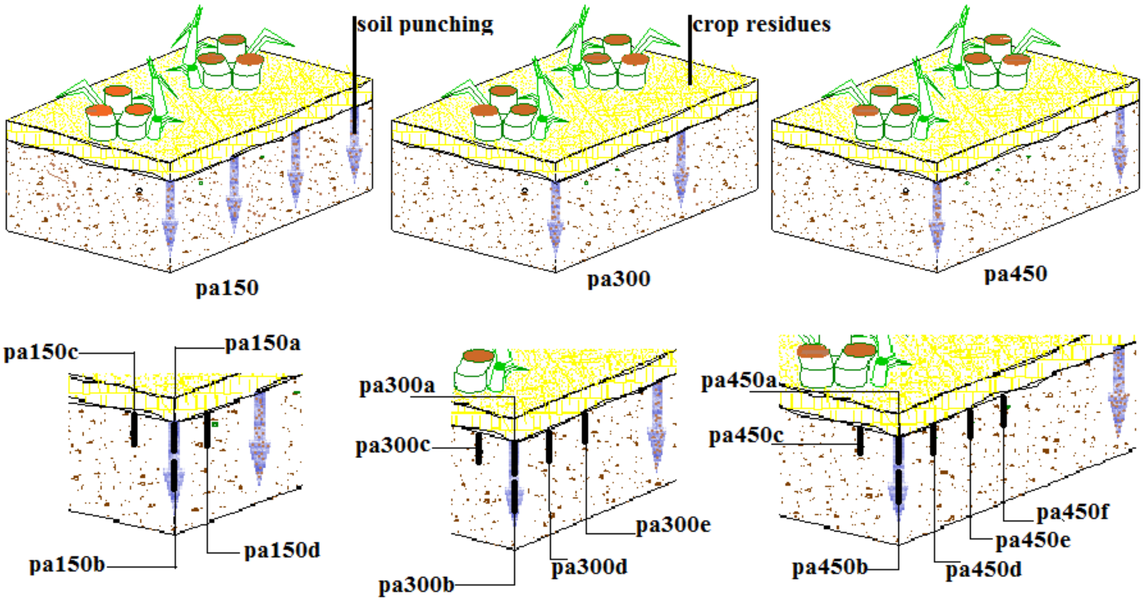
The N fertilizer placement was performed approximately 200 mm beside the cane rows (at one or both sides). On the surface, the liquid fertilizer was sprinkled on the crop residues by a banded application of ~50 mm wide. For continuous deep placement, the crop residues were partially removed to the interrow space to opening furrows of ~100 mm deep; after this process, the liquid fertilizer was sprinkled inside the furrows, followed by incorporation with the mobilized soil and return of the crop residues. In the soil punching applications (pa150, pa300, pa450), we used a metallic bar (15 mm diameter) to drill up to 100 mm deep. The liquid fertilizer dosage (D, Eq. 1) applied per soil punch was determined according to N concentration (0.21 kg L^{-1}), N fertilizer rate (100 kg ha^{-1}), interrow spacing (1.5 m) and soil punching distance (Sdist equals to 0.15, 0.3 or 0.45 m $cycle^{-1}$). For application, we used a hand syringe as a simple pump to measure and inject the liquid fertilizer into the punching orifices. For continuous applications, glassware (beaker) was used for uniform placement.

$$\mathrm{D\ (mL\ cycle^{-1})} = \frac{\mathrm{rate(kg\ ha^{-1}) * interrow\ (m) * S_{dist}\ (m\ cycle^{-1}) * 10^{3}(mL\ L^{-1})}}{\mathrm{concentration(kg\ L^{-1}) * 10^{4}(m^{2}\ ha^{-1})}} \tag{1}$$

5.2.3 Soil mineral N evaluations

We evaluated the soil mineral N availability for the days after fertilization (DAF). Throughout the cane cycle, soil sampling was performed fourteen times, but more often at the beginning, after the N fertilization (7, 14, 21, 28, 42, 57, 70, 100, 123, 158, 191, 247, 282, and 365 DAF). The soil samples were taken on the central rows of the plots using a soil sampler probe (Sondaterra, Model S-60, Piracicaba, São Paulo, Brazil). For each evaluation of the continuous placement treatments, one soil sample was taken per plot, near the cane row (exactly at the same spot where the fertilizer was placed). The soil sampling was similar to the control treatment. However, for the soil punching treatments, more samples were taken to observe the mineral N diffusion around the application point. In pa150, four samples were collected per plot; the first two samples were taken from one of the drillings (marked by thin bamboo sticks randomly arranged along the application points) at 0-100 mm and 100-200 mm depths (pa150a and pa150b, Figure 25). The second point was collected in the transverse direction of the cane row (pa150c) and the third point was sampled in the cane row direction, at an intermediate distance between the application points (pa150d); both samples were taken at 0-100 mm depth. For the pa300 and pa450 treatments, more samples were taken between the application points using a similar procedure.

Figure 25 – Soil sampling procedure used in the soil punching methods



The collected samples were stored in a cold chamber under 5 ºC to decrease microbiological activity, in order to maintain the ammonium (NH_4^+-N) and nitrate (NO_3^--N) levels until extraction and analysis. For NH_4^+-N and NO_3^--N extraction from the soil samples, we mixed 5 g of soil with 25 mL of KCl solution (2 mol L^{-1}). The extract mixture was shaken for 1 hour (Ethik Technology, orbital shaker 109/2TC, Vargem Grande Paulista-SP, Brazil). In sequence, the mixture was filtered on filter paper (nº. 42). The mineral N content was determined using a flow injection analysis system. First, to measure the NH_4^+-N content, a conductivity method was used (REIS et al., 1997). For this, NH_3 was produced in an alkaline medium permeated through a hydrophobic membrane (PTFE), collected by a deionized water stream, and injected towards the conductivity meter (Gehaka, Model CG1400, São Paulo-SP, Brazil). NO_3^--N was determined using a colorimetric method. The NO_3^--N was reduced to NO_2^- using a copperized Cd column. In sequence, the NO_2^- was diazotized and coupled with N-(1-naphthyl) ethylenediammonium dichloride (GINÉ et al., 1980). According to the NO_2^- concentration, the color intensity was measured using a spectrophotometer (Bel Photonics, Model S-05, Piracicaba-SP, Brazil). In addition, the soil samples were oven dried at 105 °C for 48 hours to measure soil water content and express NH_4^+–N and NO_3^-–N concentrations as a function of the soil mass (dry weight basis).

5.2.4 Crop evaluations

At 84, 125, 190 and 247 DAF, a portable chlorophyll index meter (Konica Minolta, Model SPAD-502, Osaka-Japan) was used to measure leaf greenness, as an indicator parameter to assess plant N status. For these evaluations, we randomly selected 10 leaves +1 (the first leaf from the top with clearly visible dewlap) per plot, always on the central rows. To determine the average value per leaf, three measurements were taken around the midpoint, excluding the midrib (a similar procedure is described in Amaral and Molin, 2014; Radhamani et al., 2015). From these measurements, average values were determined for plots and treatments. Also at 125, 190 and 247 DAF, to evaluate N nutritional status by means of leaf analysis, the leaves selected for chlorophyll measurements were stored in paper bags. Then, the midribs, bases, and tips were cut by scissors and discarded. The samples were dried in an air-circulation oven at 65 °C for 72 hours; then, the dried leaves were ground in a Wiley mill (Tecnal, Model TE-650, Piracicaba, SP, Brazil). After this procedure, the samples were sent for laboratory analysis, where the N content in plant tissues was determined by the digestion of plant material using H_2SO_4 and H_2O_2, with subsequent steam distillation and titration of the samples (NELSON and SOMMERS, 1973).

Before the harvest (at 373 DAF), a random point was select per plot (in the central rows) where ten stalk units were sampled and sent to the laboratory to measure quality attributes (cane pol, juice pol, brix, and total sugar recovery) using a methodology based on Fernandes (2003). The cane harvesting was performed on June 17, 2015 (387 DAF). To measure the stalk yield, the sugarcane was harvested using a mechanical green harvester accompanied by a cane-truck instrumented with load cells. On evaluation, the cane mass was measured in the three central rows of each plot. Then, an average value was determined for plots and treatments. To contribute to the analysis of the crop measures (chlorophyll index, N content in vegetal tissues, stalk yield and quality attributes), the statistics were explored using Matlab (MathWorks, Version R2012a, Natick, MA, USA). The results were submitted to ANOVA via test F and Tukey's test for the comparison of means ($p \leq 0.05$).

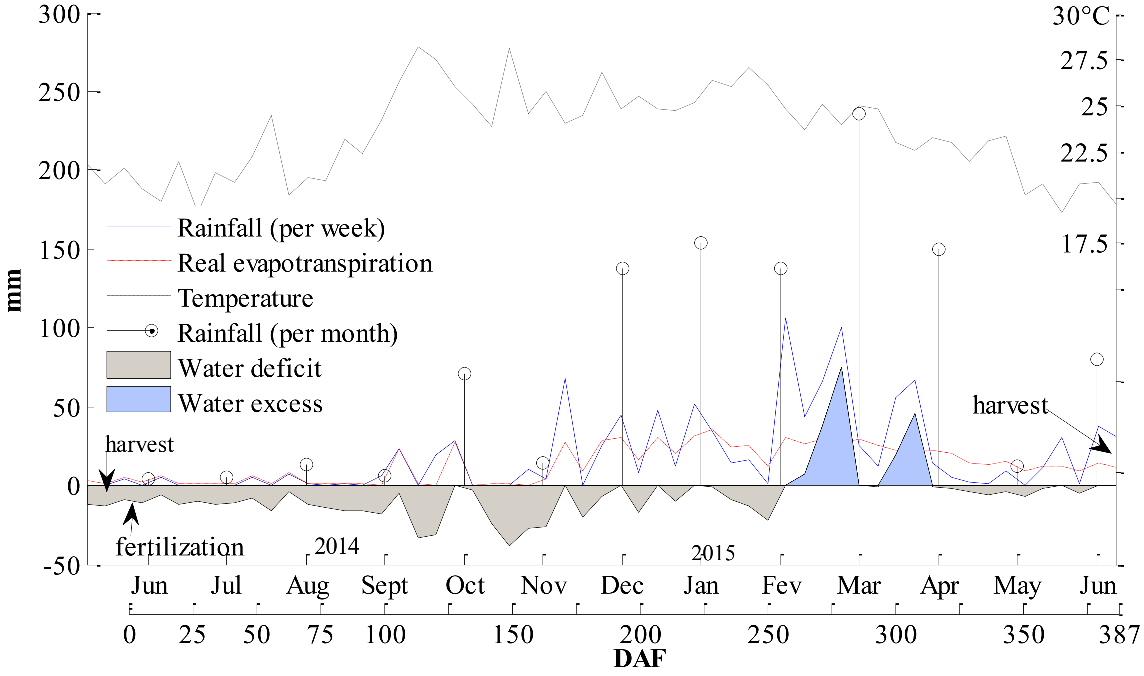
5.2.5 Climatic condition descriptions to the ratoon cane

The experimental period included the sugarcane harvest and N fertilization (near to the autumn end). Historically, the local climate is characterized by lower temperatures (14-23ºC) and lower rainfall (~60 mm accumulated per month), with similar conditions extended into the winter (INMET, 2015). After the cane harvest, ratoon cane needs approximately one year to complete the growth cycle (sprouting, growth, and maturation). Throughout this period, climate conditions have a significant influence on biomass accumulation (stalk yield) and quality parameters (sucrose, brix, cane pol). In particular, the available water in the soil (nutrient influx in the plants) and evapotranspiration are important. In general, lower temperatures and rainfall are favourable for sucrose accumulation in the maturation phase; on the other hand, it may produce negative effects on ratoon sprouting and biomass accumulation. In São Paulo state, the sugarcane harvest is predominantly concentrated at the autumn and winter seasons (70% of the cane production, equivalent to ~271 million Mg (UNICA, 2015)). In this context, N fertilization is a common practice after the sugarcane harvest.

Optimal sugarcane growth occurs at 22 to 30 °C, with a water demand of approximately ~1,400 mm, which must be primarily distributed during sprouting and growth (EMBRAPA, 2015). According to the local rainfall history, the annual average rainfall is approximately 1,335 mm and is essentially concentrated in the spring and summer. In the

2014/2015 season, the rainfall totalled 941 mm during the ratoon cane cycle (52% in the summer). This rainfall was considered insufficient, because it was less than the total required by sugarcane (30% lower than the local rainfall precipitation average). The critical rainfall situation occurred after N fertilization, during the sprouting and sugarcane growth periods (Figure 26). Combined with the lower average temperatures (~21 °C) during autumn and winter, these conditions produced a water deficit in the soil and low evapotranspiration (near zero); this water deficit was extended up to the medium sugarcane growth. From October 2014, increases were recorded in the rainfall and temperature. Nonetheless, the water deficit was prolonged until the end of 2014.

Figure 26 – Annual water balance during cane cycle (2014-2015)



Source: CIIAGRO (2015)

5.3 RESULTS AND DISCUSSION

5.3.1 Mineral N diffusion through the point deep placement of the liquid fertilizer

A larger distance between application points received a proportionally larger dosage per punch. This was evidenced by the mineral N concentration in pa450a being higher than pa150a (Figure 27), especially at the first days after fertilization, when the $NH4^+$-N concentration was approximately 1.5 times greater (2800 mg kg^{-1} versus 1650 mg kg^{-1}, at 7 DAF). In contrast to the placement points, the mineral N availability was lower in the intermediate space between the soil punches. In pa450 and pa300 (Figure 27B and C), the sampled points (pa450f, pa450e and pa300e) revealed results equivalent to the control. On the other hand, in the intermediate space between applications distanced every 150 mm (pa150d), a significant mineral N availability was recorded, although lower than at the punching point (pa150a).

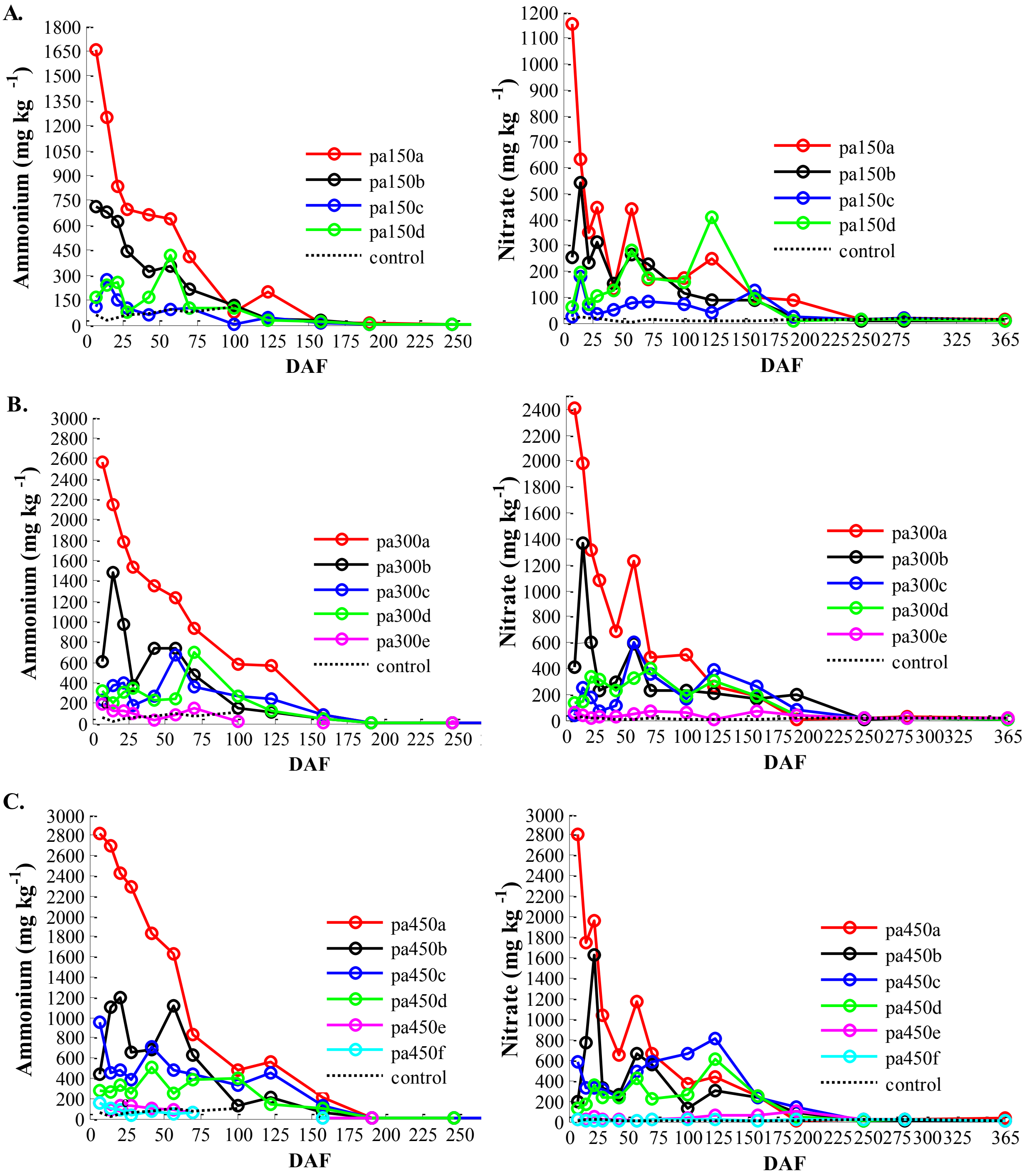
In general, the NH_4^+-N availability was higher than the NO_3^- -N after N fertilization. Throughout the cycle, both N mineral forms were lower at the evaluated points, but the NH_4^+-N was reduced with greater intensity, possibly due to nitrification mediated by the soil microorganisms (the ammonia-oxidizing archaea "AOA" and bacteria "AOB") that convert ammonia to nitrate (via nitrite route, NO_2^-). This process is considered a major pathway to N loss in terrestrial ecosystems and agricultural systems (BANNING et al., 2015).

During the period of evaluation, the mineral N was increased around the application point (pa150c,d; pa300c,d; pa450c,d). This behavior was observed mainly for NO_3^--N concentration. At 125 DAF, soil samples taken 75 mm beside pa150a showed a higher NO_3^--N concentration (250 mg kg^{-1} for pa150a versus 400 mg kg^{-1} for pa150d). This result was attributed to nitrification and nitrate mobility through the soil, although mineral N was mostly concentrated in the application points (until ~150 DAF for NH_4^+-N and until ~75DAF for NO_3^--N). The N fertilizer losses to the environment may be easily due to the high point concentration availability of inorganic N, especially when the soluble concentration exceeds the plant needs, the nutrient uptake capacity and soil mineral N retention (CHIEN et al., 2009).

The mineral N diffusion was mainly around the application points (just at 75 mm beside). Lower values were also observed in the vertical depth (at 100 – 200 mm deep, below the soil punching, Figure 27); however, significant results were attributed to the liquid fertilizer infiltration. The scarce rainfall and low soil moisture may help to explain the mineral N diffusion. In the range of 100 to 175 DAF, temperature increase and rainfall frequency (Figure 26) also contribute to understand the mineral N decrease around the applications. Better conditions related to soil water content and higher temperatures may have contributed to increase the microbial activity (mineral N transformations), N mineral uptake by the plants, and N losses (THORBURN et al., 2005).

Among the soil punching methods, the mineral N diffusion was better when the liquid fertilizer was applied distanced every 150 mm. This was seen in the concentration level measured at intermediate points between the applications, especially for NO_3^--N. In addition, the mechanized soil punching to liquid injection may improve the mineral N distribution, because the liquid jet velocity must achieve a liquid penetration into the soil and produce a wet bulb around the application point. On injection, the liquid penetration into the soil occurring due to the jet pressure is enough to locally reduce and crack the soil binding mechanisms (NIEMOELLER et al., 2011).

Figure 27 – Soil mineral N availability considering the point deep placement. The soil punching distanced: a. 150 mm (pa150); b. 300 mm (pa300); c. 450 mm (pa450)



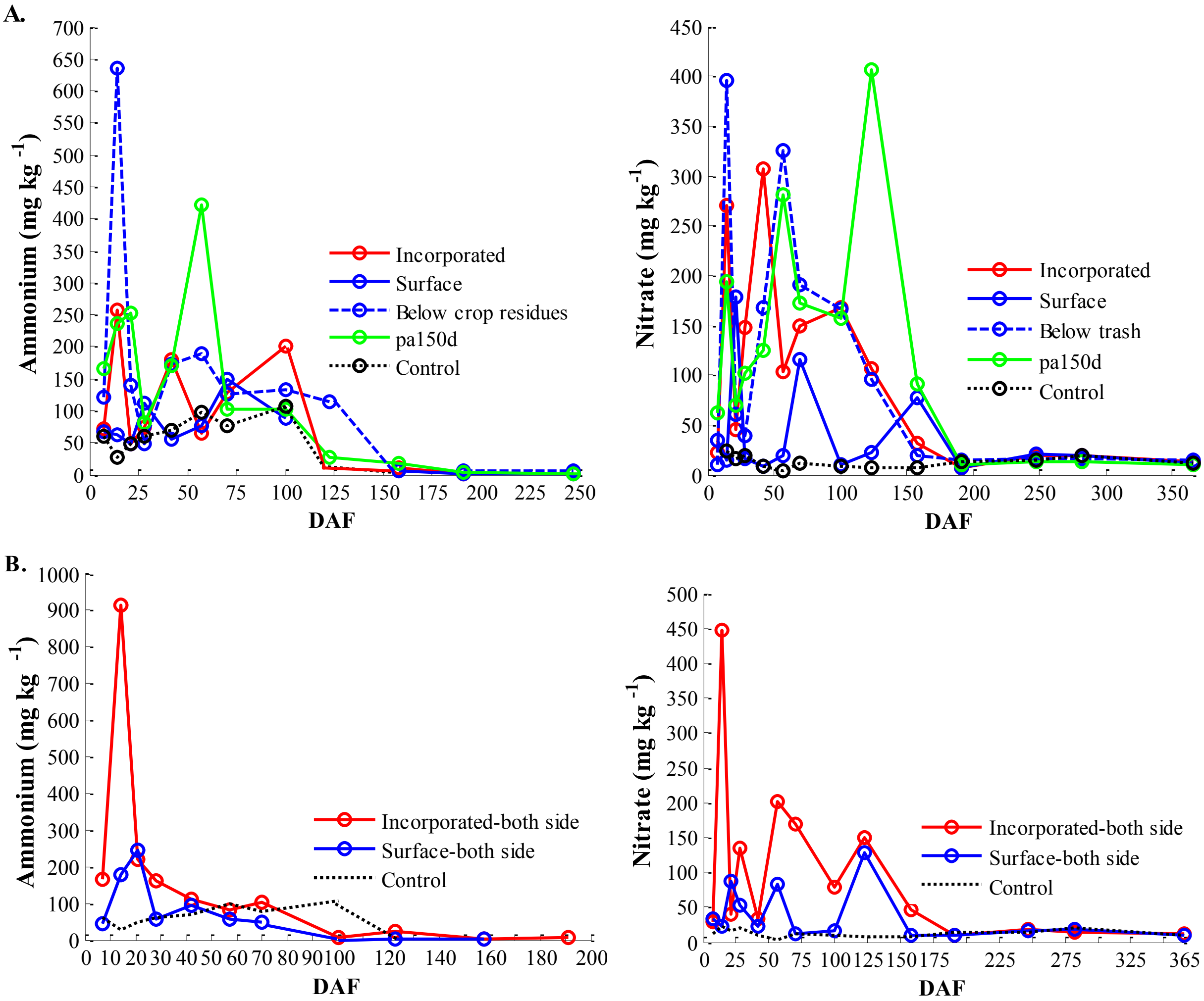
5.3.2 Effect of N fertilizer placement on mineral N availability

Before the N fertilization, the NH_4^+-N average was 16.54 mg kg^{-1} and the NO_3^--N average was 28.19 mg kg^{-1}. After fertilization, we observed a similar behavior for the NH_4^+-N and the NO_3^--N. Essentially, mineral N concentrations were higher on the first DAF, followed by a decrease along the cycle (Figure 27 and Figure 28). Along the cycle, a greater mineral N availability was measured from the deep placement methods compared to the treatments where liquid fertilizer was applied on the surface of the crop residue. This behavior was mainly expressed in the surface placement at both side of the sugarcane rows (Figure 28b), where, in addition to the differences in the soil mineral N, the longer time to achieve maximum values was attributed to the crop residue, which acts as a transition zone between fertilizer and soil. In the continuous incorporation at both sides, the maximum NH_4^+-N concentration was recorded for 14 DAF (900 mg kg^{-1}), whereas for surface placement, NH_4^+-N peaked at 21 DAF (250 mg kg^{-1}). In general, these results are aligned with similar studies of deep placement effectiveness associated with mineral N availability (PRASERTSAK et al., 2002; MA et al., 2009; LIU et al., 2015; CASTRO et al., 2016).

In contrast, when the liquid fertilizer was applied below the crop residues, the soil mineral N was equivalent to the continuous incorporation method (Figure 28a). This condition was associated with contact between the liquid fertilizer and soil surface, which allows infiltration towards the deep layer. Regarding the continuous incorporation or placement below the crop residues, pa150 achieved the most similar results for mineral N availability among the point deep placement methods. A significant concentration of the mineral N in the intermediate point between the soil punching applications (pa150d) was observed (Figure 28a), in which the highest NO_3^--N at pa150d was 410 mg kg^{-1} (at 123 DAF), versus 307 mg kg^{-1} when liquid fertilizer was continuously incorporated (at 42 DAF).

In addition, the NH_4^+-N content when the fertilizer was applied on the surface of the crop residue was similar to the control; although a significant NO_3^--N level was attributed to the mineral N mobility (THORBURN et al., 2005). In general, the ammonium nitrate source produces low losses associated with ammonia volatilization (VITTI, A. C.; TRIVELIN, P C. O.; GAVA; FRANCO; BOLOGNA; et al., 2007), however, the mineral NH_4^+-N availability in the crop residues may favor nutrient immobilization by the microorganisms, due to a higher C:N ratio of ~100:1 (FORTES, C. et al., 2012). Favorable conditions for N immobilization appear especially when the C:N ratio is greater than 44:1 (CHEN et al., 2014). This process contributes to crop residue decomposition, and may help to add soil mineral N in the long-term (FORTES, C. et al., 2012). This occurs to both mineral forms (NH_4^+ and NO_3^-); however, microorganisms prefer NH_4^+ rather than NO_3^-. For assimilation, NO_3^- reduction needs more energy (MARIANO, E. et al., 2016); this may also explain the higher NO_3^--N content in the soil extracts. Plants can assimilate both N forms but sugarcane also prefers NH_4^+ for uptake (ROBINSON et al., 2011).

Figure 28 – Soil mineral N availability. a. Placement at one side of the cane rows. b. Placement at both sides of the cane rows



The soil mineral N availability was decreased to near the control values until the intermediate growth stage (until ~100-150 DAF for NH_4^+-N and until ~200 DAF for NO_3^--N). The reduction was attributed to the nutrient uptake by the plants or inclusion into the N dynamic routes of the soil-plant-atmosphere. Soil mineral N was derived from fertilizer and soil organic nitrogen mineralization, where availability depends on biochemical transformations. The common possible routes to the mineral N losses refer to leaching, runoff, denitrification, and ammonification. These processes are interrelated with mineral N pathways including biotic immobilization-remineralization, abiotic immobilization, soil organic N mineralization and plant residue organic mineralization (CHEN et al., 2014).

5.3.3 Chlorophyll index in the sugarcane leaves

Previous researchers have demonstrated that leaf chlorophyll index may contribute to determining the nutritional status of plants, especially leaf N (COSTA et al., 2001; ARGENTA et al., 2004; RIOS; MOLIN, 2011; AMARAL et al., 2015). N nutrients contribute to chlorophyll and amino acid synthesis; thus, a deficiency can produce negative effects on growth and yield (FRANCO et al., 2011). Indeed, SPAD measurements are highly efficient to assess the chlorosis level in sugarcane leaves and are an appropriate non-destructive method to analyze sugarcane biomass (correlation r equals 0.93, according to Radhamani et al., 2015).

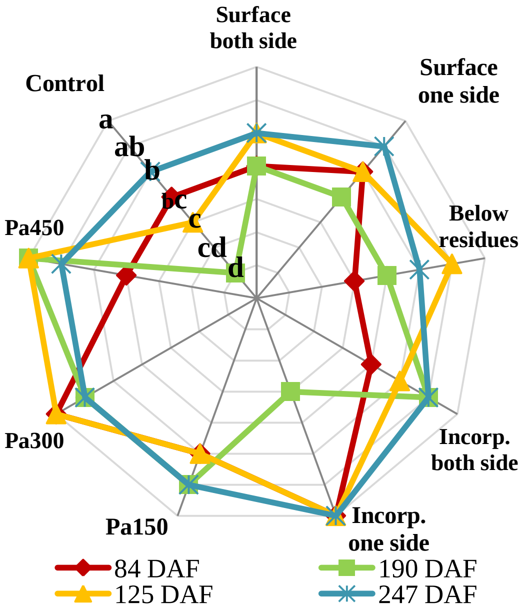
In our work, higher chlorophyll indexes were measured on the first evaluations (84 and 125 DAF). This characteristic is associated with the growth stage, period of maximum vegetative vigor. At the last evaluation (at 247 DAF, near the maturation phase), we perceived slight differences among them (maximum 3%). In general, the N fertilization methods were significant to the chlorophyll indexes when compared to the control values (Figure 29). Essentially, the placement methods presented a chlorophyll index trend. According to multiple comparisons (Figure 29b), better results were achieved for the deep placement methods (pa300, pa450, and continuous incorporation at both side of the cane rows); on the other hand, when the liquid fertilizer was applied on surface of the crop residue were achieved lower indexes. These observations were aligned with mineral N assessments (Figure 28); thus, the mineral N availability in the deep placement may contribute to explain the chlorophyll indexes as indicative of better vegetative vigor during the sugarcane growth stage.

Figure 29 – N fertilizer placement effect measured by the chlorophyll index. A. Spad measurements. b. The multiple comparisons summary from chlorophyll index analyses

Placem. methods	84 DAF		125 DAF		190DAF		247DAF	
Surface both side	47.5	bc	52.6	b	44.6	bc	42.0	b
Surface one side	48.8	b	53.3	b	45.1	bc	42.7	ab
Below c. residues	46.6	c	54.2	ab	44.8	bc	42.1	b
Incorp. both side	47.7	bc	52.7	b	45.9	ab	42.5	ab
Incorp. one side	50.8	a	54.6	a	44.0	c	43.3	a
Pa150	49.0	b	52.9	b	45.5	ab	42.8	ab
Pa300	51.7	a	54.9	a	46.0	ab	42.7	ab
Pa450	47.7	bc	55.1	a	46.6	a	42.2	ab
Control	48.1	bc	47.8	c	38.6	d	42.1	b
L.S.D.	1.6		1.2		1.3		1.2	
C.V. (%)	4.8		3.3		4.2		3.9	

Values followed by the same letter within a column do not differ according to Tukey's test at $p < 0.05$; least significant difference (L.S.D.) and coefficient of variation (C.V.).

(a)



(b)

5.3.4 N fertilizer placement effect in the N leaf

The leaf N content was lower to the control, similar to the chlorophyll index analysis (Table 6). At 190 DAF, we observed a significant difference in the leaf N content when the continuous incorporation at both sides (18.3 g kg^{-1}) was compared to the control (13.3 g kg^{-1}). Further, analogous to the chlorophyll index, higher N contents were achieved at the first evaluations, and at 247 DAF (last evaluation), the lowest values were associated with the beginning of the maturation phase. However, we could not perceive a similar trend for the placement methods with regards to the leaf N content. At 190 DAF, the leaf N for the surface placement method (18.1 g kg^{-1}) was higher than for the placement below the crop residues (16.6 g kg^{-1}), where higher mineral N availability was observed (Figure 28). As one suggestion to explain this result, the leaf N may have been exuded to the atmosphere, translocated to other plant parts (stalk, rhizomes or roots), or reversed from the vegetal tissues toward the soil (PRASERTSAK et al., 2002).

The ideal leaf N content for leaves from the top visible dewlap of sugarcane ranges from 18 to 25 g kg^{-1} (RAIJ and CANTARELLA, 1996). Therefore, the N fertilization produced an appropriate N nutrition (values greater than 18 g kg^{-1}), especially in the two first assessments. However, despite N fertilization relevance to nutritional balance, sugarcane efficiently uses the mineral N derived from soil organic mineralization (compounds derived from dry matter); this behavior occurs mainly due to extensive root systems, a long growth period (longer than other annual crops, such as maize, rice, and wheat), as well as reserves in rhizomes and roots, accumulated during previous cycles (VIEIRA-MEGDA et al., 2015). Even though, the N fertilizer placement methods can have a positive influence, as shown by Prasertsak et al. (2002), when the deep placement resulted in a higher N content in the sugarcane tissues. In the sugarcane tissues, the N content derived from the fertilizer may range 60 to 70% in the early stages, followed by a reduction towards 10 to 20% near the harvest (FRANCO et al., 2011; VIEIRA-MEGDA et al., 2015). This behavior can sustain the observations of leaf N content in the first evaluations associated with N fertilization (Table 6).

Table 6 – Leaf N according to the N fertilizer placement methods

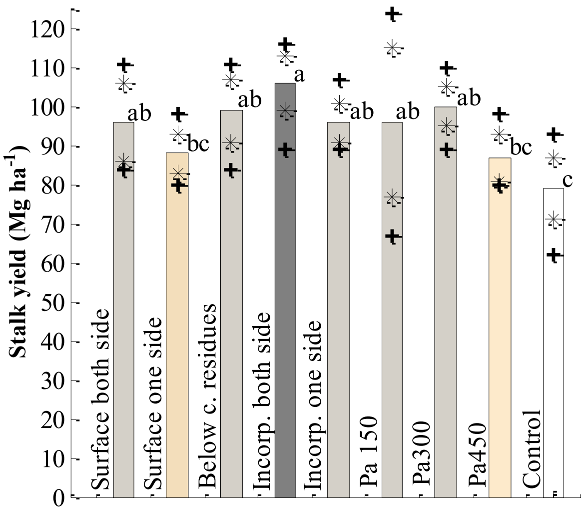
Placement methods	125 DAF		190 DAF		247 DAF	
	-----------------g kg^{-1}------------------					
Surface - both side	19.2	ab	18.1	a	17.1	ab
Surface - one side	20.0	a	18.0	a	17.0	ab
Below c. residues	18.9	b	16.6	c	16.8	ab
Incorporated-both side	18.9	b	18.3	a	17.6	a
Incorporated-one side	19.7	ab	18.1	a	17.1	ab
pa150	19.8	ab	17.2	b	16.7	ab
pa300	19.4	ab	17.7	ab	16.5	b
pa450	19.7	ab	17.5	b	17.1	ab
Control	14.8	c	13.3	d	14.8	c
L.S.D.	1.0		0.5		0.9	
C.V. (%)	1.9		0.9		1.8	
mean	18.9		17.2		16.7	

Values followed by the same letter within a column (treatments) do not differ according to Tukey’s test at $p < 0.05$; least significant difference (L.S.D.); coefficient of variation (C.V.).

5.3.5 N fertilizer placement effect on the cane stalk yield

At sugarcane harvesting, the stalk yield was significantly different according to the N fertilizer placement method (Figure 30). The highest stalk yield was achieved when the liquid fertilizer was continuously incorporated at both side of the cane rows (106 Mg ha^{-1}) and when the liquid fertilizer was applied using soil punches distanced every 300 mm (100 Mg ha^{-1}). On the other hand, the lowest stalk yield was measured in the control treatment (79 Mg ha^{-1}); when compared to the highest stalk yield, the result was significantly different (34%). Essentially, the stalk yield was associated with the mineral N availability achieved through the N fertilizer placement strategies. Distinct results were observed for fertilizer distribution (at both sides or at one side of the rows) and the position where fertilizer was placed (on the surface or incorporated). In the continuous incorporation methods, a higher stalk yield was associated with better fertilizer distribution around the bulb of roots (both sides (106 Mg ha^{-1}) versus at one side (96 Mg ha^{-1})). An analogous trend was observed for the methods with N fertilizer placement on the surface of the crop residues (at both sides (96 Mg ha^{-1}) versus at one side (88 Mg ha^{-1})). When the N fertilizer was applied at both sides of the cane rows, the continuous incorporation resulted in greater stalk yield than the placement on the surface (106 Mg ha^{-1} vs. 96 Mg ha^{-1}).

Figure 30 – Sugarcane stalk yield related to N fertilizer placement methods. Values followed by the same letter at the top of the bars do not differ according to Tukey's test at $p < 0.05$, least significant difference (L.S.D.) equals 12 Mg ha^{-1}, [*] Standard deviation, and [+] maximum and minimum values



Additionally, the millable stalk harvested at pa300 (100 Mg ha^{-1}) and pa150 (96 Mg ha^{-1}) were grouped together with the results from the continuous incorporation at one side (96 Mg ha^{-1}) and placement below the crop residues (99 Mg ha^{-1}); these methods were interrelated with greater soil mineral availability in the subsurface at one side of the sugarcane rows. Here, we guaranteed the ideal continuous fertilizer incorporation; however, under GCTB management, the mechanized soil punching is a viable strategy to access subsurface without needs of mobilization and cutting soil, crop residues and roots (SILVA et al., 2017). The soil punching process may overcome currently difficulties previously reported by Mariano (2016) at placement of nutrients near of the cane roots, caused by the crop residues that remains on surface after the mechanical green harvest.

Although, a lowest stalk yield was observed from the soil punching distanced every 450 mm (87 Mg ha^{-1}, Figure 30). This result was attributed to the larger distance between the application points, considered unfavorable to the N fertilizer availability in the intermediate space between the drillings (Figure 27c). In pa450, besides the worst distribution, the concentration level in the application points may have exceeded the local uptake capacity of the roots; also, higher N fertilizer concentration (especially NH_4^+) may produce toxicity symptoms in the plants (BRITTO and KRONZUCKER, 2002).

In general, these findings contribute to support BMPs taking into account the GCTB systems. In recent research performed to assess the N fertilizer placement effect in ratoon cane, Castro et al. (2016) also highlights advantages to the deep placement of NUE compared to the placement on the surface of the crop residue. To support BMPs for N stewardship in ratoon crop fields, past studies have been primarily targeted to assess the most appropriate N sources, such as urea, ammonium nitrate, ammonium sulfate, or uran (COSTA et al., 2003; VIEIRA-MEGDA et al., 2012; MARIANO et al., 2015), and the N fertilizer rates evaluation, ranging from 40 to 210 kg ha^{-1} (FORTES et al., 2013; VALE et al., 2013; CASTRO et al., 2014; LOFTON and TUBAÑA, 2015; SILVA et al., 2015). However, in addition to the N fertilizer source and application rate relevance, the placement methods also showed an influence on mineral N availability and consequently produced changes in stalk yield. These are aligned to other studies that used a similar comparison, where better results were observed for N fertilizer deep placement, when these principles were applied to the wheat crop (JAT et al., 2014), rice (MOHANTY et al., 1999; LIU et al., 2015), and maize (FEDEROLF et al., 2016).

5.3.6 N fertilizer placement effect on the sugarcane quality parameters

The placement methods for N fertilization also influenced the technological quality parameters (

Table 7). In general, better results were associated with continuous incorporation at both sides. On the other hand, the worst quality parameters were related to the treatment without fertilizer. The major differences were observed for the potential for sugar yield (TPH - tons of pol per hectare). The placement method with continuous incorporation at both sides resulted in a TPH 44% greater than the control treatment (16.7 Mg ha^{-1} versus 11.6 Mg ha^{-1}). In addition, contrasted with surface placement at one side, the TPH was 26% greater (16.7 Mg ha^{-1} versus 13.3 Mg ha^{-1}).

Based on the sugarcane quality related to N fertilizer placement methods, we perceive some analogies with the stalk yield results. When the N fertilizer was incorporated into the soil or applied on the surface of the crop residue, the highest quality indexes (cane pol, juice pol, brix, TPH and TSR) were associated with better N fertilizer distribution at both sides of the rows. Also, where the N fertilizer was applied below the crop residue, continuously incorporated at one side, or soil punches distanced every 300 mm or 150 mm, the TPH results were associated with the soil mineral N similarities.

Table 7 – Sugarcane quality parameters

Placement methods	Cane Pol		Juice Pol		Brix		TSR		TPH	
	---% cane---		-------------% juice------------				kg Mg^{-1}		Mg ha^{-1}	
Surface - both side	15.7	a	17.9	a	20.1	a	156.3	a	15.1	b
Surface - one side	15.3	bc	17.4	b	19.5	b	151.4	bc	13.3	c
Below c. residues	15.5	ab	17.7	ab	19.2	b	154.1	ab	14.9	b
Incorporated - both side	15.7	ab	17.9	a	20.0	a	155.4	ab	16.7	a
Incorporated - one side	15.6	ab	17.7	ab	19.6	ab	154.6	ab	14.6	b
Pa150	15.6	ab	17.8	ab	19.9	ab	155.2	ab	14.2	bc
Pa300	15.1	c	17.3	bc	19.9	ab	151.8	bc	15.2	b
Pa450	15.7	ab	18.0	a	20.0	ab	155.2	ab	13.1	c
Control	14.9	c	16.9	c	19.1	b	148.5	c	11.6	d
L.S.D.	0.4		0.5		0.6		3.9		1.4	
C.V.(%)	1.0		0.8		1.1		1.0		7.0	

Values followed by the same letter within a column (treatments) do not differ according to the Tukey test at $p < 0.05$; least significant difference (L.S.D.); coefficient of variation (C.V.); total sugar recovery (TSR); tons of pol per hectare (TPH).

However, the sugarcane quality differences related to N fertilizer placement methods were very small (especially the cane pol, juice pol, brix and TSR). Previous studies conducted with N fertilization under GCTB conditions generally have shown a positive response for stalk yield (VIEIRA-MEGDA et al., 2012; FORTES, C. et al., 2013; VALE et al., 2013; RODRIGUES JR. et al., 2013; MARIANO et al., 2015; SILVA et al., 2015; CASTRO et al., 2016), but significant differences related to the quality parameters are less common (RIOS and MOLIN, 2011; VIEIRA-MEGDA et al., 2012; FORTES et al., 2013; YANG et al., 2013; LOFTON and TUBAÑA, 2015; CASTRO et al., 2016). Overall, the significant difference is limited to TPH analysis due to the stalk yield influence.

5.4 CONCLUSIONS

The N fertilizer placement methods produced differences in the soil mineral N availability (NH_4^+-N and NO_3^--N) around the application point. In general, the highest NH_4^+-N and NO_3^--N concentrations were found for the deep placement methods when compared to the common practice that uses N fertilizer placement on the surface of the crop residue. Among the methods, a similar mineral N availability was observed for the placement below the crop residue, continuous incorporation at one side, and soil punching distanced every 150 mm. In contrast, lower mineral N availability was achieved for the surface placement methods, where the crop residue acts as a transition zone between fertilizer and topsoil, or when the liquid fertilizer was applied through the soil punching distanced every 450 mm, associated with not enough diffusion around the application points.

In general, the best results (mineral N availability, chlorophyll index, stalk yield and TPH) were observed for the deep fertilizer placement methods, especially when the liquid fertilizer was continuously incorporated at both sides of the cane rows. On the other hand, the worst results were found where the N fertilizer was applied on the surface of the crop residues at one side, or else in the soil punching distanced every 450 mm. In addition, we observed an equivalence among the continuous incorporation, the soil punching methods (application points distanced every 150 mm and 300 mm), and placement below the crop residue (all applied at one side of the cane rows).

Taking into account the N fertilization process in the GCTB system, the liquid fertilizer placement on the surface is less complex, but it was less effective when performed only to one side of sugarcane rows. The N fertilizer deep placement was confirmed as the most appropriate for the site-specific management. In this context, the point deep placement represented an effective alternative to access the soil subsurface under the GCTB system, equivalent to the common continuous incorporation method. These findings contribute to orientate BMPs under the GCTB system, providing support to improve the mechanized process for the liquid fertilizer application.

5.5 REFERENCES

AMARAL, L. R.; MOLIN, J. P. The effectiveness of three vegetation indices obtained from a canopy sensor in identifying sugarcane response to nitrogen. **Agronomy Journal**, v. 106, n. 1, p. 273–280, 2014.

AMARAL, L. R.; MOLIN, J. P.; PORTZ, G.; FINAZZI, F. B.; CORTINOVE, L. Comparison of crop canopy reflectance sensors used to identify sugarcane biomass and nitrogen status. **Precision Agriculture**, v. 16, n. 1, p. 15–28, 2015.

ARGENTA, G.; SILVA, P. R. F.; SANGOI, L. Leaf relative chlorophyll content as an indicator parameter to predict nitrogen fertilization in maize. **Ciência Rural**, v. 34, n. 5, p. 1379–1387, 2004.

BANNING, N. C.; MACCARONE, L. D.; FISK, L. M.; MURPHY, D. V. Ammonia-oxidising bacteria not archaea dominate nitrification activity in semi-arid agricultural soil. **Scientific reports**, v. 5, n. May, p. 11146, 2015. Nature Publishing Group.

BASANTA, M. V.; DOURADO-NETO, D.; REICHARDT, K.; et al. Management effects on nitrogen recovery in a sugarcane crop grown in Brazil. **Geoderma**, v. 116, p. 235–248, 2003.

BIANCHINI, A.; MAGALHÃES, P. S. G. Evaluation of coulters for cutting sugar cane residue in a soil bin. **Biosystems Engineering**, v. 100, n. 3, p. 370–375, 2008.

BRITTO, D. T.; KRONZUCKER, H. J. NH4+ toxicity in higher plants: a critical review. **Journal of Plant Physiology**, v. 159, n. 3, p. 567–584, 2002.

CASTRO, S. G. Q.; DECARO, S. T.; FRANCO, H. C. J.; et al. Best practices of nitrogen fertilization management for sugarcane under green cane trash blanket in Brazil. **Sugar Tech**, p. 1–6, 2016.

CASTRO, S. G. Q.; FRANCO, H. C. J.; MUTTON, M. A. Harvest Managements and Cultural Practices in Sugarcane Harvest Managements and Cultural Practices in Sugarcane. **Revista Brasileira de Ciência do Solo**, v. 38, n. 1, p. 299–306, 2014.

CHEN, B.; LIU, E.; TIAN, Q.; YAN, C.; ZHANG, Y. Soil nitrogen dynamics and crop residues. A review. **Agronomy for Sustainable Development**, v. 34, n. 2, p. 429–442, 2014.

CHIEN, S. H.; PROCHNOW, L. I.; CANTARELLA, H. **Chapter 8 Recent Developments of Fertilizer Production and Use to Improve Nutrient Efficiency and Minimize Environmental Impacts**. 1st ed. Elsevier Inc., 2009.

CIIAGRO. Integrated Center of agrometeorological information: water balance. Disponível em: <http://www.ciiagro.sp.gov.br/ciiagroonline/Listagens/BH/LBalancoHidricoLocal.asp>. Acesso em: 1/1/2015.

CONAB. Monitoring the Brazilian Safra - Sugarcane. Disponível em: <http://www.conab.gov.br/OlalaCMS/uploads/arquivos/15_12_17_09_03_29_boletim_cana_portugues_-_3o_lev_-_15-16.pdf>. Acesso em: 1/1/2016.

COSTA, C.; DWYER, L. M.; DUTILLEUL, P.; et al. Inter-Relationships of Applied

Nitrogen, Spad, and Yield of Leafy and Non-Leafy Maize Genotypes. **Journal of Plant Nutrition**, v. 24, n. 8, p. 1173–1194, 2001.

COSTA, M. C. G.; VITTI, G. C.; CANTARELLA, H. N-NH3 losses from nitrogen sources applied over unburned sugarcane straw. **Revista Brasileira de Ciência do Solo**, v. 27, n. 4, p. 631–637, 2003.

CTC. census of sugarcane variety and yield. Disponível em: <http://www.ctcanavieira.com.br/downloads/Censo2012.pdf>. Acesso em: 13/7/2016.

DATTAMUDI, S.; WANG, J. J.; DODLA, S. K.; ARCENEAUX, A.; VIATOR, H. P. Effect of nitrogen fertilization and residue management practices on ammonia emissions from subtropical sugarcane production. **Atmospheric Environment**, v. 139, p. 122–130, 2016.

DORDAS, C. **Nutrien management perspectives in conservation agriculture, in: Farooq & Siddique - Conservation agriculture (book)**. 1st ed. Springer, 2015.

EMBRAPA. **Brazilian agricultural research corporation: Brazilian system of soil classification**. 2 ed. ed. Rio de Janeiro: EMBRAPA, 2006.

EMBRAPA. Brazilian agricultural research corporation: Embrapa’s technological information agency. Disponível em: <http://www.agencia.cnptia.embrapa.br/gestor/cana-de-acucar/arvore/CONTAG01_10_711200516716.html>. Acesso em: 6/1/2015.

FAO. Food and agriculture organization of the united nations: Statics division. Disponível em: <http://faostat3.fao.org/>. Acesso em: 11/08/2016.

FEDEROLF, C.-P.; WESTERSCHULTE, M.; OLFS, H.-W.; BROLL, G.; TRAUTZ, D. Enhanced nutrient use efficiencies from liquid manure by positioned injection in maize cropping in northwest Germany. **European Journal of Agronomy**, v. 75, p. 130–138, 2016.

FERNANDES, A. C. **Calculations at sugarcane agribusiness (Cálculos na Agroindústria de cana-de-açúcar)**. 2 ed. ed. Piracicaba: STAB. Açúcar, Álcool e Subprodutos, 2003.

FORTES, C.; TRIVELIN, P. C. O.; VITTI, A. C. Long-term decomposition of sugarcane harvest residues in Sao Paulo state, Brazil. **Biomass and Bioenergy**, v. 42, p. 189–198, 2012.

FORTES, C.; TRIVELIN, P. C. O.; VITTI, A. C.; et al. Stalk and sucrose yield in response to nitrogen fertilization of sugarcane under reduced tillage. **Pesquisa Agropecuaria Brasileira**, v. 48, n. 1, p. 88–96, 2013.

FORTES, C.; VITTI, A. C.; OTTO, R.; et al. Contribution of nitrogen from sugarcane harvest residues and urea for crop nutrition. **Scientia Agrícola**, v. 70, n. October, p. 313–320, 2013.

FRANCO, H. C. J.; OTTO, R.; FARONI, C. E.; et al. Nitrogen in sugarcane derived from fertilizer under Brazilian field conditions. **Field Crops Research**, v. 121, n. 1, p. 29–41, 2011.

GINÉ, M. F.; BERGAMIN F, H.; ZAGATTO, E. A. G.; REIS, B. F. Simultaneous determination of nitrate and nitrite by flow injection analysis. **Analytica Chimica Acta**, v. 114, p. 191–197, 1980.

INMET. Brazilian National Institute of Meteorology: Climate history in Iracemapolis - SP. Disponível em: <http://www.climatempo.com.br/climatologia/2341/iracemapolis-sp>. Acesso em: 6/1/2015.

JAT, M. L.; BIJAY-SINGH; GERARD, B. **Nutrient Management and Use Efficiency in Wheat Systems of South Asia**. 1st ed. Elsevier Inc., 2014.

LEAL, M. R. L. V.; GALDOS, M. V.; SCARPARE, F. V.; et al. Sugarcane straw availability, quality, recovery and energy use: A literature review. **Biomass and Bioenergy**, v. 53, p. 11–19, 2013.

LIU, T. Q.; FAN, D. J.; ZHANG, X. X.; et al. Deep placement of nitrogen fertilizers reduces ammonia volatilization and increases nitrogen utilization efficiency in no-tillage paddy fields in central China. **Field Crops Research**, v. 184, p. 80–90, 2015.

LOFTON, J.; TUBAÑA, B. Effect of nitrogen rates and application time on sugarcane yield and quality. **Journal of Plant Nutrition**, v. 38, n. 2, p. 161–176, 2015.

MA, Q.; RENGEL, Z.; ROSE, T. The effectiveness of deep placement of fertilisers is determined by crop species and edaphic conditions in Mediterranean-type environments: A review. **Australian Journal of Soil Research**, v. 47, n. Alston 1980, p. 19–32, 2009.

MARIANO, E.; JONES, D. L.; HILL, P. W.; TRIVELIN, P. C. O. Mineral nitrogen forms alter 14C-glucose mineralisation and nitrogen transformations in litter and soil from two sugarcane fields. **Applied Soil Ecology**, v. 107, p. 154–161, 2016. Elsevier B.V.

MARIANO, E.; LEITE, J. M.; MEGDA, M. X. V; TORRES-DORANTE, L.; TRIVELIN, P. C. O. Influence of nitrogen form supply on soil mineral nitrogen dynamics, nitrogen uptake, and productivity of sugarcane. **Agronomy Journal**, v. 107, p. 641–650, 2015.

MATSUOKA, S.; ARIZONO, H.; BASSINELLO, A. I.; et al. Super precocious varieties of sugarcane. **Álcool & Açúcar**, , n. 78, p. 22–30 (in portuguese), 1995.

MOHANTY, S. K.; SINGH, U.; BALASUBRAMANIAN, V.; JHA, K. P. Nitrogen deep-placement technologies for productivity , profitability , and environmental quality of rainfed lowland rice systems. **Nutrient Cycling in Agroecosystems**, p. 43–57, 1999.

NASCIMENTO, C. A. C. DO; VITTI, G. C.; FARIA, L. D. A.; LUZ, P. H. D. C.; MENDES, F. L. Ammonia volatilization from coated urea forms. **Revista Brasileira de Ciência do Solo**, v. 37, n. 1, p. 1057–1063, 2013.

NELSON, D. W.; SOMMERS, L. E. Determination of Total Nitrogen in Plant Material. **Agronomy Journal**, v. 65, p. 109–112, 1973.

NIEMOELLER, B.; HARMS, H. H.; LANG, T. Injection of liquids into the soil with a high-pressure jet. **Agricultural Engineering International: CIGR Journal**, v. 13, n. 2, p. 1–15, 2011.

OTTO, R.; CASTRO, S. A. Q.; MARIANO, E.; et al. Nitrogen Use Efficiency for Sugarcane-Biofuel Production: What Is Next? **BioEnergy Research**, v. 1, p. 1–18, 2016.

PRASERTSAK, P.; FRENEY, J. R.; DENMEAD, O. T.; SAFFIGNA, P. G.; PROVE, B. G.

Effect of fertilizer placement on nitrogen loss from sugarcane in tropical Queensland. **Nutrient Cycling in Agroecosystems**, v. 62, n. 3, p. 229–239, 2002.

RADHAMANI, R.; KANNAN, R.; RAKKIYAPPAN, P. Leaf chlorophyll meter readings as an indicator for sugarcane yield under iron deficient typic haplustert. **Sugar Tech**, v. 18, n. 1, p. 61–66, 2015.

RAIJ, B. VAN; CANTARELLA, H. Lime and fertilizer recommendations for the State of Sao Paulo. **Van Raij, B. Cantarella, H. Quaggio, J. A. Furlani, A. M. C.** 2nd ed., p.233– 243., 1996. Campinas, SP, Brazil: Fundação IAC.

RAIJ, V. B.; ANDRADE, J. C.; CANTARELLA, H.; QUAGGIO, J. A. **Chemical analysis for evaluation of the fertility of tropical soils**. 2 ed ed. Campinas, SP, Brazil: Instituto Agronômico; Fundação IAC., 2001.

REIS, B. F.; VIEIRA, J. A.; KRUG, F. J.; GINÉ, M. F. Development of a flow injection system with two analytical paths for ammonium determination in soil extracts by conductometry. **Journal of the Brazilian Chemical Society**, v. 8, n. 5, p. 523–528, 1997.

RIOS, L.; MOLIN, P. Sensor óptico no auxílio à recomendação de adubação nitrogenada em cana ‐ de ‐ açúcar. n. 1, p. 1633–1642, 2011.

ROBINSON, N.; BRACKIN, R.; VINALL, K.; et al. Nitrate paradigm does not hold up for sugarcane. **PloS one**, v. 6, n. 4, p. e19045, 2011.

RODRIGUES JR., F. A.; MAGALHÃES, P. S. G.; FRANCO, H. C. J. Soil attributes and leaf nitrogen estimating sugar cane quality parameters: Brix, pol and fibre. **Precision Agriculture**, v. 14, n. 3, p. 270–289, 2013.

SILVA, G. P.; PRADO, R. M.; ALMEIDA, T. B. F.; CAMPOS-NÓIA, N. R. Response of a fourth ratoon sugarcane crop to nitrogen, silicon, and lime fertilization. **Agrociencia**, v. 49, n. 5, p. 533–544, 2015.

SILVA, M. J.; FRANCO, H. C. J.; MAGALHÃES, P. S. G. Liquid fertilizer application to ratoon cane using a soil punching method. **Soil & Tillage Research**, v. 165, p. 279–285, 2017.

SILVA, M. J.; MAGALHÃES, P. S. G. Design of a mechanical system for liquid fertilizers injection in ratoon cane. ASABE and CSBE/SCGAB Annual International Meeting. **Anais...** . p.10p, 2014. Montreal-CAN.

SOIL SURVEY STAFF. **Keys to Soil Taxonomy**. 11th ed. Washington: USDA- Natural Resources Conservation Service, 2010.

SOMMER, S. G.; SCHJOERRING, J. K.; DENMEAD, O. T. Ammonia emission from mineral fertilizers and fertilized crops. **Advances in Agronomy**, v. 82, p. 557–622, 2004.

THORBURN, P. J.; MEIER, E. A.; PROBERT, M. E. Modelling nitrogen dynamics in sugarcane systems: Recent advances and applications. **Field Crops Research**, v. 92, p. 337–351, 2005.

UNICA. Sugarcane harvesting monitoring. Disponível em: <https://www.novacana.com/pdf/acompanhamento_quinzenal-16-04-2015.pdf>. Acesso em: 8/3/2016.

VALE, D. W.; PRADO, R. DE M.; CANTARELLA, H.; et al. Ammonium and Nitrate in Soil and Ratoon Sugarcane Grown in Function of Nitrogen on Oxisol. **Journal of Plant Nutrition**, v. 36, n. 2, p. 201–213, 2013.

VIEIRA-MEGDA, M. X.; MARIANO, E.; LEITE, J. M.; et al. Contribution of fertilizer nitrogen to the total nitrogen extracted by sugarcane under Brazilian field conditions. **Nutrient Cycling in Agroecosystems**, v. 101, p. 241–257, 2015.

VIEIRA-MEGDA, M. X.; TRIVELIN, P. C. O.; FRANCO, H. C. J.; OTTO, R.; VITTI, A. C. Agronomic efficiency of nitrogen fertilizers on green harvesting sugarcane ratoon. **Pesquisa Agropecuaria Brasileira**, v. 47, n. 1, p. 1681–1690, 2012.

VITTI, A. C.; TRIVELIN, P. C. O.; GAVA, G. J. C.; et al. Sugarcane yield as related to the location of N fertilizer applied on top of unburnt sugarcane residues. **R. Bras. Ci. Solo Bras**, v. 31, p. 491–498, 2007.

YANG, W.; LI, Z.; WANG, J.; WU, P.; ZHANG, Y. Crop yield, nitrogen acquisition and sugarcane quality as affected by interspecific competition and nitrogen application. **Field Crops Research**, v. 146, p. 44–50, 2013.

CAPÍTULO VI

6 DISCUSSÃO GERAL

Para atender os pré-requisitos da operação de aplicação localizada de adubo líquido em cana-soca, alinhado aos princípios da agricultura conservacionista e boas práticas de manejo da adubação, nós desenvolvemos um equipamento para realizar a operação mecanizada de puncionamento vertical, equidistante no solo. A concepção da operação foi fundamentada na distância entre aplicações de 300 mm, uma distância média entre as soqueiras de cana-de-açúcar, com profundidade de perfuração de até 100 mm, considerada suficiente para disponibilizar os nutrientes próximos às raízes das plantas e reduzir o impacto das perdas do fertilizante. Em análise sobre a operação de puncionamento, percebemos que o processo mecanizado de perfuração do solo exige baixa potência mecânica; além disso, pode disponibilizar o fertilizante próximo as raízes da cana-de-açúcar, com mínima mobilização do sistema (solo, raízes e resíduos vegetais).

Entre os principais parâmetros com influência na qualidade da operação, identificamos as diferenças no microrrelevo do solo (profundidade das punções), a resistência do solo à penetração (exigências de torque e potência) e sincronismo da frequência do ciclo de puncionamento em relação ao movimento de avanço do equipamento (distância entre as punções).

No processo mecanizado de puncionamento, para disponibilizar o fertilizante líquido na subsuperfície do solo, nós desenvolvemos um sistema hidráulico dosador-injetor, centrado no projeto de uma bomba de pistão, na qual, o came excêntrico foi responsável pela a aplicação sincronizada ao ciclo de puncionamento, enquanto, a variação na dosagem foi realizada através do retorno hidráulico para o reservatório, por meio de sulco projetado em função da posição angular radial do pistão.

Em análise sobre a operação de injeção do fertilizante líquido, percebemos que processo pode melhorar a qualidade da operação de aplicação (c.v. menor que 2% na avaliação em bancada e c.v. em torno de 11% nas avaliações em caixa de solo). Além disso, as operações foram satisfatórias, porque (i) o puncionamento mecanizado foi sincronizado a injeção do líquido no solo, em profundidade superior a 50 mm, uma condição considerada favorável à redução de perdas e disponibilidade do nutriente próximo às raízes das plantas; ademais, (ii) o controle de dosagem foi realizado em faixa representativa de 5 a 18 mL ciclo-

1, desse modo, demonstrando potencial para aplicação com taxa variável de acordo com a recomendação agronômica.

Em área experimental de cana-de-açúcar, o método proposto para aplicação localizada de nutrientes foi comparado com outros métodos comuns de adubação (superfície ou incorporado em sulcos). Em análise sobre os métodos, uma maior disponibilidade do N mineral no solo (NH_4^+-N e NO_3^--N) foi observada a partir das aplicações na subsuperfície. Entretanto, para o método de puncionamento no solo, verificamos que a difusão do fertilizante através da subsuperfície foi limitada em torno dos pontos de aplicação. Desse modo, os métodos avaliados com menor distância entre as punções (150 e 300 mm) obtiveram uma maior similaridade em relação à aplicação incorporada contínua.

Em condições de operação similar (paralelo a um lado da linha de cultivo), o método de puncionamento (distância entre aplicações a cada 150 e 300 mm) obteve resultados equivalentes à adubação incorporada. Em geral, a deposição do fertilizante em profundidade no solo (camada subsuperficial) resultou em maior nível de N-foliar, produtividade de colmos e potencial de produção de açúcar (toneladas de pol por hectare); os quais, associados à disponibilidade do N mineral no solo. Em contraposição, apesar da menor complexidade da aplicação do fertilizante em superfície, o método resultou em uma menor eficácia da adubação, atribuído à camada de resíduos vegetais, uma “barreira” entre o fertilizante e a subsuperfície do solo.

CAPÍTULO VII

7 CONCLUSÃO GERAL

A aplicação por meio de puncionamento e injeção de fertilizante líquido em cana-soca é um método viável para fornecer os nutrientes em subsuperfície, com mínima mobilização do sistema (solo, resíduos vegetais e raízes). O processo proposto possui equivalência à operação comum de adubação incorporada em sulcos. Contudo, a estratégia representa uma alternativa tecnológica para superar dificuldades no acesso a subsuperfície do solo, em áreas com cobertura de resíduos vegetais na superfície, além disso, a operação é fundamentada no cultivo conservacionista e boas práticas de manejo dos nutrientes.

8 BIBLIOGRAFIA GERAL

AMARAL, L. R.; MOLIN, J. P. Sensor óptico no auxílio à recomendação de adubação nitrogenada em cana-de-açúcar. **Pesquisa Agropecuaria Brasileira**, v. 46, n. 1, p. 1633–1642, 2011.

AMARAL, L. R.; MOLIN, J. P. The effectiveness of three vegetation indices obtained from a canopy sensor in identifying sugarcane response to nitrogen. **Agronomy Journal**, v. 106, n. 1, p. 273–280, 2014.

AMARAL, L. R.; MOLIN, J. P.; PORTZ, G.; FINAZZI, F. B.; CORTINOVE, L. Comparison of crop canopy reflectance sensors used to identify sugarcane biomass and nitrogen status. **Precision Agriculture**, v. 16, n. 1, p. 15–28, 2015.

ANGLUND, E. A.; AYERS, P. D. Field evaluation of response times for a variable rate (pressure–based and injection) liquid chemical applicator. **Applied Engineering in Agriculture**, v. 19, n. 3, p. 273–282, 2003.

ARGENTA, G.; SILVA, P. R. F.; SANGOI, L. Leaf relative chlorophyll content as an indicator parameter to predict nitrogen fertilization in maize. **Ciência Rural**, v. 34, n. 5, p. 1379–1387, 2004.

ASABE. **Standard - Procedures for Using and Reporting Data Obtained with the Soil Cone Penetrometer. ASAE EP542 FEB1999 (R2009)**. St. Joseph, Mich., 2009.

AZEVEDO, M. C. B. DE; CHOPART, J. L.; MEDINA, C. D. C. Sugarcane root length density and distribution from root intersection counting on a trench-profile. **Scientia Agricola**, v. 68, n. February, p. 94–101, 2011.

BAKER, J. L.; COLVIN, T. S.; MARLEY, S. J.; DAWELBEIT, M. A point-injector applicator to improve fertilizer management. **Appl. Eng. Agric**, v. 5, p. 334–338, 1989.

BANNING, N. C.; MACCARONE, L. D.; FISK, L. M.; MURPHY, D. V. Ammonia-oxidising bacteria not archaea dominate nitrification activity in semi-arid agricultural soil. **Scientific reports**, v. 5, n. May, p. 11146, 2015. Nature Publishing Group. Disponível em: <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=4459192&tool=pmcentrez&rendertype=abstract>. .

BASANTA, M. V.; DOURADO-NETO, D.; REICHARDT, K.; et al. Management effects on nitrogen recovery in a sugarcane crop grown in Brazil. **Geoderma**, v. 116, p. 235–248, 2003.

BAUTISTA, E. U.; KOIKE, M.; SUMINISTRADO, D. C. Mechanical deep placement of nitrogen in wetland rice. **Journal of Agricultural Engineering Research**, v. 78, n. 4, p. 333–346, 2001.

BAUTISTA, E. U.; SUMINISTRADO, D. C.; KOIKE, M. Mechanical deep placement of fertilizer in puddled soils: evaluation of nitrogen losses and yield of transpanted and direct-seeded rice. **Journal of Japanese Society of Agricultural Machinery**, v. 62, n. 1, 2000.

BENNUR, P. J.; TAYLOR, R. K. Evaluating the response time of a rate controller used with a sensor-based, variable rate application system. **Applied Engineering in Agriculture**, v. 26, n. 6, p. 1069–1075, 2010.

BIANCHINI, A.; MAGALHÃES, P. S. G. Evaluation of coulters for cutting sugar cane residue in a soil bin. **Biosystems Engineering**, v. 100, n. 3, p. 370–375, 2008.

BOARETTO, A. E.; CRUZ, A. P.; LUZ, P. H. C. **Adubo líquido: produção e uso no Brasil**. 1st ed. Campinas: Fundação Cargil, 1991.

BRAUNACK, M. V.; ARVIDSSON, J.; HÅKANSSON, I. Effect of harvest traffic position on soil conditions and sugarcane (Saccharum officinarum) response to environmental conditions in Queensland, Australia. **Soil and Tillage Research**, v. 89, n. 1, p. 103–121, 2006.

BRITTO, D. T.; KRONZUCKER, H. J. NH4+ toxicity in higher plants: a critical review. **Journal of Plant Physiology**, v. 159, n. 3, p. 567–584, 2002.

CAMPBELL, C. M.; FULTON, J. P.; WOOD, C. W.; MCDONALD, T. P.; ZECH, W. C. Utilizing nutrient over mass distribution patterns for assessment of Poultry litter spreaders. **Transactions of the ASAE**, v. 53, n. 3, p. 659–666, 2015.

CANTARELLA, H.; ROSSETTO, R. Fertilizers for sugarcane. In: L. A. B. Cortez (Ed.); **Sugarcane bioethanol R&D for productivity and Sustainability**. First ed., p.405–422, 2010. São Paulo: Blucher & Fapesp.

CANTARELLA, H.; TRIVELIN, P. C. O.; CONTIN, T. L. M.; et al. Ammonia volatilisation from urease inhibitor-treated urea applied to sugarcane trash blankets. **Scientia Agricola**, v. 65, n. August, p. 397–401, 2008.

CASTRO, S. G. Q.; DECARO, S. T.; FRANCO, H. C. J.; et al. Best practices of nitrogen fertilization management for sugarcane under green cane trash blanket in Brazil. **Sugar Tech**, p. 1–6, 2016.

CASTRO, S. G. Q.; FRANCO, H. C. J.; MUTTON, M. A. Harvest Managements and Cultural Practices in Sugarcane Harvest Managements and Cultural Practices in Sugarcane. **Revista Brasileira de Ciência do Solo**, v. 38, n. 1, p. 299–306, 2014.

CATANIA, A. E.; FERRARI, A. Experimental Analysis, Modeling, and Control of Volumetric Radial-Piston Pumps. **Journal of Fluids Engineering**, v. 133, n. 8, p. 081103, 2011. Disponível em: <http://fluidsengineering.asmedigitalcollection.asme.org/article.aspx?articleid=1438842>. Acesso em: 9/3/2014.

CHEN, B.; LIU, E.; TIAN, Q.; YAN, C.; ZHANG, Y. Soil nitrogen dynamics and crop residues. A review. **Agronomy for Sustainable Development**, v. 34, n. 2, p. 429–442, 2014.

CHEN, Y. . Liquid manure injection tool adapted to different soil conditions. **Transactions of the ASAE**, v. 45, n. 6, p. 1729–1736, 2002.

CHIEN, S. H.; PROCHNOW, L. I.; CANTARELLA, H. **Chapter 8 Recent Developments of Fertilizer Production and Use to Improve Nutrient Efficiency and Minimize Environmental Impacts**. 1st ed. Elsevier Inc., 2009.

CHUNFENG, Z.; XIU, W. Development and experiments on the injection system of the self-propelled liquid fertilizer machine. The 5th annual IEEE international conference on cyber technology in automation, control and intelligent systems. **Anais...** . p.1650–1654, 2015. Shenyang, China.

CIIAGRO. Integrated Center of agrometeorological information: water balance. Disponível em: <http://www.ciiagro.sp.gov.br/ciiagroonline/Listagens/BH/LBalancoHidricoLocal.asp>. Acesso em: 1/1/2015.

CILIA, C.; PANIGADA, C.; ROSSINI, M.; et al. Nitrogen status assessment for variable rate fertilization in maize through hyperspectral imagery. **Remote Sensing**, v. 6, n. 7, p. 6549–6565, 2014.

CONAB. Monitoring the Brazilian Safra - Sugarcane. Disponível em: <http://www.conab.gov.br/OlalaCMS/uploads/arquivos/15_12_17_09_03_29_boletim_cana_portugues_-_3o_lev_-_15-16.pdf>. Acesso em: 1/1/2016.

COSTA, C.; DWYER, L. M.; DUTILLEUL, P.; et al. Inter-Relationships of Applied Nitrogen, Spad, and Yield of Leafy and Non-Leafy Maize Genotypes. **Journal of Plant Nutrition**, v. 24, n. 8, p. 1173–1194, 2001. Disponível em: <http://www.tandfonline.com/doi/abs/10.1081/PLN-100106974>. .

COSTA, M. C. G.; VITTI, G. C.; CANTARELLA, H. N-NH3 losses from nitrogen sources applied over unburned sugarcane straw. **Revista Brasileira de Ciência do Solo**, v. 27, n. 4, p. 631–637, 2003.

CTC. census of sugarcane variety and yield. Disponível em: <http://www.ctcanavieira.com.br/downloads/Censo2012.pdf>. Acesso em: 13/7/2016.

DATTAMUDI, S.; WANG, J. J.; DODLA, S. K.; ARCENEAUX, A.; VIATOR, H. P. Effect of nitrogen fertilization and residue management practices on ammonia emissions from subtropical sugarcane production. **Atmospheric Environment**, v. 139, p. 122–130, 2016. Elsevier Ltd.

DORDAS, C. **Nutrien management perspectives in conservation agriculture, in: Farooq & Siddique - Conservation agriculture (book)**. 1st ed. Springer, 2015.

EMBRAPA. **Empresa Brasileira de Pesquisa Agropecuária - Centro Nacional de Pesquisa de Solos Sistema Brasileiro de classificação de solos**. 2nd ed. Rio de Janeiro, 2006a.

EMBRAPA. **Brazilian agricultural research corporation: Brazilian system of soil classification**. 2 ed. ed. Rio de Janeiro: EMBRAPA, 2006b.

EMBRAPA. Brazilian agricultural research corporation: Embrapa’s technological information agency. Disponível em: <http://www.agencia.cnptia.embrapa.br/gestor/cana-de-acucar/arvore/CONTAG01_10_711200516716.html>. Acesso em: 6/1/2015.

FAO. Food and agriculture organization of the united nations: Statics division. Disponível em: <http://faostat3.fao.org/>. Acesso em: 1/1/2016.

FEDEROLF, C.-P.; WESTERSCHULTE, M.; OLFS, H.-W.; BROLL, G.; TRAUTZ, D. Enhanced nutrient use efficiencies from liquid manure by positioned injection in maize cropping in northwest Germany. **European Journal of Agronomy**, v. 75, p. 130–138, 2016. Elsevier B.V.

FERNANDES, A. C. **Calculations at sugarcane agribusiness (Cálculos na Agroindústria de cana-de-açúcar)**. 2 ed. ed. Piracicaba: STAB. Açúcar, Álcool e Subprodutos, 2003.

FILLERY, I. R. P.; KHIMASHIA, N. Procedure to estimate ammonia loss after N fertiliser application to moist soil. **Soil Research**, v. 54, p. 1–10, 2016.

FORTES, C.; TRIVELIN, P. C. O.; VITTI, A. C. Long-term decomposition of sugarcane harvest residues in Sao Paulo state, Brazil. **Biomass and Bioenergy**, v. 42, p. 189–198, 2012. Elsevier Ltd.

FORTES, C.; TRIVELIN, P. C. O.; VITTI, A. C.; et al. Stalk and sucrose yield in response to nitrogen fertilization of sugarcane under reduced tillage. **Pesquisa Agropecuaria Brasileira**, v. 48, n. 1, p. 88–96, 2013.

FORTES, C.; TRIVELIN, P. C. O.; VITTI, A. C. A. C. Long-term decomposition of sugarcane harvest residues in Sao Paulo state, Brazil. **Biomass and Bioenergy**, v. 42, p. 1–10, 2012. Elsevier Ltd.

FORTES, C.; VITTI, A. C.; OTTO, R.; et al. Contribution of nitrogen from sugarcane harvest residues and urea for crop nutrition. **Scientia Agrícola**, v. 70, n. October, p. 313–320, 2013.

FRANCIS, D. D.; PIEKIELEK, W. P. **Site-specific management Guidelines: assessing crop nitrogen needs with chlorophyll meters**. 1st ed. Peachtree Corners, GA-USA: IPNI-International Plant Nutrition Institute, 2016.

FRANCO, H. C. J.; OTTO, R.; FARONI, C. E.; et al. Nitrogen in sugarcane derived from fertilizer under Brazilian field conditions. **Field Crops Research**, v. 121, n. 1, p. 29–41, 2011.

FRANCO, H. C. J.; TRIVELIN, P. C. O.; FARONI, C. E.; VITTI, A. C.; OTTO, R. Stalk yield and technological attributes of planted cane as related to nitrogen fertilization relacionados com a adubação nitrogenada. **Scientia Agricola**, v. 67, n. 5, p. 579–590, 2010.

FRANCO, H. C. J.; TRIVELIN, P. C. O.; FARONI, C. E.; VITTI, A. C.; OTTO, R. Stalk yield and technological attributes of planted cane as related to nitrogen fertilization. **Scientia Agricola**, v. 67, n. 5, p. 579–590, 2010.

FULTON, J. P.; SHEARER, S. A; HIGGINS, S. F.; DARR, M. J.; STOMBAUGH, T. S. Rate response assessment from various granular VRT applicators. **Transactions of the Asae**, v. 48, n. 6, p. 2095–2103, 2005.

FULTON, J. P.; SHEARER, S. A.; CHABRA, G.; HIGGINS, S. F. Performance assessment and model development of a variable-rate, spinner-disc fertilizer applicator. **Transactions of the ASAE**, v. 44, n. 5, p. 1071–1081, 2001.

FULTON, J. P.; SHEARER, S. A.; HIGGINS, S. F.; MCDONALD, T. P. A method to generate and use as-applied surfaces to evaluate variable-rate fertilizer applications. **Precision Agriculture**, v. 14, p. 184–200, 2013.

GESP - SECRETARIA DO ESTADO DO MEIO AMBIENTE. **Protocolo Agroambiental**. São Paulo, 2007.

GINÉ, M. F.; BERGAMIN F, H.; ZAGATTO, E. A. G.; REIS, B. F. Simultaneous determination of nitrate and nitrite by flow injection analysis. **Analytica Chimica Acta**, v. 114, p. 191–197, 1980.

HWANG, J.; BAE, C.; GUPTA, T. Application of waste cooking oil (WCO) biodiesel in a compression ignition engine. **Fuel**, v. 176, p. 20–31, 2016. Elsevier Ltd.

HYPRO. Liquid fertilizer nozzles. Disponível em: <http://www.hypro-eu.com/en-gb/Our+Products/Spray+Nozzles/Liquid+Fertiliser+Spraying/>. Acesso em: 23/8/2016.

IBGE. Instituto Brasileiro de Geografia e Estatística - Levantamento sistemático da produção agrícola. Confronto das Safras de 2014 e das Estimativas para 2015 – Brasil. Disponível em: <http://www.ibge.gov.br/home/estatistica/indicadores/agropecuaria/lspa/lspa_201504_5.shtm>. Acesso em: 26/5/2015.

IFA. **International fertilizer industry association: Mineral fertilizer use and the environment**. 2000.

INMET. Brazilian National Institute of Meteorology: Climate history in Iracemapolis - SP. Disponível em: <http://www.climatempo.com.br/climatologia/2341/iracemapolis-sp>. Acesso em: 6/1/2015.

JAT, M. L.; BIJAY-SINGH; GERARD, B. **Nutrient Management and Use Efficiency in Wheat Systems of South Asia**. 1st ed. Elsevier Inc., 2014.

JOHANN, A. L.; RUSSO, E.; CAPPELLI, N. L.; UMEZU, C. K. Development and evaluation of a low cost servo-valve for liquid inputs application. **Engenharia Agrícola**, v. 26, n. 1, p. 142–150, 2006.

KALIATKA, A.; VAIŠNORAS, M.; VALINČIUS, M. Modelling of valve induced water hammer phenomena in a district heating system. **Computers and Fluids**, v. 94, p. 30–36, 2014.

KARNEY, B. W.; SIMPSON, A. R. In-line check valves for water hammer control. **Journal of Hydraulic Research**, v. 45, n. March 2015, p. 547–554, 2007.

KEGL, B.; KEGL, M.; PEHAN, S. Optimization of a fuel injection system for diesel and biodiesel usage. **Energy & Fuels**, v. 22, p. 1046–1054, 2008.

KENNCO. Liquid fertilizer injection wheel. Disponível em: <http://www.kenncomfg.com/products/fertilizer-applicators>. Acesso em: 23/8/2016.

KNUTSON, A. L.; VEN, J. D. VAN DE. Modelling and experimental validation of the displacement of a check valve in a hydraulic piston pump. **International Journal of Fluid Power**, v. 9776, n. April, p. 1–11, 2016.

KORNDÖRFER, G. H.; ANDERSON, D. L.; MUNDIM, V. C.; SIMÕES, M. S. Produção de adubos fluidos para cana-de-açúcar. **Revista STAB**, v. 14, n. 2, p. 25–29, 1995.

LANG, C.; WANG, J.; SHI, Y.; XI, X. Design and Development Control System for Deep-Fertilization Variable Liquid Fertilizer Applicator. **2011 Second International Conference on Digital Manufacturing & Automation**, p. 369–372, 2011. Ieee.

LARA CABEZAS, W. A. R.; TRIVELIN, P. C. O.; KONDÖRFER, G. H.; PEREIRA, S. Nitrogen Balance of solid and liquid nitrogen sources on side-dressed no-till corn system at triângulo mineiro (MG). **R. Bras. Ci. Solo Bras**, v. 24, p. 363–376, 2000.

LEAL, M. R. L. V.; GALDOS, M. V.; SCARPARE, F. V.; et al. Sugarcane straw availability, quality, recovery and energy use: A literature review. **Biomass and Bioenergy**, v. 53, p. 11–19, 2013.

LIQUIJET. Fertilizer applicator: Spike wheel. Disponível em: <http://www.spikewheel.com/spikewheel.htm>. Acesso em: 23/8/2016.

LIU, T. Q.; FAN, D. J.; ZHANG, X. X.; et al. Deep placement of nitrogen fertilizers reduces ammonia volatilization and increases nitrogen utilization efficiency in no-tillage paddy fields in central China. **Field Crops Research**, v. 184, p. 80–90, 2015.

LIU, Y.; WANG, J. J.; WANG, J. J.; GE, Y. Optimal Design and Analysis on Pricking Hole Mechanism with Planetary Elliptic Gears for Deep-Fertilization Liquid Fertilizer Applicator. **2011 Second International Conference on Digital Manufacturing & Automation**, p. 809–812, 2011. Ieee.

LOFTON, J.; TUBAÑA, B. Effect of nitrogen rates and application time on sugarcane yield and quality. **Journal of Plant Nutrition**, v. 38, n. 2, p. 161–176, 2015.

MA, Q.; RENGEL, Z.; ROSE, T. The effectiveness of deep placement of fertilisers is determined by crop species and edaphic conditions in Mediterranean-type environments: A review. **Australian Journal of Soil Research**, v. 47, n. Alston 1980, p. 19–32, 2009.

MAGALHÃES, P. S. G.; BIANCHINI, A.; BRAUNBECK, O. A. Simulated and

Experimental Analyses of a Toothed Rolling Coulter for Cutting Crop Residues. **Biosystems Engineering**, v. 96, p. 193–200, 2007.

MAGALHÃES, P. S. G.; NOGUEIRA, L. A. H.; CANTARELLA, H.; et al. Agro-industrial technological paths. In: M. K. Poppe; L. A. B. Cortez (Eds.); **Sustainability of Sugarcane bioenergy**. First ed., v. 1, p.27–71, 2012. Brasilia, DF: Center of Strategic Studies and Management (CGEE).

MAGALHÃES, P. S. G.; SILVA, M. J. Equipamento com princípio de puncionamento para aplicação localizada de adubo líquido em profundidade. , 2013. Brazil.

MAGALHÃES, P. S. G.; SILVA, M. J. Sistema hidráulico dosador injetor de fluidos (Hydraulic dosing-injector system). Patent BR 10 2016 028809 6, 2016. Brazil.

MARCHI, A. S.; ROCHA, A. A. S. P. D. E. DA; SILVA, J. E. A. R. DA. Unburned cane harvesting with trash recovery routes. In: S. J. Hassuani; M. R. L. Verde Leal; I. C. I. de C. Macedo (Eds.); **Biomass power generation, Sugar cane bagasse and trash**. p.65–69, 2005. Piracicaba, SP: PNUD Brasil.

MARIANO, E.; JONES, D. L.; HILL, P. W.; TRIVELIN, P. C. O. Mineral nitrogen forms alter 14C-glucose mineralisation and nitrogen transformations in litter and soil from two sugarcane fields. **Applied Soil Ecology**, v. 107, p. 154–161, 2016. Elsevier B.V.

MARIANO, E.; LEITE, J. M.; MEGDA, M. X. V; TORRES-DORANTE, L.; TRIVELIN, P. C. O. Influence of nitrogen form supply on soil mineral nitrogen dynamics, nitrogen uptake, and productivity of sugarcane. **Agronomy Journal**, v. 107, p. 641–650, 2015.

MARIANO, E.; LEITE, J. M.; VIEIRA-MEGDA, M. X.; et al. Biomass and nutrient content by sugarcane as affected by fertilizer nitrogen sources. **Crop science**, v. 56, n. May-June, p. 1234–1244, 2016.

MARIANO, E.; TRIVELIN, P. C. O.; VIEIRA, M. X.; et al. Ammonia losses estimated by an open collector from urea applied to sugarcane straw. **Revista Brasileira de Ciência do Solo**, v. 36, n. 1, p. 411–419, 2012.

MATSUOKA, S.; ARIZONO, H.; BASSINELLO, A. I.; et al. Super precocious varieties of sugarcane. **Álcool & Açúcar**, , n. 78, p. 22–30 (in portuguese), 1995.

MCLAUGHLIN, N. B.; CAMPBELL, A. J. Draft-speed-depth relationships for four liquid manure injectors in a fine sandy loam soil. , v. 46, p. 1–5, 2004.

MCLAUGHLIN, N. B.; LI, Y. X.; BITTMAN, S.; et al. Draft requirements for contrasting liquid manure injection equipment. **Canadian Biosystems Engeering**, v. 48, p. 29–37, 2006.

MEENA, V. S.; VERMA, J. P.; MEENA, S. K. Towards the current scenario of nutrient use efficiency in crop species. **Journal of Cleaner Production**, v. 102, n. MAY, p. 556–557, 2015.

MENG, H. B.; LIU, Y.; LI, Y. Experiment on Water Hammer Protection Performances of the Shuttle Check Valve in Multi-Pump Parallel Connection System. **Applied Mechanics and Materials**, v. 192, p. 37–41, 2012.

MIPHOKASAP, P.; HONDA, K.; VAIPHASA, C.; SOURIS, M.; NAGAI, M. Estimating canopy nitrogen concentration in sugarcane using field imaging spectroscopy. **Remote Sensing**, v. 4, p. 1651–1670, 2012.

MOHANTY, S. K.; SINGH, U.; BALASUBRAMANIAN, V.; JHA, K. P. Nitrogen deep-placement technologies for productivity , profitability , and environmental quality of rainfed lowland rice systems. **Nutrient Cycling in Agroecosystems**, p. 43–57, 1999.

MONTGOMERY, D. **Introduction to statistical quality control**. 2009.

MOSELEY, P. J.; MISSELBROOK, T. H.; PAIN, B. F.; EARL, R.; GODWIN, R. J. The effect of injector tine design on odour and ammonia emissions following injection of bio-solids into arable cropping. **Journal of Agricultural Engineering Research**, v. 71, n. 4, p. 385–394, 1998.

MUNACK, A.; BUNING, E.; SPECKMANN, H. A high-performance control system for spreading liquid manure. **Control Engineering Practice**, v. 9, p. 387–391, 2001.

NASCIMENTO, C. A. C. DO; VITTI, G. C.; FARIA, L. D. A.; LUZ, P. H. D. C.; MENDES, F. L. Ammonia volatilization from coated urea forms. **Revista Brasileira de Ciência do Solo**, v. 37, n. 1, p. 1057–1063, 2013.

NAZEMI, M.; SHAHBAKHTI, M. Modeling and analysis of fuel injection parameters for combustion and performance of an RCCI engine. **Applied Energy**, v. 165, p. 135–150, 2016. Elsevier Ltd.

NBR-ISO-5167. **Medição de vazão de fluidos por meio de instrumentos de pressão - parte 1: placas de orifício, bocais e tubos de Venturi instalados em seção transvesal circular de condutos forçados**. 1994.

NELSON, D. W.; SOMMERS, L. E. Determination of Total Nitrogen in Plant Material. **Agronomy Journal**, v. 65, p. 109–112, 1973.

NIEMOELLER, B.; HARMS, H. H.; LANG, T. Injection of liquids into the soil with a high-pressure jet. **Agricultural Engineering International: CIGR Journal**, v. 13, n. 2, p. 1–15, 2011.

NING, S.; TAOSHENG, X.; LIANGTU, S.; RUJING, W.; YUANYUAN, W. Variable rate fertilization system with adjustable active feed-roll length. **International Journal of Agriculture & Biological Engineering**, v. 8, n. 4, p. 19–26, 2015.

NYORD, T.; SØGAARD, H. T.; HANSEN, M. N.; JENSEN, L. S. Injection methods to reduce ammonia emission from volatile liquid fertilisers applied to growing crops. **Biosystems Engineering**, v. 100, n. 2, p. 235–244, 2008.

OLIVEIRA, E. C. A.; GAVA, G. J. C.; TRIVELIN, P. C. O.; OTTO, R.; FRANCO, H. C. J. Determining a critical nitrogen dilution curve for sugarcane. **Journal of Plant Nutrition and Soil Science**, v. 176, n. 5, p. 712–723, 2013.

ORTHMAN. Liquid fertilizer applicator. Disponível em: <http://www.orthman.com/our-products.aspx?itemid=2049&prodid=10880&pagetitle=Liquid+Fertilizer+Applicator>.
Acesso em: 23/8/2016.

OTTO, R.; CASTRO, S. A. Q.; MARIANO, E.; et al. Nitrogen Use Efficiency for Sugarcane-Biofuel Production: What Is Next? **BioEnergy Research**, v. 1, p. 1–18, 2016. BioEnergy Research.

OTTO, R.; COUTINHO, H.; FRANCO, J.; et al. The Role of Nitrogen Fertilizers in Sugarcane Root Biomass under Field Conditions. **Agricultural Sciences**, v. 5, p. 1527–1538, 2014.

OTTO, R.; FRANCO, H. C. .; FARONI, C. E.; VITTI, A. C.; TRIVELIN, P. C. O. Fitomassa de raízes e da parte aérea da cana-de-açúcar relacionada à adubação nitrogenada de plantio. **Pesquisa Agropecuaria Brasileira**, v. 44, n. 1, p. 398–405, 2009.

PEI, J.; HE, C.; MIAORONG, L.; HUANG, X.; SHEN, K. The valve motion characteristics of a reciprocating pump. **Mechanical Systems and Signal Processing**, v. 66-67, p. 657–664, 2016.

PIO, L. C.; ABDALLA, S. R. S.; PROCHNOW, L. Panorama atual do setor de fertilizantes fluidos e foliares: equipamentos e tecnologia de aplicação para fertilizantes fluidos. **International Plant Nutrition Institute**, v. 123, p. 15–16, 2008.

PORTZ, G.; MOLIN, J. P.; JASPER, J. Active crop sensor to detect variability of nitrogen supply and biomass on sugarcane fields. **Precision Agriculture**, v. 13, n. 1, p. 33–44, 2012.

PRADO, R. M.; PANCELLI, M. A. Nutrição nitrogenada em soqueiras e a qualidade tecnológica da cana-de-Açúcar. **STAB**, v. 25, n. 2, p. 60–63, 2006.

PRASERTSAK, P.; FRENEY, J. R.; DENMEAD, O. T.; SAFFIGNA, P. G.; PROVE, B. G. Effect of fertilizer placement on nitrogen loss from sugarcane in tropical Queensland. **Nutrient Cycling in Agroecosystems**, v. 62, n. 3, p. 229–239, 2002.

QIU, T.; SONG, X.; LEI, Y.; et al. Effect of back pressure on nozzle inner flow in fuel injector. **Fuel**, v. 173, p. 79–89, 2016.

QUEBRAJO, L.; PÉREZ-RUIZ, M.; RODRIGUEZ-LIZANA, A.; AGÜERA, J. An approach to precise nitrogen management using hand-held crop sensor measurements and winter wheat yield mapping in a mediterranean environment. **Sensors (Switzerland)**, v. 15, n. 3, p. 5504–5517, 2015.

RADHAMANI, R.; KANNAN, R.; RAKKIYAPPAN, P. Leaf chlorophyll meter readings as an indicator for sugarcane yield under iron deficient typic haplustert. **Sugar Tech**, v. 18, n. 1,

p. 61–66, 2015. Springer India.

RAIJ, B. VAN; CANTARELLA, H. Lime and fertilizer recommendations for the State of Sao Paulo. **Van Raij, B. Cantarella, H. Quaggio, J. A. Furlani, A. M. C.** 2nd ed., p.233– 243., 1996. Campinas, SP, Brazil: Fundação IAC.

RAIJ, B. VAN.; CANTARELLA, H.; QUAGGIO, J. A.; A. M. C. FURLANI. **Recomendações de adubação e calagem para o Estado de São Paulo. Campinas**. Campinas: Instituto Agronômico; Fundação IAC., 1997.

RAIJ, V. B.; ANDRADE, J. C.; CANTARELLA, H.; QUAGGIO, J. A. **Chemical analysis for evaluation of the fertility of tropical soils**. 2 ed ed. Campinas, SP, Brazil: Instituto Agronômico; Fundação IAC., 2001.

REETZ, H. F.; FIXEN, P. E. **Site-specific management Guidelines: strategic approach to site-specific systems**. 1st ed. Peachtree Corners, GA-USA: IPNI-International Plant Nutrition Institute, 2016.

REIS, B. F.; VIEIRA, J. A.; KRUG, F. J.; GINÉ, M. F. Development of a flow injection system with two analytical paths for ammonium determination in soil extracts by conductometry. **Journal of the Brazilian Chemical Society**, v. 8, n. 5, p. 523–528, 1997.

REYES, J. F.; ESQUIVEL, W.; CIFUENTES, D.; ORTEGA, R. Field testing of an automatic control system for variable rate fertilizer application. **Computers and Electronics in Agriculture**, v. 113, p. 260–265, 2015.

RIOS, L.; MOLIN, P. Sensor óptico no auxílio à recomendação de adubação nitrogenada em cana‐de‐açúcar. , , n. 1, p. 1633–1642, 2011.

ROBINSON, N.; BRACKIN, R.; VINALL, K.; et al. Nitrate paradigm does not hold up for sugarcane. **PloS one**, v. 6, n. 4, p. e19045, 2011.

ROCHETTE, P. .; ANGERS, D. A. .; CHANTIGNY, M. H. .; et al. Reducing ammonia volatilization in a no-till soil by incorporating urea and pig slurry in shallow bands. **Nutrient Cycling in Agroecosystems**, v. 84, p. 71–80, 2009.

RODRIGUES JR., F. A.; MAGALHÃES, P. S. G.; FRANCO, H. C. J. Soil attributes and leaf nitrogen estimating sugar cane quality parameters: Brix, pol and fibre. **Precision Agriculture**, v. 14, n. 3, p. 270–289, 2013.

RODRIGUES, M. B.; KIEHL, J. C. Volatilização de amônia após emprego da ureia em diferentes doses e modos de aplicação. **Rev. Bras. Ciência do Solo**, v. 10, p. 37–43, 1986.

ROQUE, A. A. O.; SOUZA, Z, M.; BARBOSA, R. S.; SOUZA, G. S. Controle de tráfego agrícola e atributos físicos do solo em área cultivada com cana‐de‐açúcar. **Pesquisa Agropecuaria Brasileira**, v. 45, n. 7, p. 744–750, 2010.

ROSA, H. J. A.; AMARAL, L. R. DO; MOLIN, J. P.; CANTARELLA, H. Sugarcane response to nitrogen rates, measured by a canopy reflectance sensor. **Pesquisa Agropecuaria Brasileira**, v. 50, n. 1, p. 840–848, 2015.

SAEYS, W.; DEBLANDER, J.; RAMON, H.; ANTHONIS, J. High-performance flow control for site-specific application of liquid manure. **Biosystems Engineering**, v. 99, n. 1, p. 22–34, 2008.

SHARDA, A.; FULTON, J. P.; TAYLOR, R. K. Performance of variable-orifice nozzles for Liquid fertilizer applications. **Applied Engineering in Agriculture**, v. 32, n. 3, p. 347–352, 2016.

SILVA, G. P.; PRADO, R. M.; ALMEIDA, T. B. F.; CAMPOS-NÓIA, N. R. Response of a fourth ratoon sugarcane crop to nitrogen, silicon, and lime fertilization. **Agrociencia**, v. 49, n. 5, p. 533–544, 2015.

SILVA, M. J. **Processo de aplicação de fluidos em profundidade com mínima mobilização do solo**. 82 p. Dissertação (Mestrado em Engenharia Agrícola) – Universidade Estadual de Campinas "UNICAMP", Campinas. 2013.

SILVA, M. J.; FRANCO, H. C. J.; MAGALHÃES, P. S. G. Liquid fertilizer application to ratoon cane using a soil punching method. **Soil & Tillage Research**, v. 165, p. 279–285, 2017. Elsevier B.V.

SILVA, M. J.; MAGALHÃES, P. S. G. Design of a mechanical system for liquid fertilizers injection in ratoon cane. ASABE and CSBE/SCGAB Annual International Meeting. **Anais...** . p.10p, 2014. Montreal-CAN.

SNYDER, C. S.; BRUULSEMA, T. W.; JENSEN, T. L.; FIXEN, P. E. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. **Agriculture, Ecosystems and Environment**, v. 133, n. August, p. 247–266, 2009.

SOIL SURVEY STAFF. **Keys to Soil Taxonomy**. 11th ed. Washington: USDA- Natural Resources Conservation Service, 2010.

SOMMER, S. G.; SCHJOERRING, J. K.; DENMEAD, O. T. Ammonia emission from mineral fertilizers and fertilized crops. **Advances in Agronomy**, v. 82, p. 557–622, 2004.

SONG, L. Q.; ZENG, L. P.; ZHANG, S. P.; ZHOU, J. D.; NIU, H. E. Design and analysis of a dual mass flywheel with continuously variable stiffness based on compensation principle. **Mechanism and Machine Theory**, v. 79, n. 174, p. 124–140, 2014.

SOUSA, A. C. M.; MATSURA, E. E.; ELAIUY, M. L. C.; et al. Root system distribution of sugarcane irrigated with domestic sewage effluent application by subsurface drip system. **Engenharia Agrícola**, v. 33, n. 4, p. 647–657, 2013.

SOUZA, G. S.; SOUZA, Z. M.; SILVA, R. B.; BARBOSA, R. S.; ARAÚJO, F. S. Effects of traffic control on the soil physical quality and the cultivation of sugarcane. **R. Bras. Ci. Solo Bras**, v. 38, p. 135–146, 2014.

STEWART, M. Conserving resources and building productivity. **Best Management Practices for Fertilizer**, 2006. IPNI-International Plant Nutrition Institute. Disponível em: <http://www.ipni.net/ppiweb/ppinews.nsf/0/AFFACB3FAA07E205852571170058CA2E/$FILE/SCGP BMPs.pdf>. .

THORBURN, P. J. J.; BIGGS, J. S. S.; WEBSTER, A. J. J.; BIGGS, I. M. M. An improved way to determine nitrogen fertiliser requirements of sugarcane crops to meet global environmental challenges. **Plant and Soil**, v. 339, n. 1, p. 51–67, 2011.

THORBURN, P. J.; MEIER, E. A.; PROBERT, M. E. Modelling nitrogen dynamics in sugarcane systems: Recent advances and applications. **Field Crops Research**, v. 92, p. 337–351, 2005.

UNICA. Sugarcane harvesting monitoring. Disponível em: <https://www.novacana.com/pdf/acompanhamento_quinzenal-16-04-2015.pdf>. Acesso em: 8/3/2016.

VALE, D. W.; PRADO, R. DE M.; CANTARELLA, H.; et al. Ammonium and Nitrate in Soil and Ratoon Sugarcane Grown in Function of Nitrogen on Oxisol. **Journal of Plant Nutrition**, v. 36, n. 2, p. 201–213, 2013.

VIEIRA-MEGDA, M. X.; MARIANO, E.; LEITE, J. M.; et al. Contribution of fertilizer nitrogen to the total nitrogen extracted by sugarcane under Brazilian field conditions. **Nutrient Cycling in Agroecosystems**, v. 101, p. 241–257, 2015.

VIEIRA-MEGDA, M. X.; TRIVELIN, P. C. O.; FRANCO, H. C. J.; OTTO, R.; VITTI, A. C. Agronomic efficiency of nitrogen fertilizers on green harvesting sugarcane ratoon. **Pesquisa Agropecuaria Brasileira**, v. 47, n. 1, p. 1681–1690, 2012.

VIRK, S. S.; MULLENIX, D. K.; SHARDA, A.; et al. Case study: distribution uniformity of a blended fertilizer applied using a variable-rate spinner-disc spreader. **Applied Engineering in Agriculture**, v. 29, n. 5, p. 627–636, 2013.

VITTI, A. C.; TRIVELIN, P. C. O.; GAVA, G. J. C.; PENATTI, C. P.; BOLOGNA, I. R.; et al. Sugar cane yield related to the residual nitrogen from fertilization and the root system. **Pesquisa Agropecuaria Brasileira**, v. 42, n. 2, p. 249–256, 2007.

VITTI, A. C.; TRIVELIN, P. C. O.; GAVA, G. J. C.; FRANCO, H. C. J.; et al. Produtividade da cana-de-açúcar relacionada à localização de adubos nitrogenados aplicados sobre os resíduos culturais em canavial sem queima. **R. Bras. Ci. Solo Bras**, v. 26, n. 4, p. 491–498, 2007.

VITTI, A. C.; TRIVELIN, P. C. O.; GAVA, G. J. C.; FRANCO, H. C. J.; BOLOGNA, I. R.; et al. Sugarcane yield as related to the location of N fertilizer applied on top of unburnt sugarcane residues. **R. Bras. Ci. Solo Bras**, v. 31, p. 491–498, 2007.

VITTI, A. C.; TRIVELIN, P. C. O.; GAVA, G. J. C.; PENATTI, C. P.; et al. Produtividade da cana-de-açúcar relacionada ao nitrogênio residual da adubação e do sistema radicular.

Pesquisa Agropecuária Brasileira, v. 42, n. 2, p. 249–256, 2007.

WANG, G.; ZHONG, L.; HE, X.; et al. Dynamic behavior of reciprocating plunger pump discharge valve based on fluid structure interaction and experimental analysis. **PLoS ONE**, v. 10, n. 10, p. 1–20, 2015.

WANG, J.; JU, J.; WANG, J. Experimental study on pricking hole performances of deep application liquid fertilizer device. 2011 Fourth international conference on intelligent computation technology and automation. **Anais...** . p.71–76, 2011. Ieee. Disponível em: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5750837>. Acesso em: 30/7/2012.

WANG, J.; JU, J.; WANG, J. Experimental Study on Pricking Hole Performances of Deep Application Liquid Fertilizer Device. **Fourth International Conference on Intelligent Computation Technology and Automation**, p. 71–76, 2011. Ieee.

WOMAC, A. R.; TOMPKINS, F. D. Probe-type injector for fluid fertilizers. **Agricultural Engineering**, v. 6, n. March, p. 149–154, 1990.

XI, X.; WANG, J.; LANG, C. Module design for parameter optimization of pricking hole mechanism of deep-fertilization liquid fertilizer applicator. 2011 International Conference on Computer Distributed Control and Intelligent Environmental Monitoring. **Anais...** . p.480–482, 2011. Ieee. Disponível em: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5747861>. Acesso em: 30/7/2012.

XU, B.; HU, M.; ZHANG, J.; SU, Q. Characteristics of volumetric losses and efficiency of axial piston pump with respect to displacement conditions *. **Applied Physics & Engineering: Zhejiang Univ-Sci**, v. 17, n. 3, p. 186–201, 2016.

XU, B.; SUN, Y.; ZHANG, J.; SUN, T.; MAO, Z. A new design method for the transition region of the valve plate for an axial piston pump. **Applied Physics & Engineering: Zhejiang Univ-Sci**, v. 16, n. 3, p. 229–240, 2015. Disponível em: <http://link.springer.com/10.1631/jzus.A1400266>. .

XU, H.; GUANG, Z. M.; QI, Y. Y. Hydrodynamic characterization and optimization of Contra-push check valve by numerical simulation. **Annals of Nuclear Energy**, v. 38, n. 6, p. 1427–1437, 2011.

YAMIN, M.; SMAIL, W. I. W.; KASSIM, M. S. M.; AZIZ, S. A.; SHAMSHIRI, R. VRT liquid fertilizer applicator for soil nutrient management. **Jurnal Teknologi**, v. 2, p. 73–78, 2016.

YANG, C. A variable rate applicator for controlling rates of two liquid fertilizers. **Applied Engineering in Agriculture**, v. 17, n. 3, p. 409–417, 2001.

YANG, W.; LI, Z.; WANG, J.; WU, P.; ZHANG, Y. Crop yield, nitrogen acquisition and sugarcane quality as affected by interspecific competition and nitrogen application. **Field**

Crops Research, v. 146, p. 44–50, 2013. Elsevier B.V.

ZAMYKAL, D.; EVERINGHAM, Y. L. Quantifying variability is only half the story - a review. In: E. Lichtfouse (Ed.); **Sugarcane and Precision Agriculture**. 1st ed., p.189–218, 2009. Dordrecht: Springer Netherlands.

ZHANG, X.; QUAN, L.; YANG, Y.; WANG, C.; YAO, L. Output characteristics of a series three-port axial piston pump. **Chinese Journal of Mechanical Engineering**, v. 25, n. 3, p. 498–505, 2012. Disponível em: <http://www.springerlink.com/index/10.3901/CJME.2012.03.498>. .

ZUTI, Z.; SHUPING, C.; XIAOHUI, L.; YUQUAN, Z.; WEIJIE, S. Design and Research on the New Type Water Hydraulic Axis Piston Pump. **Journal of Pressure Vessel Technology**, v. 138, n. 3, p. 031203, 2016.

9 APÊNDICES

APÊNDICE A: Sugestões de trabalhos futuros

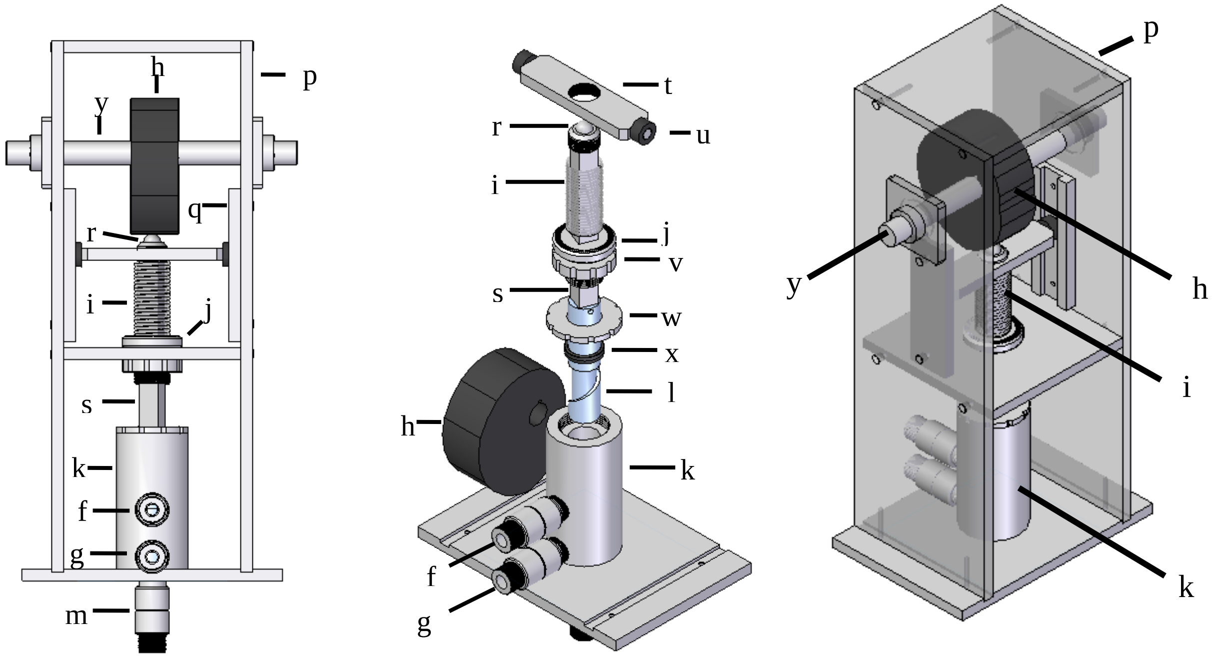
Próximos trabalhos podem prosseguir com o aprimoramento e elaboração de soluções para aplicação localizada de fertilizante líquido. Entre os desafios técnicos a serem abordadas em próximas versões do sistema de puncionamento no solo e injeção de adubo líquido, estão: a definição da unidade motriz (autopropelida ou tratora), o número de linhas de aplicação, o volume do reservatório, o acionamento do sistema puncionador-injetor (tomada de potência mecânica, hidráulica ou elétrica), a variação da distância entre as punções, especificações da sonda injetora (diâmetro do tubo, espessura da parede, comprimento, número de orifícios injetores e diâmetro dos orifícios injetores), o emprego de mecanismo protetor contra excesso de resistência à penetração, a aplicação de sistema pantográfico para auxiliar no seguimento do microrrelevo do solo em relação à profundidade de puncionamento.

O método de puncionamento pode ser avaliado utilizando outras fontes de fertilizante nitrogenado, como a aquamônia, ureia + água, uran. O processo alternativo também pode ser comparado aos métodos comuns de aplicação, com avaliações da: volatilização da amônia, emissão de gases do efeito estufa (N_2O e CH_4), disponibilidade de N mineral no solo, conteúdo do N-foliar vegetal e produtividade de colmos. Trabalho semelhante também pode ser conduzido em outros cultivos agrícolas, nos quais a adubação nitrogenada de cobertura é comum (lavouras de milho, arroz e trigo). Além disso, o processo desenvolvido para adubação localizada em cana-soca pode ser combinado com o uso de sensores de índices de vegetação, para a definição de aplicação com taxa variável com malha fechada. Neste modelo de operação, além da deposição do fertilizante em subsuperfície do solo com mínima mobilização, próximo às raízes das plantas, o sistema também pode fornecer uma concentração do nutriente adequado à exigência da planta.

APÊNDICE B: Descrição detalhada da unidade dosadora injetora

A unidade dosadora injetora (Figura 31) foi montada em um chassi (p) que apresenta estrutura constituída por placas metálicas retangulares utilizadas para garantir rigidez suporte à câmara (k) e ao eixo motor acoplado ao acionamento motor (y), o qual transmite potência ao came excêntrico (h) que transforma a rotação em movimento axial alternativo no pistão (l) por meio do seguidor mecânico de esfera (r). No sistema, a guia auxiliar (q, t, u) anula o momento angular produzido pela transmissão do came excêntrico (h) em relação ao eixo axial de seção transversal quadrada (s) montado através da mola de compressão (i). No movimento axial do eixo do pistão injetor (l) foi utilizada uma luva vazada com seção quadrada (j) empregada no ajuste de dosagem por meio da variação do ângulo radial. A posição radial do pistão injetor (l) conectado ao eixo de seção quadrada (s) é fixada por um elemento roscado (v). Para evitar o vazamento de fluido, na porção superior da câmara de aplicação (k) foi montada uma gaxeta (x) junto à vedação roscada (w). O pistão injetor (l) permite a comunicação do fluido com a linha hidráulica de retorno e a válvula de retenção na via hidráulica de retorno (f) em função da posição angular radial do sulco projetado. A comunicação da câmara com as vias hidráulicas é realizada pelas válvulas direcionais de retenção, posicionadas no retorno (f), sucção (g) e injetora (m).

Figura 31 – Unidade dosadora injetora. a. Vista frontal. b. Vista explodida. c. Vista isométrica.

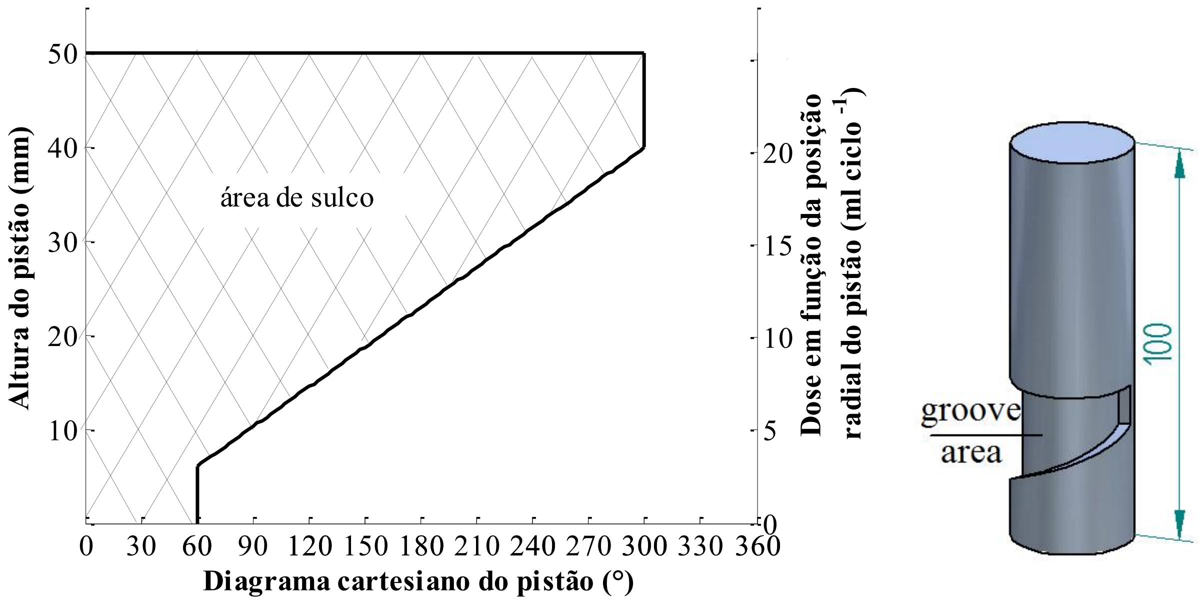


(a) (b) (c)

APÊNDICE C: Projeto do pistão injetor de fluidos

Na unidade dosadora e injetora, o volume direcionado para a injeção foi determinado pelas dimensões do pistão, amplitude de deslocamento axial e formato do sulco desenhado no pistão, o qual permite a comunicação do fluido com a via hidráulica de retorno. Para tanto, o ajuste do volume de injeção foi determinado em função do ângulo radial do pistão em relação à via hidráulica de retorno. A capacidade máxima de aplicação (até 20 mL por ciclo) foi garantida pelo diâmetro útil do pistão (ϕ 25,4 mm) e deslocamento axial de 40 mm. A Figura 32 mostra diagrama do projeto do sulco, considerando um ajuste linear da faixa de dosagem (5 a 20 mL ciclo^{-1}).

Figura 32 – Características do projeto do pistão injetor. a. Diagrama projetado para ajuste da dose de acordo com a posição angular do pistão. b. Projeção isométrica do pistão

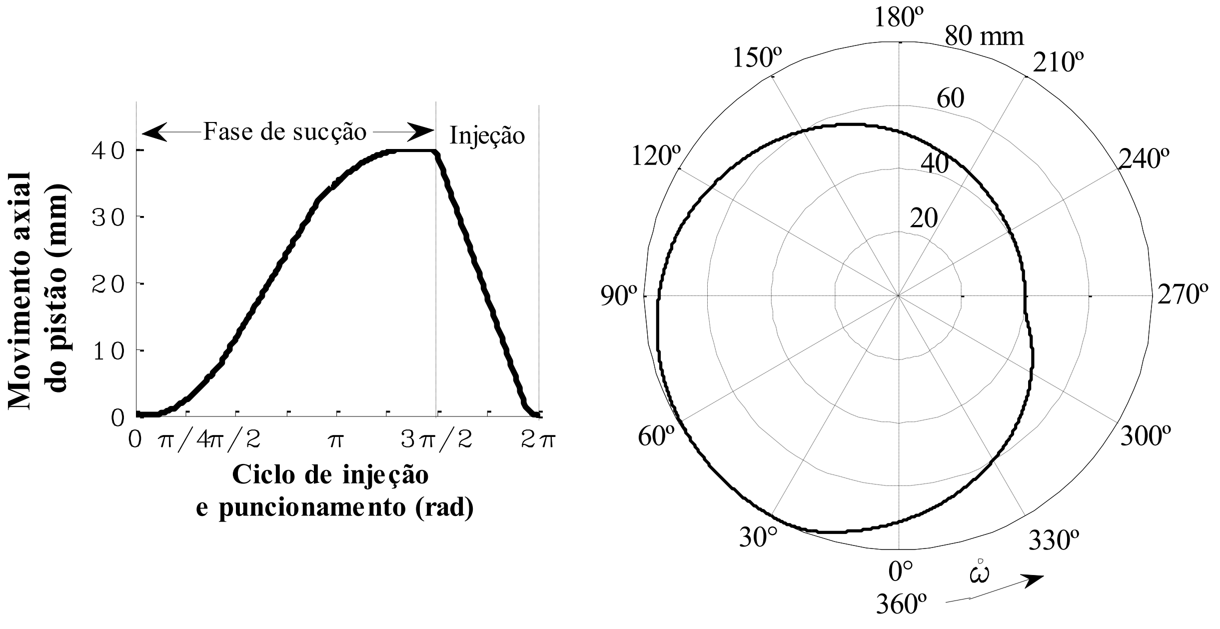


(a) (b)

APÊNDICE D: Projeto do came excêntrico aplicado no injetor de fluidos

A Figura 33a representa o deslocamento axial do pistão acionado pelo mecanismo de transmissão came, durante um ciclo de operação. A amplitude do movimento axial (40 mm) foi determinada em função do volume de aplicação (20 mL) e diâmetro interno da câmara (25,4 mm). No ciclo de puncionamento, durante o intervalo do movimento do puncionador sobre o solo (0 a $3\pi/2$ rad), o deslocamento axial do pistão da unidade dosadora foi projetado para realizar a sucção do fluido, e no intervalo de punção no solo ($3\pi/2$ a 2π rad) a injeção do fluido pelo pistão (Figura 33a). A partir do deslocamento axial em função das fases de sucção e injeção, nós projetamos o came excêntrico (Figura 33b, raio primário de 40 mm):

Figura 33 – Projeto do mecanismo de transmissão came. a. Deslocamento axial do pistão injetor em função do ciclo de puncionamento. b. Formato do came representado em diagrama polar



(a) (b)

APÊNDICE E: Modelagem em diagrama de blocos

A modelagem, simulação e análise foram utilizadas para fundamentar o dimensionamento e especificação dos elementos hidráulicos do sistema injetor. Na modelagem do sistema mecânico-hidráulico foram consideradas as características do processo proposto à operação de adubação e características do sistema mecânico (Tabela 8). Na simulação foi possível considerar diferentes cenários ao processo, como: a velocidade da máquina, a recomendação de adubação, a fonte de adubo líquido nitrogenado, a distância entre perfurações, o espaçamento entrelinhas da cultura, parâmetros dimensionais para o sistema injetor, e especificação de elementos hidráulicos, como válvulas de retenção e tubulações. A análise do atendimento das especificações do processo foi realizada a partir de variáveis como a vazão, pressão e dosagem.

A modelagem e simulação foram realizadas no Simulink que é vinculado ao Matlab (MathWorks, Version R2012a, Natick, MA, USA). O Simulink possui bibliotecas customizáveis para a programação por meio de diagramas de blocos, como o “Simscape”, no qual, são encontrados os blocos programáveis que representam válvulas, tubulações, cilindros hidráulicos, sensores de velocidade, força, pressão, e.g..

No diagrama de blocos (Figura 34), o acionamento da unidade dosadora injetora foi descrito pelo movimento axial do pistão em função do ciclo do came excêntrico (*Embedded block of Matlab Editor*). No modelo, a velocidade angular do came foi representada pelo bloco *Repeating Sequence*, por meio da modulação da frequência de operação de rotação, em ciclos de 0 a 2π rad.

A câmara e pistão foram representados por um cilindro hidráulico (*Single-Acting Hydraulic Cylinder*). Nesse, a porta *R* simboliza a entrada do sinal físico de velocidade que atua no movimento alternativo do pistão. Já a porta *A* foi associada aos orifícios das linhas hidráulicas sucção, retorno e injeção. Enquanto, a porta *C* foi vinculada a um engaste, que simboliza o chassi da unidade dosadora injetora.

A área da seção do pistão e amplitude do deslocamento alternativo foram os principais parâmetros do bloco cilindro hidráulico, o qual, associado também aos efeitos: dissipação de energia pelo amortecimento viscoso do cilindro hidráulico (bloco *Translational Damper*) e acúmulo e restituição de energia da mola (bloco *Translational Spring*). O deslocamento foi registrado pelo bloco sensor de movimento (*Ideal Translational Motion Sensor*).

Tabela 8 – Parâmetros utilizados na modelagem e simulação

Características da operação	
Dist. entre punções	0.3 m ciclo^{-1}
Espaç. entre linhas	1,5 m
Vel. de avanço	0,5 a 3,0 m s^{-1}
Taxa de adubação	100-120 kg ha^{-1} of N
Produto	Uran
Dose	8,0-17 mL ciclo $^{-1}$
Pistão e câmara	
Diâmetro	25,4 mm
Desl. alternativo do pistão	40 mm
Sonda injetora	
Diâmetro da sonda	15,87 mm
Diâmetro do oríficio	2 mm
Numero de oríficios	6
Área do oríficio	1,885 x 10^{-5} m^{2}
Válvulas de retenção: sucção e retorno	
Pressão de abertura	0,022 bar
Max. pressão de abertura	0,3 bar
Max. vazão	24 L min^{-1}
Válvulas de retenção: injeção	
Pressão de abertura	1,73bar
Max. pressão de abertura	2,07 bar
Max. vazão	24 L min^{-1}

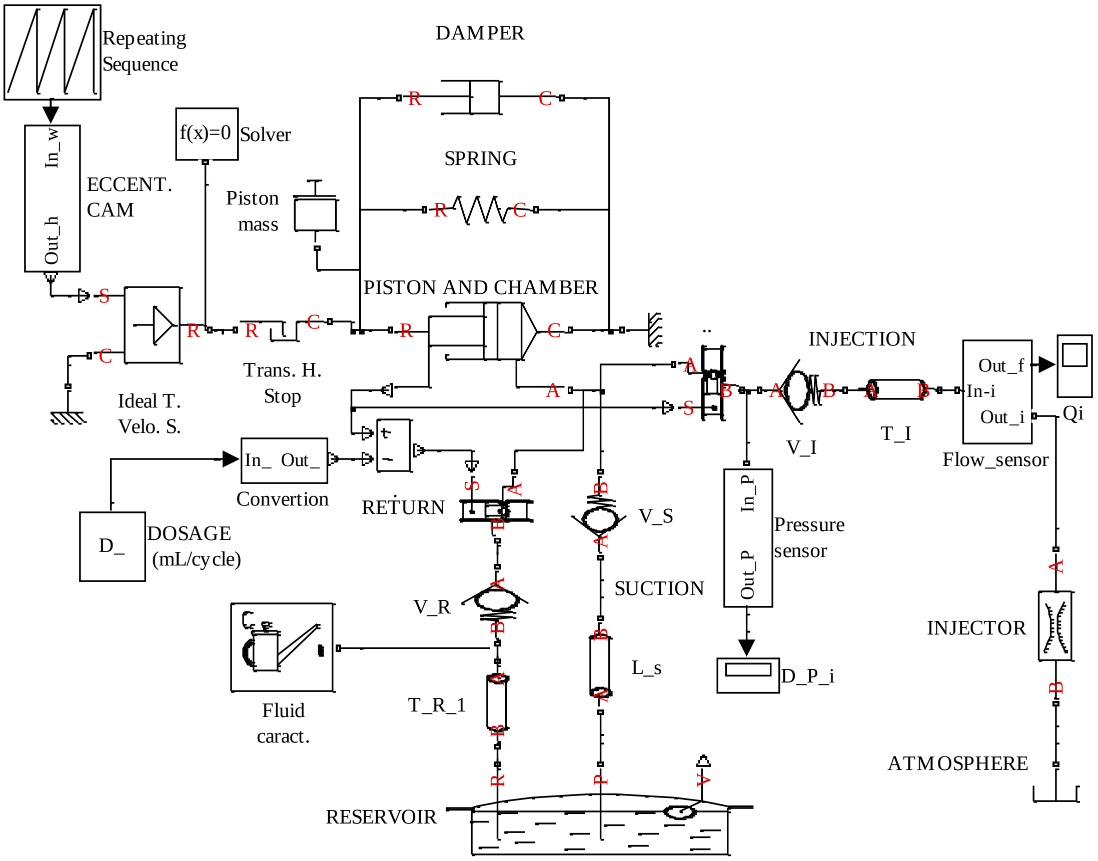
De acordo com o princípio de funcionamento do sistema, durante o intervalo de compressão do pistão, o fluido pode ser destinado ao injetor ou reservatório. No modelo, o processo foi simbolizado pelo bloco de orifício de área variável (*Orifice with Variable Area Round Holes*). O bloco representa fisicamente um carretel cilíndrico com movimento axial em uma luva perfurada, em que, a passagem de fluxo através do orifício é condicionada a posição axial do carretel. No bloco, as portas *A* e *B* são respectivamente a entrada e saída do fluido. Já a porta *S* representa a entrada do sinal físico de controle do movimento do carretel. O carretel recebe o mesmo sinal físico de movimento do deslocamento do pistão, sendo a abertura do fluxo para linha de retorno condicionada em função da posição axial e radial do pistão.

De modo similar ao sistema físico, na fase de injeção, quando o fluido se comunica simultaneamente com as vias hidráulicas de injeção e retorno, o fluxo é encaminhado através da menor resistência (menor diferencial de pressão), o retorno para o reservatório. Na fase de sucção do fluido do reservatório (*Reservoir block*), o pistão é impulsionado pela força da mola, com movimento de retração. O fluido de trabalho foi caracterizado pela densidade e viscosidade cinemática (*Custom Hydraulic Fluid block*).

Nas linhas hidráulicas, os principais parâmetros das tubulações (*hydraulic pipeline block*) foram: o diâmetro interno, comprimento, tipo de tubulação (flexível ou rígida) e os números limites de Reynolds para os regimes laminar e turbulento. Já as válvulas de retenção (*Check Valve block*) possuem como parâmetros a pressão de abertura, perda de carga máxima a partir da abertura, coeficiente de descarga, área interna máxima para a passagem do fluxo. Nas linhas hidráulicas, a pressão e vazão foram registradas simbolicamente pelos blocos da biblioteca de instrumentação (*Hydraulic Pressure Sensor and Hydraulic Flow Rate Sensor*).

Para a injeção do fluido no solo, a sonda injetora foi descrita no modelo por um orifício de área constante (*Fixed orifice block*), sendo a comunicação fluídica com o solo simbolizada pela referência hidráulica atmosférica (*Hydraulic reference block*). Como parâmetros dimensionais ao injetor foram considerados a área do orifício, o coeficiente de descarga e o número de Reynolds crítico (regime de fluxo indeterminado).

Figura 34 – Circuito hidráulico do sistema injetor de fertilizante líquido em montagem no Matlab/Simulink.



APÊNDICE F: Imagens

Figura 35 – Elementos da bomba de pistão: (i) came excêntrico, (ii) chassi, (iii) vedação da câmara, (iv) gaxeta de vedação, (v) mola de compressão, (vi) pistão, (vii) câmara, (viii) luva de ajuste angular do pistão, (ix) eixo quadrado de movimento linear (x) válvulas de retenção direcionais, (xi) guia auxiliar

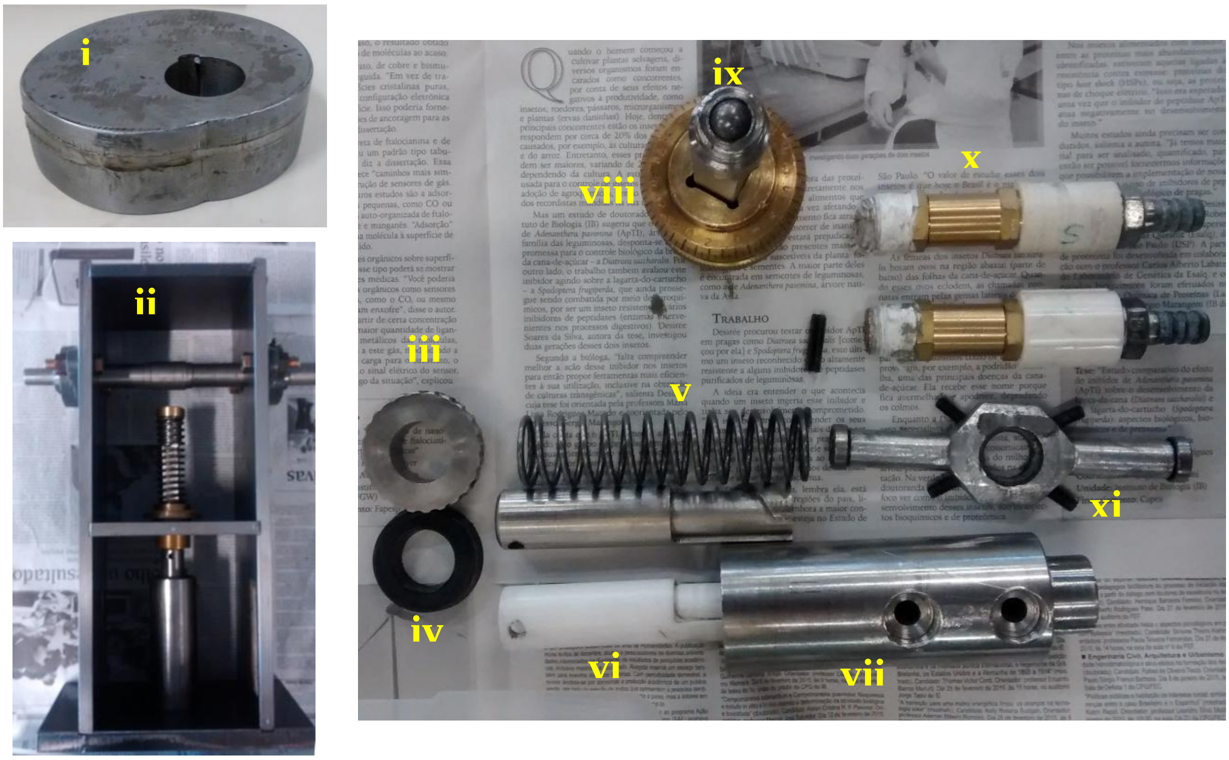
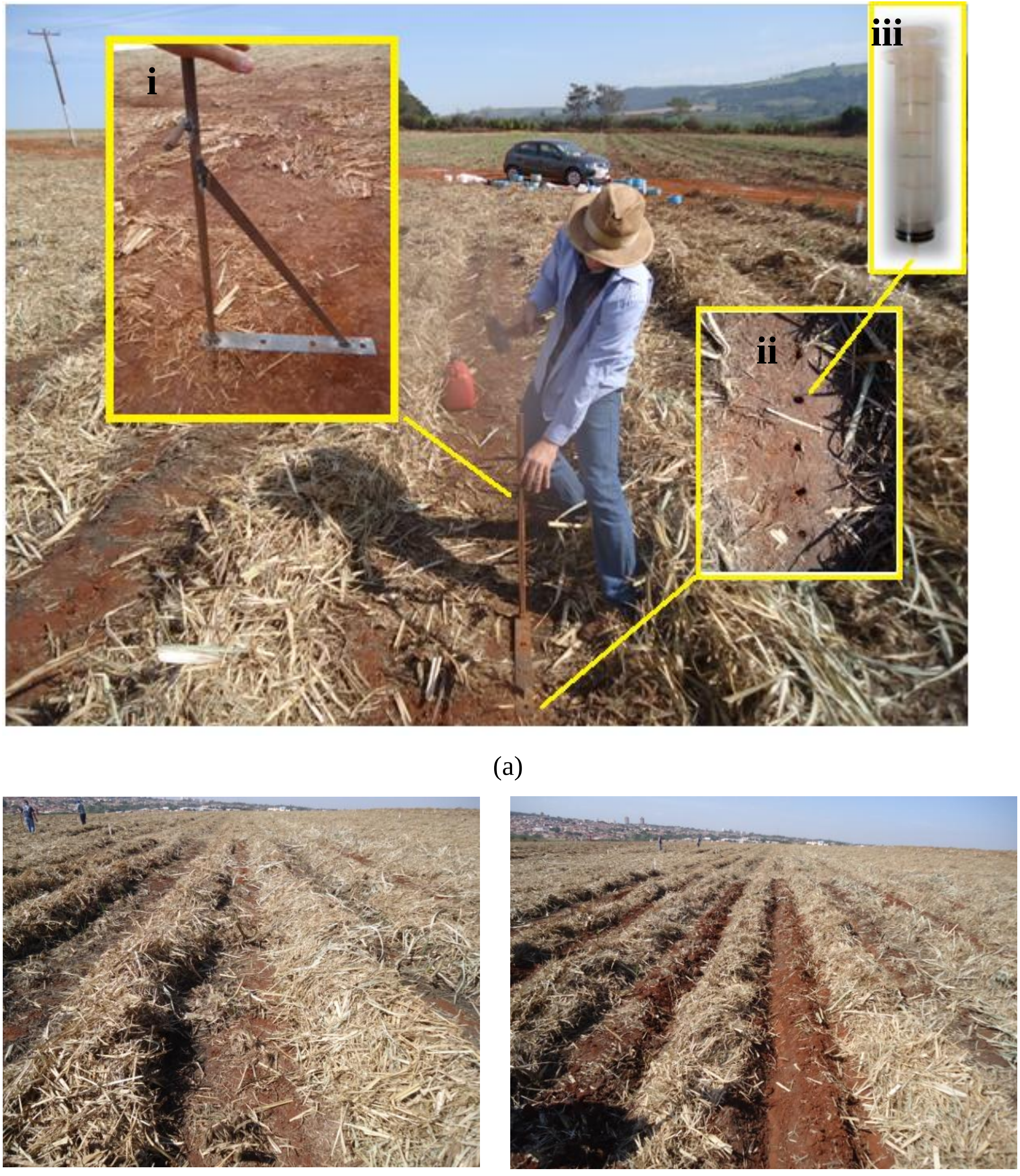


Figura 36 – Experimento realizado em caixa de solo

Figura 37 – Instalação do experimento sobre os métodos de adubação em área de cana-soca. a. Processo manual de aplicação, utilizando (i) puncionador para a (ii) perfuração do solo e (iii) injeção do fertilizante. b. Aplicação do fertilizante sob os resíduos vegetais. c. aplicação incorporada por meio de sulcos, em ambos os lados da linha de cana-de-açúcar

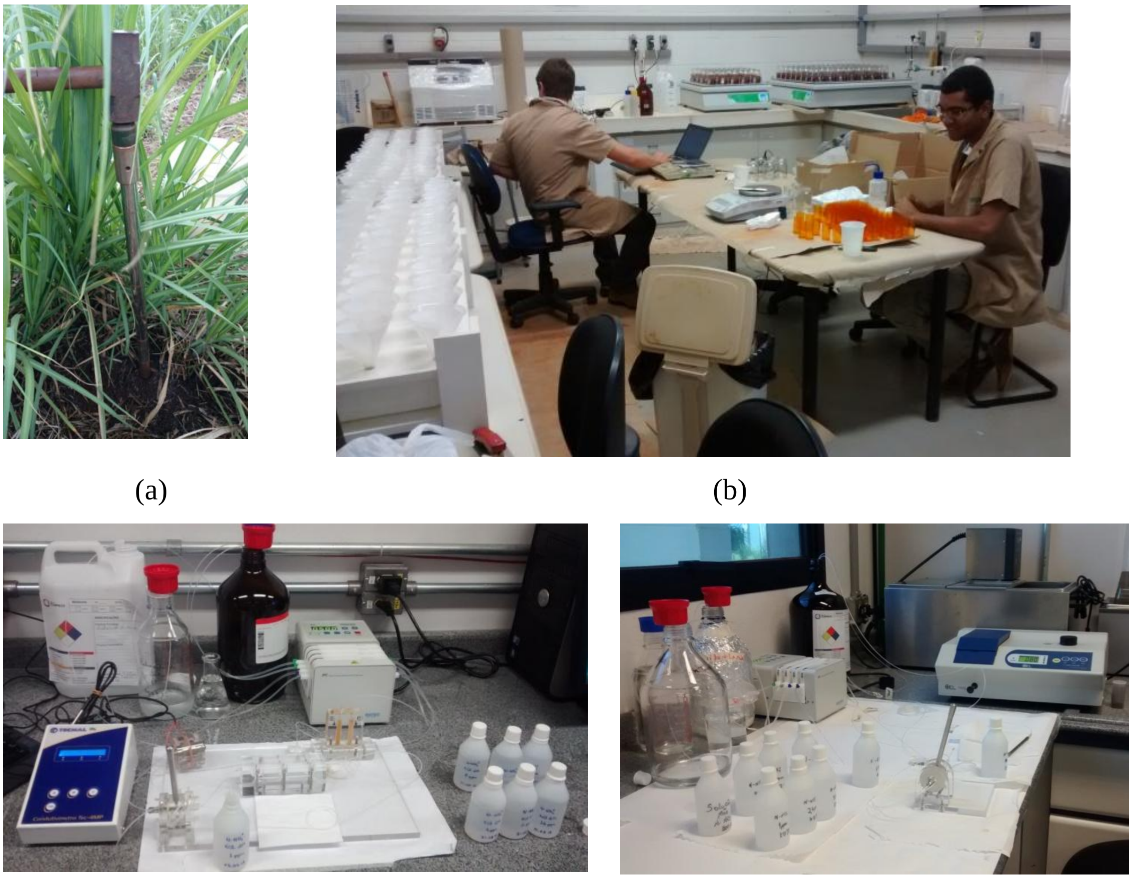


(a)

(b)

(c)

Figura 38 – Representações das etapas para determinação do N mineral do solo. a. Coleta. b. Extração. c. amônio (NH_4^+ - N). d. nitrato (NO_3^--N)



(a) (b)

(c) (d)

Figura 39 – Etapas do experimento de adubação. a. Instalação do experimento aos 0 DAF[2]. b. 130 DAF[3]. c. 250 DAF[2]. d. 375 DAF[4]

(a) (b)

(c) (d)

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[2] Dias após a aplicação do fertilizante

[3] Coleta de folhas +1 para determinação do N-foliar, avaliação do indíce de clorofila foliar, coleta de solo para determinação do N mineral

[4] Avaliações de biometria, coleta de material para análise de qualidade tecnológica