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EVALUATION OF VARIABLE-RATE SPRAY APPLICATION ON TREE CROP

JOÃO EDUARDO RIBEIRO DA SILVA

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Tese apresentada à Universidade Federal de Uberlândia, como parte das exigências do Programa de Pós-Graduação em Agronomia – Doutorado, para obtenção do título de "Doutor".

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DEDICATÓRIA

Dedico esta tese a Deus.
Criador de tudo que existe.
Minha fé está em Ti.

AGRADECIMENTOS

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SUMÁRIO

GENERAL ABSTRACT

SILVA, JOÃO EDUARDO RIBEIRO. **Evaluation of variable-rate spray application on tree crop**. 2017. 59f. Thesis (PhD degree in Agronomy / Crop Protection) – Federal University of Uberlandia[1].

Abstract: On tree crops, a great diversity of canopy structure and density is found. Using conventional sprayers, much of the sprayed material is wasted. The variability of the tree canopies is most of the times not taken into consideration, generating conditions of underspray, overspray and drift. Tree Row Volume (TRV) methods have been developed to indirect measure the canopy and adjust the sprayed volume to the plants characteristics. However, the constant rate application does not eliminate overspray and underspray, as well as application between trees, which could lead to spray drift. The use of sensors for tree crops canopy characterization together with variable-rate spray application can produce efficient spray deposition and coverage on tree crops, and reduce the drift. However, variable-rate sprayers modulate the number of operating nozzles and the duty cycle constantly, causing an effect on the system pressure. A variable-rate intelligent sprayer implementing a high speed laser scanner was developed for tree crops customized spraying. It had 40 nozzles on total, with the nozzles being independently capable of spraying at 10 percentages of the maximum flow rate (duty cycle). The nozzle output was adjusted by solenoid valves. Experiments were conducted to further evaluate the performance under field conditions of the variable-rate intelligent sprayer and a conventional constant-rate sprayer, studying the spray drift, spray coverage and deposition inside Ash tree canopies. A second role of tests was realized to evaluate the pressure behavior and its effect on flow rate of the intelligent sprayer on several combinations of duty cycle and number of operating nozzles. The flow rate was measured for the different combinations and the pressure was checked. The deposition test was at factorial scheme 2 x 3 (two sprayers and three travel speeds), with three replications in blocks randomized. The drift test was at factorial scheme 2 x 3 x 5 (two sprayers, three travel speeds and, five distances of drift collectors, in split-plot), with three replications in blocks randomized. For these tests it was used the tracer Brilliant Sulphoflavine (BSF) at 2.0 g L^{-1} concentration. The first test for evaluation of the intelligent sprayer's flow-rate and pressure behavior was at factorial scheme 10 x 40 (10 duty cycles and 1-40 operating nozzles), being the sprayer's pressure set to 50 PSI (344.7 kPa) at the beginning of the test (varied pressure condition). The second test on the intelligent sprayer was at factorial scheme 10 x 5 (10 duty cycles and 1, 10, 20, 30 or 40 operating nozzles), with the pressure staying constant at 35 PSI (241 kPa) (constant pressure condition). The use of sensors together with variable-rate delivery systems, implementing mostly solenoid valves to control spray application, have proportionated pesticide savings and drift reduction. The variable-rate intelligent sprayer reduced the application rate in 64%, drift to the air in 92-94% and drift to the ground in 58-98%. Spray coverage and deposition were similar for both sprayers and not affected by sprayers travel speed. It was observed more accentuated pressure decay on the varied pressure condition. The flow rate of the variable-rate intelligent sprayer could be described through a polynomial regression curve, for both varied and constant pressure conditions.

Keywords: airblast sprayer, laser scanning, application technology, TRV.

[1]Guidance Committee: João Paulo Arantes Rodrigues da Cunha - UFU (Major Professor) and Heping Zhu – USDA.

RESUMO GERAL

SILVA, JOÃO EDUARDO RIBEIRO. **Avaliação de aplicação à taxa variada em cultura arbórea**. 2017. 59f. Tese (Doutorado em Agronomia / Fitotecnia). Universidade Federal de Uberlândia[2].

Resumo: Nas culturas arbóreas, existe grande diversidade na estrutura e na densidade das copas das plantas. Métodos para medição indireta das copas foram desenvolvidos, como o "Tree Row Volume" (TRV), para melhor ajuste do volume de pulverização dos defensivos agrícolas às características das plantas. No entanto, a aplicação a taxa constante não elimina aplicações fora da área da planta. O uso de sensores para a caracterização das copas, em conjunto com aplicação em taxa variada, deverá produzir deposição e cobertura de calda satisfatórias em culturas arbóreas, e ainda reduzir a deriva. No entanto, os pulverizadores de taxa variada modulam frequentemente o número de pontas em operação e a vazão destas, gerando oscilação na pressão do sistema hidráulico. Um pulverizador inteligente de aplicação em taxa variada, equipado com sensor laser de alta velocidade, foi desenvolvido para aplicação em culturas arbóreas. O pulverizador possuia 40 pontas no total, sendo cada ponta capaz de pulverizar em 10 porcentagens da sua vazão máxima (ciclo de trabalho – "duty cycle"), sendo controladas por válvulas solenóides. Dois experimentos de campo (deriva e deposição) foram conduzidos para avaliar o desempenho do pulverizador à taxa variada e de um pulverizador convencional de taxa constante, quanto a deriva de pulverização, cobertura e deposição de calda na copa das árvores de Ash. Um segundo conjunto de testes foi realizado para avaliar o comportamento da pressão e seu efeito sobre a vazão do pulverizador inteligente em várias combinações de ciclo de trabalho e número de pontas em operação. A vazão foi determinada para as diferentes combinações de ciclo de trabalho x número de pontas, e verificou-se a pressão. O teste de deposição em campo foi em esquema fatorial 2 x 3 (dois pulverizadores e três velocidades de deslocamento), com três repetições em blocos casualizados. O teste de deriva foi no esquema fatorial 2 x 3 x 5 (dois pulverizadores, três velocidades de deslocamento e cinco distâncias dos coletores de deriva, em parcelas subdivididas), com três repetições em blocos casualizados. Para estes testes utilizou-se o corante Sulfoflavina Brilhante (BSF) a 2,0 g por L^{-1} de concentração. O primeiro teste de avaliação da vazão e comportamento da pressão do pulverizador inteligente foi em esquema fatorial 10 x 40 (10 ciclos de trabalho e 1-40 bicos em operação), sendo a pressão do pulverizador ajustada para 50 PSI (344,7 kPa) no início do teste (pressão variada). O segundo teste de vazão no pulverizador inteligente foi em esquema fatorial 10 x 5 (10 ciclos de trabalho e 1, 10, 20, 30 ou 40 bocais em operação), mantendo-se a pressão constante em 35 PSI (241 kPa) (pressão constante). O uso de sensores juntamente com sistemas de distribuição à taxa variada proporciona redução no volume aplicado e na deriva. O pulverizador inteligente reduziu a taxa de aplicação em 64%, a deriva para o ar em 92-94% e a deriva para o solo em 58-98%. A cobertura de pulverização e a deposição se mostraram semelhantes para ambos os pulverizadores e não foram afetadas pela velocidade de deslocamento. Observou-se um decréscimo mais acentuado da pressão no teste com pressão variada. A vazão do pulverizador inteligente de taxa variável pode ser predita através de curva de regressão polinomial, para as duas condições de pressão.

Palavras-chave: pulverizador hidropneumático, laser, tecnologia de aplicação, TRV.

[2]Comitê Orientador: João Paulo Arantes Rodrigues da Cunha - UFU (Orientador) e Heping Zhu – USDA.

CHAPTER 1

DEVELOPMENT OF AIRBLAST SPRAYER APPLICATION TECHNOLOGY ON TREE CROPS

Abstract: On tree crops, a great diversity of canopy structure and density is found. Using conventional sprayers, much of the sprayed material is wasted. The variability of the tree canopies is most of the times not taken into consideration, generating conditions of underspray, overspray and drift. Tree Row Volume (TRV) methods have been developed to indirect measure the canopy and adjust the sprayed volume to the plants characteristics. However, the constant rate application does not eliminate overspray and underspray, as well as application between trees, which could lead to spray drift. The use of sensors for tree crops canopy characterization together with variable-rate spray application can produce efficient spray deposition and coverage on tree crops, and reduce the drift. However, variable-rate sprayers modulate the number of operating nozzles and the duty cycle constantly, causing an effect on the system pressure. A variable-rate intelligent sprayer implementing a high speed laser scanner was developed for tree crops customized spraying. It had 40 nozzles on total, with the nozzles being independently capable of spraying at 10 percentages of the maximum flow rate (duty cycle). The nozzle output was adjusted by solenoid valves. Experiments were conducted to further evaluate the performance under field conditions of the variable-rate intelligent sprayer and a conventional constant-rate sprayer, studying the spray drift, spray coverage and deposition inside Ash tree canopies. A second role of tests was realized to evaluate the pressure behavior and its effect on flow rate of the intelligent sprayer on several combinations of duty cycle and number of operating nozzles. The flow rate was measured for the different combinations and the pressure was checked. The deposition test was at factorial scheme 2 x 3 (two sprayers and three travel speeds), with three replications in blocks randomized. The drift test was at factorial scheme 2 x 3 x 5 (two sprayers, three travel speeds and, five distances of drift collectors, in split-plot), with three replications in blocks randomized. For these tests it was used the tracer Brilliant Sulphoflavine (BSF) at 2.0 g L^{-1} concentration. The first test for evaluation of the intelligent sprayer's flow-rate and pressure behavior was at factorial scheme 10 x 40 (10 duty cycles and 1-40 operating nozzles), being the sprayer's pressure set to 50 PSI (344.7 kPa) at the beginning of the test (varied pressure condition). The second test on the intelligent sprayer was at factorial scheme 10 x 5 (10 duty cycles and 1, 10, 20, 30 or 40 operating nozzles), with the pressure staying constant at 35 PSI (241 kPa) (constant pressure condition). The use of sensors together with variable-rate delivery systems, implementing mostly solenoid valves to control spray application, have proportionated pesticide savings and drift reduction. The variable-rate intelligent sprayer reduced the application rate in 64%, drift to the air in 92-94% and drift to the ground in 58-98%. Spray coverage and deposition were similar for both sprayers and not affected by sprayers travel speed. It was observed more accentuated pressure decay on the varied pressure condition. The flow rate of the variable-rate intelligent sprayer could be described through a polynomial regression curve, for both varied and constant pressure conditions.

Keywords: variable-rate, spray application, laser sensor, flow rate.

CAPÍTULO 1

DESENVOLVIMENTO DA TECNOLOGIA DE APLICAÇÃO DE PULVERIZADORES HIDROPNEUMÁTICOS EM CULTURAS ARBÓREAS

Resumo: Nas culturas arbóreas, existe grande diversidade na estrutura e na densidade das copas das plantas. Métodos para medição indireta das copas foram desenvolvidos, como o "Tree Row Volume" (TRV), para melhor ajuste do volume de pulverização dos defensivos agrícolas às características das plantas. No entanto, a aplicação a taxa constante não elimina aplicações fora da área da planta. O uso de sensores para a caracterização das copas, em conjunto com aplicação em taxa variada, deverá produzir deposição e cobertura de calda satisfatórias em culturas arbóreas, e ainda reduzir a deriva. No entanto, os pulverizadores de taxa variada modulam frequentemente o número de pontas em operação e a vazão destas, gerando oscilação na pressão do sistema hidráulico. Um pulverizador inteligente de aplicação em taxa variada, equipado com sensor laser de alta velocidade, foi desenvolvido para aplicação em culturas arbóreas. O pulverizador possuia 40 pontas no total, sendo cada ponta capaz de pulverizar em 10 porcentagens da sua vazão máxima (ciclo de trabalho – "duty cycle"), sendo controladas por válvulas solenóides. Dois experimentos de campo (deriva e deposição) foram conduzidos para avaliar o desempenho do pulverizador à taxa variada e de um pulverizador convencional de taxa constante, quanto a deriva de pulverização, cobertura e deposição de calda na copa das árvores de Ash. Um segundo conjunto de testes foi realizado para avaliar o comportamento da pressão e seu efeito sobre a vazão do pulverizador inteligente em várias combinações de ciclo de trabalho e número de pontas em operação. A vazão foi determinada para as diferentes combinações de ciclo de trabalho x número de pontas, e verificou-se a pressão. O teste de deposição em campo foi em esquema fatorial 2 x 3 (dois pulverizadores e três velocidades de deslocamento), com três repetições em blocos casualizados. O teste de deriva foi no esquema fatorial 2 x 3 x 5 (dois pulverizadores, três velocidades de deslocamento e cinco distâncias dos coletores de deriva, em parcelas subdivididas), com três repetições em blocos casualizados. Para estes testes utilizou-se o corante Sulfoflavina Brilhante (BSF) a 2,0 g por L^{-1} de concentração. O primeiro teste de avaliação da vazão e comportamento da pressão do pulverizador inteligente foi em esquema fatorial 10 x 40 (10 ciclos de trabalho e 1-40 bicos em operação), sendo a pressão do pulverizador ajustada para 50 PSI (344,7 kPa) no início do teste (pressão variada). O segundo teste de vazão no pulverizador inteligente foi em esquema fatorial 10 x 5 (10 ciclos de trabalho e 1, 10, 20, 30 ou 40 bocais em operação), mantendo-se a pressão constante em 35 PSI (241 kPa) (pressão constante). O uso de sensores juntamente com sistemas de distribuição à taxa variada proporciona redução no volume aplicado e na deriva. O pulverizador inteligente reduziu a taxa de aplicação em 64%, a deriva para o ar em 92-94% e a deriva para o solo em 58-98%. A cobertura de pulverização e a deposição se mostraram semelhantes para ambos os pulverizadores e não foram afetadas pela velocidade de deslocamento. Observou-se um decréscimo mais acentuado da pressão no teste com pressão variada. A vazão do pulverizador inteligente de taxa variável pode ser predita através de curva de regressão polinomial, para as duas condições de pressão.

Palavras-chave: taxa variada, aplicação, sensor laser, vazão, volume da planta.

1. INTRODUCTION

Foliar pesticide applications are the most effective method to prevent the yield losses caused from the attack of pests and diseases. On tree crops, a great diversity of canopy structure and density is found. It is common to have crops with plants of different ages in the same nursery. This way, foliar spray applications often results in overspray (CHEN et al., 2012).

Using conventional sprayers, much of the sprayed material is wasted. The excessive use of pesticides increases the production cost and the potential for environmental contamination (ZHU et al., 2006).

The application technology of plant protection products (PPP) for tree crops has been widely studied, taking in account important features like the plant canopy, which varies a lot. Tree crops have canopies that vary in shape and size, even during the same growing season, requiring a continuous adjust of the spray application rate to optimize the coverage and deposition on the plants (SOLANELLES et al., 2002).

According to Zhu et al. (2011a), the spray applications for floral, nursery, and tree fruit crops requires excessive amounts of liquid and PPP to control pests and diseases. The variability of the tree canopies are most of the times not taken into consideration, generating conditions of overspray, loss of product, economic loss and environmental contamination. Zhu et al. (2014) state that precision pesticide application equipment and strategies are needed to reduce pesticide usage.

2. DEVELOPMENT

On an efficient application, the PPPs are intended to be homogenously distributed over the plants, with drift and losses being as lower as possible. The PPP application technology has great importance due to economic and environmental costs derived from their use.

The application of PPP on tree crops often causes great amounts of products that end up on non-intended areas, causing environmental and economic losses. The unsuitability of the volume and dose sprayed to the crops needs contributes to this situation. Also there is little information for applicators regarded to spray volume calibration, according to the canopies characteristics.

According to Planas et al (2006), the amount of pesticide deposited on leaves and the quality of the distribution inside the canopy, depends directly on the trees structure, on parameters such as height, width, volume and leaf density.

Many PPP are still recommended based on the crops ground area. Nevertheless, same species crops can present varied spacing on field, ending up with a different population on the same ground area. Also, some species show a different leaf area index (LAI) at the different vegetative stages during the season.

Pergher and Petris (2008) demonstrated that the application of a constant dose per unit ground area gave consistent results in average foliar deposits that are inversely proportional to the LAI of the crop. Applying the same amount of liquid with the same pesticide concentration, the quantity deposited on the leaves decreases with increasing leaf area, independently of the sprayer employed (BALSARI, 2001).

The application technology for tree crops also has a challenge of deposition on the inner parts of the canopy. Especially large canopies present a protection effect caused by the outer leaves, making more difficult the penetration of droplets on the inner canopy.

The spray penetration is probably the most important issue, once that all crops show fewer depositions on the inner parts of the canopies, due to a barrier effect produced by the mass of vegetation, being this difference bigger in big trees with high leaf density canopies and smaller on low leaf density canopies (BALSARI, 2001; PERGHER AND PETRIS, 2008). According to Planas et al (2006), it is difficult to achieve uniform spray deposition on the canopies of the varieties of tree crops studied, such as pear, apple, vine and citrus, being the spray penetration an important objective for the technical development of the air-assisted sprayers for saving pesticides.

As a main objective, the spray application should proportionate the best control of the diseases and insects, with the minimum use of PPP and with lower drift loss. The spray application efficiency has been defined by Planas et al (2006) as the amount of chemical depositions on leaves in relation to the total of chemical applied.

2.1. Tree Row Volume Method (TRV)

Spray applications on tree crops have performed doses expressed as a per unit ground area until nowadays (ESCOLÀ et al., 2013). However, as early as the 1960s, Morgan (1964) stated that the dosage should take in account dimensions and geometric parameters of canopies.

Byers et al. (1971) developed a method for indirect estimation of the amount of leaves per unit ground area for tree crops, and named it tree-row-volume (TRV). The methodology was based on manual measurements of the height and width (measured in the base of the canopy) of the trees, and the distance between rows (Figure 1a). The unit calculated in this method was m^3 of canopy ha^{-1}, and the application rate was obtained after multiplication by a application rate in L per m^3 of canopy ha^{-1}. The application rate ranged from 7.5 to 10.3 m^3 L^{-1} of spray solution.

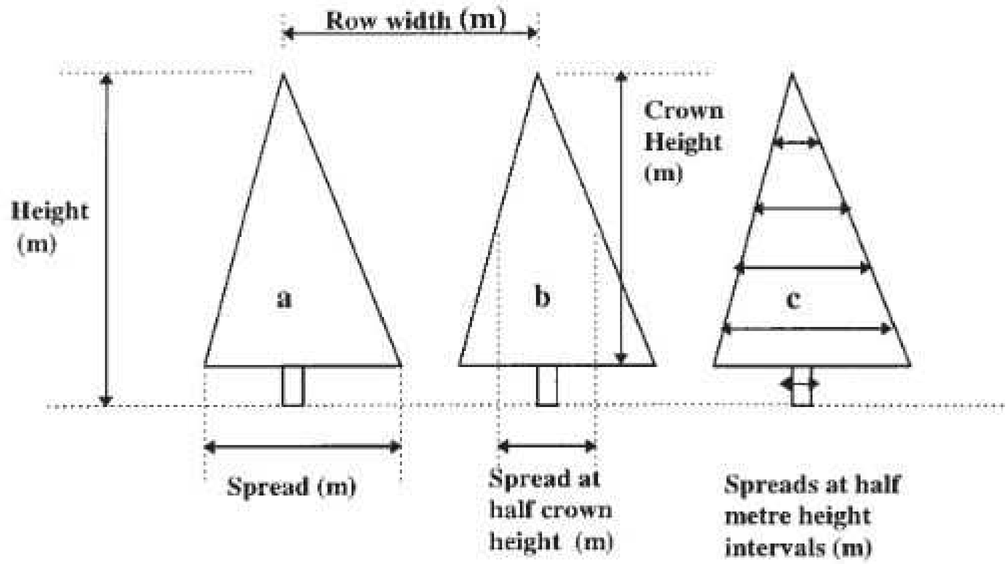

Figure 1 – Pattern for measurements of the plant characteristics for canopy volume estimation methods, taken in: a) American TRV (US-TRV); b) European half crown TRV (HC-TRV), and; c) New Zealand height stratified TRV (HS-TRV). (Adapted from Manktelow and Pratt, 1997).

This methodology fit well on American crops since it was used majorly on apple trees, which tend to have a more globular canopy shape, being so classified on later publications as United Stated Tree Row Volume (US-TRV).

On a later study, Byers et al. (1984) stated that the deposits inside the canopies were significantly different when spraying doses determined by TRV methods onto canopies with different foliage densities. Being so, Sutton and Unrath (1984) added an arbitrary coefficient to TRV method, taking in account canopy density.

However, in Europe, where the tree crops had a more triangular shape, a modification to the method was created. The measurements of height and width were taken from the canopy of the plants, and not the whole plant, being the width measured taken at the half of the crown height, or half of the canopy. The method was named half-crown height tree row volume (HC-TRV) (Figure 1b).

Finally a third modification of the method was proposed for New Zealand crops, named height stratified tree row volume (HS-TRV) (Figure 1c), with measurements of the width of the canopy being taken every 0.5 m. As more stratified the canopy was, more accurate would the measurement be. However, as stated by Manktelow and Pratt (1997), new application rates should be adopted to maintain the coverage and deposition on leaves.

The TRV method proportionate optimization and reduced use of application rates on tree crops, when the PPP dose is expressed in concentration of spray mix, and not on a per unit ground area base. Still the problem of complicated measuring systems remains, once there is not one method that can be adjusted to every tree crop canopy characteristics. Also, the constant rate application does not eliminate overspray and underspray, as well as application between trees, which could lead to drift problems.

2.2. Decision Tools

Decision tools have been developed to provide an easy way to calculate the optimal volume application rate for tree crops. For fruit crops, such as pear and apple, it was developed the "Dosafruit". An analog was developed for vineyards, the "Dosaviña" (PLANAS et al., 2006).

The expression of pesticide dose were directly related to the dimensional parameters of the trees (as vegetation volume) and to the leaf density instead of referring to the spray liquid concentration.

On those tools, special software was developed to run in PC, and the dose was directly related to the dimensional parameters of the trees and leaf density. As stated by Gil et al. (2011), "Dosaviña" is a decision support system (DSS) developed to determine the optimal volume rate for vineyard spraying. The decision tool, named as "Dosaviña" is a Microsoft Excel application based on multiple data obtained after several years of working conditions using different types of sprayers in vineyards, and includes a complete database for crop characteristics (canopy structure, crop stage, leaf area, leaf density, etc.) according to the development stage. It was developed with the objective to generate an easy-to-use DDS that was able to determine the optimal volume rate for vineyard spray applications. "Dosaviña" also quantifies, in terms of liquid loss, the effect of all parameters involved during the application process, using drift models. However, not every country has such a tool to help taking decision before PPP applications.

2.3. Variable-Rate Application on Tree Crops

As mentioned above, the estimation of the canopy can improve the spray application on tree crops significantly. However, manual measurements and decision tools imply some inaccuracy. The result of dose adjustment for tree crops represents an average, taking in account the trees measured, and not the entire plot. These methods do not take in account the spatial variability of canopy parameters, and also the space between plants that should not be sprayed. Precision agriculture began to consider this variability and to adapt the spray to the crop variability on a real-time base (ESCOLÀ et al., 2013).

The beginning of the efforts to automatic verify the tree canopies started with the implementation of optic sensors (WANGLER et al., 1994; DORUCHOWSKI et al., 1997; JAEKEN et al., 1997) to only spray in the presence of a canopy. By turning off the sprayer when no trees were detected, important reductions of PPP and drift pollution were achieved.

However, still it was a constant rate spray application, not taking in account the variability of the tree canopies. Recent research projects have considered canopy variability and adjusted the amount of sprayed PPP using electronic sensors and actuators (ESCOLÀ et al., 2013).

Aiming for a variable-rate application rate, Chen et al. (2012) stated that the efficiency of the pesticide application could be improved using sensor technologies to identify the trees and apply a certain amount of material needed for adequate control of pests and diseases. That was an evolution on the use of sensors on tree crops spray application, evolving now the real time-measuring together with a variable-rate control system to adjust the spray output.

Reinforcing this idea, Fox et al. (2008) concluded that variable-rate air-assisted sprayers were necessary to overcome disadvantages of conventional air-assisted sprayers on applications on tree crops, once that the applications were based on the canopy structure and foliage density.

2.4. Sensors

A sensor is a device that detects and responds to some type of input from the physical environment. In the application technology field of study, the specific input is the plant to be sprayed and its characteristic. The output is generally a signal that is converted to human-readable display at the sensor location or transmitted electronically over a network for reading or further processing on software.

As mentioned above, the use of sensors for target detection started in the 1990's, but its use has been improved over the years. Zhu et al. (2014) state that precision pesticide application equipment and strategies are needed to reduce pesticide usage. One way to meet this need is to use sensor technologies to identify target trees.

2.5. Ultrasonic Sensors

Ultrasonic transducers are divided into three broad categories: transmitters, receivers and transceivers. Transmitters convert electrical signals into ultrasound, receivers convert ultrasound into electrical signals, and transceivers can both transmit and receive ultrasonic waves.

Ultrasonic sensors are based on measuring the properties of sound waves with frequency above the human audible range. The human audible frequency range is between 20 – 20 kHz, and ultrasonic sensors operate on frequencies close to 40 kHz.

Ultrasonic sensors for agricultural purposes operate on the principle of the time-of-flight between the transmission of the ultrasonic wave and its receiving back. They do not require physical contact with the target, and can detect certain clear or shiny targets otherwise obscured to some vision-based sensors. On the other hand, their measurements can be very sensitive to the air temperature and to the angle of the target.

Figure 2 shows the ultrasonic waves being emitted and received, a sensing method based on the time-of-flight of the wave.

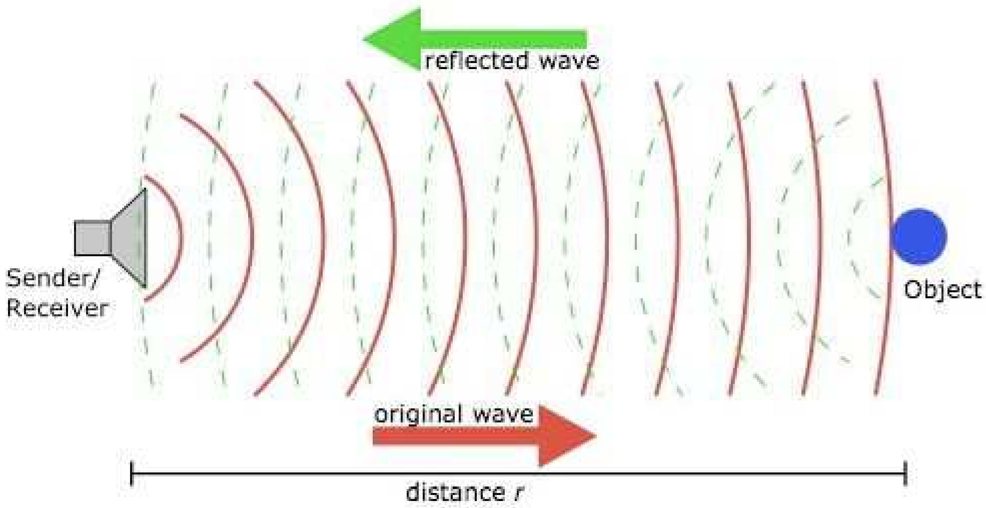

Figure 2 – Ultrasonic waves target detection using the time-of-flight of the wave principle, showing the emission and reception of the waves, with the use of a sender/receiver sensor.

The first efforts for real-time measuring of canopies using ultrasonic sensors showed the great ability of these for tree canopies characterization. Ultrasonic sensors were vastly studied, adding great savings and enhancing the spray penetration and coverage.

To reduce chemical use in nurseries and orchards, researchers have designed several variable-rate sprayers with different ultrasonic sensors. Giles et al. (1989), Escola et al. (2003), Solanelles et al. (2006), and Gil et al. (2007) developed variable-rate sprayers with integration of ultrasonic sensors and documented savings in spray application amount. Jeon et al. (2011) and Jeon and Zhu (2012) also used 20 Hz ultrasonic sensors in a vertical boom variable-rate spraying system developed for nursery liner-size trees and reported that the sprayer could reduce the spray volume by over 70% compared to conventional constant-rate sprayers.

Moltó et al. (2001) developed a sprayer capable of applying at three rates; full dose, half dose and no dose. The canopy characteristics were estimated using two ultrasonic sensors, one on each side of the sprayer. Using a model developed for the sprayer, a threshold was established for changing from full dose to half dose, and no spray was applied when no trees were detected. The authors obtained savings of 37% without compromising the treatments efficacy.

A prototype was developed by Solanelles et al. (2006) using ultrasonic sensors for canopy characterization. The sensor measured the canopy width in two heights (two halves) and then estimated the canopy volume. Using a special developed algorithm installed on an embedded computer, the flow rate was adjusted in a continuous way through electric solenoid valves connected upstream the nozzles. The algorithm used was based on TRV for it took into consideration the canopy volume.

Planas et al (2006) compared a prototype sprayer equipped with ultrasonic sensor and a variable-rate application system with the same sprayer with the variable-rate function turned off (constant flow rate), and concluded that the efficiency of the spray application was increased in 13% to 17% on apple trees.

Gil et al. (2007) related savings of 57% in the application volume while maintaining coverage and penetration rates similar to conventional spraying methods, using a variable-rate sprayer equipped with ultrasonic sensor.

A project denominated “Precispray” was developed for precise application on tree crops. Among other technologies, the “Precispray” project implemented a sprayer prototype to adjust both liquid and air flow spraying rates to the tree canopy according to previously defined contour maps (previous scanning of the crop). The biological efficiency tests showed that the sprayer was at least as effective as the conventional sprayer, with reduced spraying amounts up to 36% (VAN DE ZANDE et al., 2003).

Variable-rate sprayers have been developed implementing ultrasonic sensors (SOLANELLES et al., 2006; DORUCHOWSKI et al., 2011). However, according to Jeon et al. (2011), ultrasonic sensors present some limitations; such as detection distance, temperature, humidity and ground speed. They show low measurements resolutions, and their response can be easily influenced by tractor operating speed (ZHU et al., 2014). Also interference can occur between ultrasonic sensors, due to the overlap of the ultrasonic beams. One response to these problems is the laser sensor.

2.6. Laser Sensors

The word laser stands for “Light Amplification by Stimulated Emission of Radiation”. It is a technology developed in the late 1960s and applied nowadays on many human activities.

Laser is the device that produces electromagnetic radiation with particular features: it is monochrome (has a wavelength very well defined), coherent (the photons that compose the beam are in phase) and, collimated (the waves in the beam are practically parallels).

Photons are the elementary particles of the electromagnetic radiation, including the light. They have different wavelengths, frequency and energy. The light is composed by a great number of photons, and its intensity or brightness is a function of the number of photons.

The laser beam can be of different colors, depending on the wavelength of the photons, when it is between 400-700 nm (visible for human eyes). Also, invisible laser beams can be produced when the wavelength is situated in the UV or infrared regions.

For agricultural purposes, the laser can be used in sensors for scanning plants and mapping the canopy shape and leaf density. For that, the principle of time-of-flight between the laser beam emission and its return to the sensor is used, knowing that in the air, the beam travels at the constant speed of light.

The type of laser sensors used for agricultural purposes are reflectorless. They can measure the distance to an object without the need of reflective material. The other key to reflectorless measurements is that the laser sensor can be aligned to the target from practically any distance or angle within its range. Laser sensors will also return an accurate measurement to more difficult targets, including most liquids and solids.

The great majority of the laser sensors found in bibliography operates in the infrared (IR) zone. Some key benefits of infrared laser sensors are: fast data rates, ability to penetrate air-borne particulates, scanning capabilities, multiple target detection, and measurements to most surfaces and targets that are independent of incident angle.

Studies led to the conclusion that laser scanning sensors are able to characterize crop structures with higher accuracy and reliability than ultrasonic sensor technology (TUMBO et al., 2002; WEI and SALYANI, 2004, 2005). Because of their advantages, laser scanning sensors were considered to have a great potential for use in variable-rate sprayers.

The accuracy of laser sensors is stable and independent of the environmental conditions (ZHU et al., 2014), and they can produce three –dimensional profiles of canopies when positioned on moving platforms (ROSELL et al., 2009a, 2009b; CHEN et al., 2012).

Chen et al. (2012) developed a variable-rate sprayers equipped with a laser sensor for applications on tree crops. The sprayer consists of a laser scanning sensor control system and an air and liquid delivery system. The spray nozzles coupled with a pulse width modulated (PWM) solenoid valve, to spray on a variable-rate based on occurrence, height, and width of the target tree and its foliage density. Other components of the sensor control system included a algorithm for variable-rate control that could instantaneously process measurements of the tree canopy.

The authors stated that outdoor tests demonstrated the sprayer's capabilities to achieve variable-rate spray with acceptable variations in spray coverage inside tree canopies, however needing more studies to prove it's efficacy on different types of canopies.

The new sprayer increased spray efficiency and improved spray accuracy on the tree canopies tested. The possibility of overspray was greatly lowered, resulting in reduced spray costs and potential reduction of environmental pollution (Chen et al., 2012).

2.7. Drift Reduction Potential of Variable-Rate Sprayers

The application using a precise amount of materials is needed for adequate pest and disease control, and to mitigate problems of PPP drift, leading to the contamination of the environment (ZHU et al., 2014). This can be achieved using variable-rate sprayers with sensor technology for target detection and characterization, thus calculating the spray output needs.

It was observed on tree crops applications that the application volume is often high, causing excess of product applied. Also the sprayers are not always well fitted to the crops height, being a consistent part of the application lost above the canopy. Spaces between trees also contribute to the drift process.

Airborne drift can be reduced by changes in droplet size, air velocity, and sprayer design (FOX et al., 2008). Drift retardants have been used to reduce the number of drift-prone droplets (OZKAN et al., 1993; ZHU et al., 1997). However, changing fluid physical properties has no effect on off-target losses to the ground and through application between the spaces of two adjacent trees.

Minimizing spray on non-target areas can directly reduce off-target losses. This goal can be achieved with real-time measuring of the spray target to control the actual spray application (WALKLATE et al., 2002; FOX et al., 2008). The target tree parameters can be acquired by using sensors, for target detection and measurement.

3. CONCLUSIONS

Attempts to improve spray applications on tree crops, in a way of adjusting the amount sprayed to the canopy characteristics have led to the development of various methods for canopy size, format and density estimation. The different methods allowed a variety of solutions for canopy estimation, with the use of different technologies.

Tree row volume methods (TRV) present an improvement in tree crops applications. Still, the constant rate application does not eliminate overspray and underspray on tree crops, as well as application over and between trees, that could cause drift problems.

The use of sensors for tree crops canopy characterization and customized spray application can produce efficient deposition and coverage on tree canopies, while lowering the drift both to the air and to the soil.

Laser sensors are the ultimate technology for canopy characterization, being stable under outdoor working conditions such as temperature, humidity and wind.

The use of sensors together with variable-rate delivery systems, for spray application, has proportionated products savings and drift reduction.

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CHAPTER 2

SPRAY DEPOSITION INSIDE TREE CANOPIES, DRIFT AND OFF-TARGET LOSSES FROM A VARIABLE-RATE SPRAYER

Abstract: Ash tree (*Fraxinus* spp.) is a widely used species of tree. It's grown in wide planted fields on nursery farms for commercialization. Likely other widely planted trees, Ash trees are attacked by many pests and diseases. Tree crops vary in height, width, shape of the canopy and space between trees. It is a challenge to the application technology to apply the exact amount of spray that the plant needs, and to minimize the spray drift. Drift is the part of the agricultural pesticide spray that does not stay on the target, causing environmental and human contamination. Variable-rate application of plant protection products (PPP) is used to suit the application amount to the target needs. It has great importance in agriculture, once it minimizes the risks of environmental and human contamination, as well as better application of financial resources. A variable-rate intelligent sprayer implementing a high speed laser scanner was developed for tree crops spraying. To better evaluate how the sprayer could respond to complex conditions of trees, field experiments were conducted to achieve the objective of this research: to further evaluate the performance of the variable-rate sprayer under field conditions through comparison of the overspray possibility and the uniformity of spray coverage and deposition inside tree canopies, against a constant-rate sprayer. A spray deposition and coverage test, and a spray drift test were realized to investigate the potential of a variable-rate sprayer for Ash tree spraying. The first test (deposition test) experimental scheme was a factorial 2 x 3, with three replications in blocks randomized. The factors were two sprayers (a conventional air-assisted and an air-assisted variable-rate intelligent sprayer), and three travel speeds (3.2, 5.6 and 8.0 km h^{-1}). The second test (drift test) experimental scheme was a factorial 2 x 3 x 5, with three replications in blocks randomized. The factors were equal to the first test, with the addition of a split-plot factor that was the distances of the drift collectors downwind the last sprayed row. For the deposition and drift test it was used the tracer Brilliant Sulphoflavine (BSF) at 2.0 g L^{-1} concentration. The deposition inside the canopies, on the ground and on air targets were evaluated using artificial targets. The coverage was evaluated using water sensitive papers (WSP). The variable-rate intelligent sprayer reduced the application rate in 64%. Both variable-rate intelligent sprayer and conventional sprayer were able to produce consistent spray deposition and spray coverage inside Ash tree canopies. These variables were predominantly not affected by the sprayers travel speed. The spray deposition on ground near the application area was similar for conventional and variable-rate intelligent sprayer, and also not affected by travel speed. The variable-rate intelligent sprayer reduced the drift to the air in 92% and 94%, and the drift to the ground in 58% and 98%, at 5 m and 15 m downwind, respectively. The variance of spray deposition inside of the three Ash tree canopy axes (x, y and z) was similar between the conventional sprayer and variable-rate intelligent sprayer.

Keywords: air-assisted application, Ash tree, laser sensor, precision agriculture.

CAPÍTULO 2

DEPOSIÇÃO DE CALDA E PERDAS POR DERIVA EM APLICAÇÃO À TAXA VARIADA EM CULTURA ARBÓREA

Resumo: Ash (*Fraxinus* spp.) é uma espécie de árvore amplamente utilizada nos Estados Unidos. Ela é cultivada tanto em viveiros de mudas para comercialização, quanto em florestas plantadas para extração de madeira. Como em qualquer amplamente plantada, árvores de Ash é alvo de ataque de muitas pragas e doenças. As culturas arbóreas variam em altura, largura, forma da copa das árvores, bem como espaçamento entre plantas. É um desafio para a tecnologia de aplicação aplicar a quantidade exata de calda que a planta precisa, minimizando a deriva. Deriva é a parte da aplicação de produtos fitossanitários que não permanece no alvo, causando contaminação ao homem e ao ambiente. A aplicação de taxa variada de produtos fitossanitários tem como objetivo adequar a quantidade aplicada ao alvo. Tem grande importância na agricultura, uma vez que proporcione a minimização dos riscos de contaminação, e a economia de recursos. Um pulverizador hidropneumático de aplicação à taxa variada, equipado com um sensor laser de alta velocidade para leitura das copas das plantas foi desenvolvido para pulverização de culturas de arbóreas. Realizaram-se testes de deposição e cobertura de calda de pulverização, e um teste de deriva de pulverização, para investigar o potencial deste pulverizador de taxa variada na pulverização em árvores de Ash. O primeiro teste experimental (teste de cobertura e deposição de calda) foi um fatorial 2 x 3, com três repetições em blocos casualizados. Os fatores foram dois pulverizadores (um pulverizador hidropneumático inteligente e um pulverizador hidropneumático convencional) e três velocidades de deslocamento (3.2, 5.6 e 8.0 km h^{-1}). O segundo teste foi um fatorial 2 x 3 x 5, com três repetições em blocos randomizados. Os fatores foram iguais aos do primeiro teste, com a adição do fator distância dos coletores de deriva, que gerou uma parcela sub-dividida. Para os testes utilizou-se uma calda com corante sulfoflavina brilhante (BSF) a 2,0 g L^{-1} de concentração. A deposição dentro das copas, no solo e em alvos aéreos foi quantificada através de alvos artificiais. A cobertura foi avaliada por meio de papéis hidrossensíveis. O pulverizador inteligente de taxa variada reduziu o volume de aplicação em 64%. Tanto o pulverizador inteligente de taxa variada quanto o pulverizador convencional foram capazes de produzir deposição de calda e cobertura satisfatórias dentro da copa das plantas de Ash. Estas variáveis não foram estatisticamente afetadas pela velocidade de deslocamento dos pulverizadores. A perda de calda para o solo na área de projeção da copa foi semelhante para ambos os pulverizadores, e também não foi afetada pela velocidade de deslocamento. O pulverizador inteligente de taxa variada reduziu a deriva para o ar em 92% e 94%, e a deriva para o solo em 58% e 98%, a 5 m e 15 m a a partir da última linha aplicada, respectivamente. A variância da cobertura e deposição de pulverização nos três eixos avaliados dentro da copa das plantas (x, y, z) foi semelhante entre o pulverizador convencional e o pulverizador inteligente de taxa variada.

Palavras-chave: assistência de ar, árvore ash, sensor laser, agricultura de precisão.

1. INTRODUCTION

Ash tree (*Fraxinus* spp.) is a widely used species of tree, for ornamental purposes, shade, furniture fabrication or dye extraction. Ash tree leaves and bark are also known to contain extractable natural dyes. It's grown on wide planted fields on nursery farms for commercialization.

Likely other widely planted trees, Ash trees are attacked by many pests and diseases, being one of the most important pests the Emerald Ash Borer (*Agrilus planipennis* Fairmaire). For pests and diseases control on trees, sprayers with air assistance have been used, for application of plant protection products.

Tree crops vary in height, width, shape of the canopy and space between trees. The foliage density also changes during the trees life time and during the season. For the spray application technology, the target is the pathogen or pest that needs to be controlled, for it is preventing the plant from achieving its complete potential.

Another challenge to the application technology is to minimize the spray drift. Drift is the part of the agricultural pesticide spray that does not stay in the target, causing environmental and human contamination. It can travel in the distance with the wind and be deposited far from the application area, or in the ground inside the field.

The application technology for tree crops studies has aimed to achieve better spray deposition and coverage and less drift to the air and to the ground. One parameter of study is the application rate, which is the amount of solution applied per unit area or volume of canopy. The application rate can be adjust for tree crops using methods that indirectly estimate the volume of the canopy (SUTTON AND UNRATH 1984, 1988; SIEGFRIED et al., 2007; PERGHER and PETRIS, 2008), or through direct measuring (GIL et al., 2007; BALSARI et al., 2008; CHEN et al., 2013). Using canopy measurement, lower volumes of product applied were obtained, with depositions on the target being maintained or even improved (GIL et al., 2007; CHEN et al., 2013).

On this context, the use of ultrasonic sensors (GIL et al., 2007) or laser sensors (CHEN et al., 2013) to scan tree canopies in real-time and apply variable-rates was tested and proved the efficacy in reducing the application rate.

Variable-rate application is used to suit the application amount to the target need. It has great importance in agriculture, once that it proportionates the minimization of the risk of environmental and human contamination, as well as better appliance of financial resources.

An experimental variable-rate sprayer implementing a high-speed laser scanning sensor was developed for orchard and nursery applications (CHEN et al., 2012). The sprayer has the capability to automatically adjust the spray output to match tree characteristics in real time. Laboratory evaluations of the sprayer performance demonstrated that it could deliver liquids to different parts of the tree canopy with satisfactory coverage uniformity. To better evaluate how the sprayer could respond to complex conditions of trees, field experiments were conducted to achieve the objective of this research: to further evaluate the performance of the variable-rate sprayer under field conditions through comparison of the overspray possibility and the uniformity of spray coverage and deposition inside tree canopies with constant-rate sprayers.

2. MATERIAL AND METHODS

2.1. Spray Deposition and Coverage Test, and Spray Drift Test

The spray deposition and coverage test was realized on July 21st and 22nd of 2015, at the OARDC Ash tree experimental field, located at the Ohio Agriculture Research and Development Center (OARDC), in Wooster, OH, USA. The Ash trees were 2.5 m apart between trees and 6.4 m between tree rows. The crop was on a full foliage stage, with a leaf area index (LAI) of 0.93 m^2 m^{-2}, and with an average height of 2.7 m.

The experimental scheme was a factorial 2 x 3, with three replications in blocks randomized. The factors were two air-assisted sprayers: a conventional air-blast sprayer and the ATRU air-assisted variable-rate intelligent sprayer, and three sprayer travel speeds (3.2, 5.6 and 8.0 km h^{-1}). Artificial targets were positioned on the Ash tree canopy and on the ground next to the trees. Each experimental plot was composed of three Ash trees that were sprayed. Each replication was made in the same area, changing artificial targets on the three trees, and ground near them. The test aimed to evaluate the variables spray deposition, spray coverage, both to the canopy and to the ground.

A second test was realized on the OARDC Ash tree field for spray drift evaluation, on September 16th of 2015. The test aimed to quantify the spray drift, both to the air and to the ground, produced by spray application with the conventional air-assisted sprayer and the variable-rate intelligent sprayer, spraying at three travel speeds: 3.2 km h^{-1}, 5.6 km h^{-1} and 8.0 km h^{-1}.

The experimental scheme of the drift test was a factorial 2 x 3 x 5, with three replications in blocks randomized. The factors were the two sprayers; the three sprayer travel speeds; and five distances of the drift collectors, in split-plot. The split-plot scheme was due to the impossibility of randomization of the distances in the field. The drift collectors were placed downwind from the applied area, perpendicular to the Ash tree row, at 5 m, 15 m, 35 m, 65 m and 105 m. Artificial targets were positioned on the drift collectors.

The drift test was made following the ISO recommendations (ISO 22866). For that, 3.0 m high portable weather station equipped with a modified CM-6 system (Campbell Scientific, Inc., Logan, Utah) was placed in an open field 10 m away from the test site to record air temperature, relative humidity, and wind speed and direction at 1Hz frequency. The wind speed and direction sensor in the weather station was a three-axis ultrasonic anemometer with no moving parts (model 81000, R. M. Young Co., Traverse City, Mich.) with a resolution of 0.01 m s^{-1} for wind speed and 0.1° for wind direction. The collection posts were aligned parallel to the predominant wind. The predominant wind on the day of the test was from the South to the North direction.

The spray deposition and coverage, and the drift test were made using a tank solution of water and Brilliant Sulfaflavine (BSF) (MP Biochemicals, Inc., Aurora, Ohio), in a concentration of 2 g per liter. The spray deposition was collected on artificial targets nylon screens and plastic plates to evaluate the deposition and, water sensitive papers (WSP) to quantify the spray coverage.

A scheme of the experimental area is shown on Figure 1

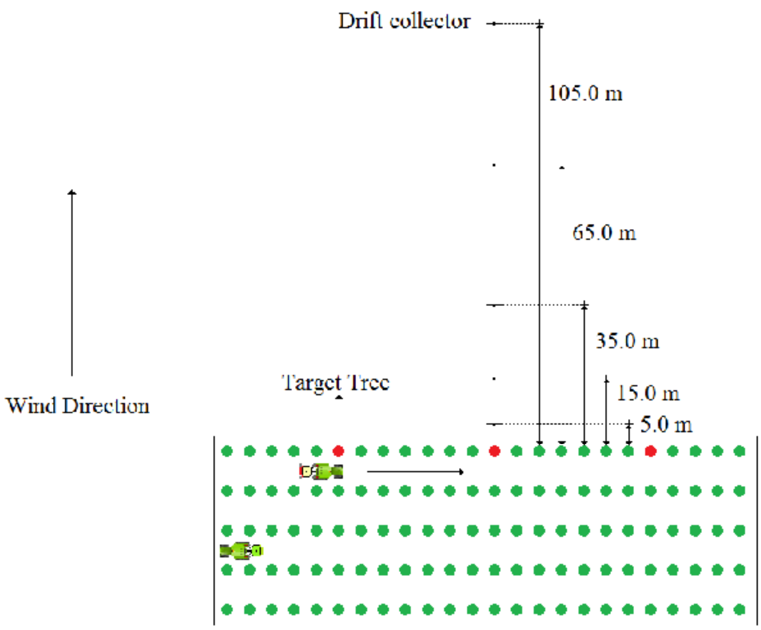


Figure 1 - Experimental Ash tree field scheme, with target trees 1, 2 and 3 and drift collection posts.

2.2. Description of the Sprayers

The ATRU air-assisted variable-rate intelligent sprayer was developed for tree crop applications at variable-rates, being capable of controlling the spray output amount to match the tree canopy characteristics. The sprayer was composed of a high-speed, 270° radial and 30 m range laser scanning sensor (UTM 30LX, Hokuyo Automatic Co., Osaka, Japan) for trees scanning, a speed sensor (RVSIII radar velocity sensor, DICKEY john Co., Auburn, Ill.), a custom designed program for signal-processing, an automatic variable rate controller unit, variable-rate solenoid valves (Capstan Ag, Inc., Topeka, Kans.), and a multi-port air-assisted delivery system. It was set over a pre-existing tractor-mounted PTO air assisted sprayer, containing a diaphragm pump, a 12 blades axial turbine fan of 0.81 m of diameter, and a 400 L spray tank (model ZENIT B11, Hardi International A/S, Taastrup, Denmark).

The variable-rate intelligent sprayer was equipped with flat-fan TeeJet XR 8002 nozzles (Spraying Systems Co., Wheaton, Ill.), positioned on a special manifold with five nozzles each, designed to hold the nozzles and direct the air stream from the fan (Zhu et al., 2006). It had four manifolds on each side of the sprayer at 0.85 m, 1.35 m, 1.85 m, and 2.35 m high above ground level with the sprayer mounted on the three point hitch and lifted to spraying position. Thus, the sprayer had 20 nozzles on each side. The distance of the laser sensor to the ground was 1.6 m. The variable-rate intelligent sprayer application rate was 0.06 L m^{-3} of tree foliage, being the leaf density measured by the laser sensor. The nozzles generated droplets with average VMD of 250 µm at the working pressure range (GU et al., 2011). The variable rate spray application was achieved independently for each nozzle through solenoid valves, and each nozzle was designated to spray a section of 0.135 m in height of the plant, totalizing 2.7 m height spraying capacity.

The conventional sprayer was air assisted for orchard and row crops (model A32TMG, Myers & Bro Co., Ashland, OH), with nine nozzles on each side, a hydraulic pump with capacity of 45 L min^{-1} at 550 rpm at PTO, a seven-blade fan with capacity of generating air streams of 46 m s^{-1} at 550 rpm at PTO and, a 400 L fiber glass spray tank.

The application rate was constant at 467 L ha^{-1} at all travel speeds with the conventional sprayer, being used three models of hydraulic nozzles to keep the same flow rate and droplet size. The variable-rate intelligent sprayer adjusts the application rate according to the trees canopy characteristics, maintaining the application rate of 0.06 L m^{-3} of tree foliage. This application rate is also adjusted based on information received from the speed sensor, keeping a constant L m^{-3} rate, independent of the travel speed. The droplet size was also maintained constant at 250 µm (GU et al., 2011). It was not possible to pre-determine the application rate of the variable-rate sprayer, once that it depends on the real-time measurements of the trees. The application rate of the variable-rate intelligent sprayer was then obtained after the experiments, calculating the difference of the spray tank capacity and tank leftover after the test, being it in average 170 L ha^{-1}, for all treatments.

The conventional sprayer used a disc-core hollow cone nozzle type, as this is the predominant technology used by the nursery growers. The variable-rate intelligent sprayer was equipped with flat-fan nozzles due to the characteristics pre-evaluated of this according to capacity of penetration, uniformity of the spray patter and droplet size. The experiment aimed to evaluate the common technology used by growers and the new one that comes with the variable-rate intelligent sprayer.

The sprayer's parameters for the test are shown on Table 1.

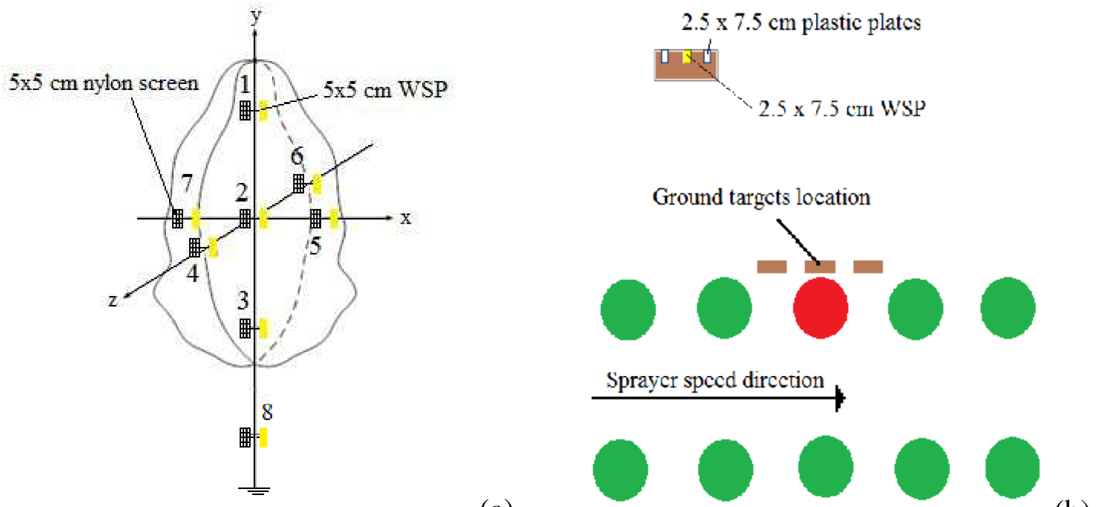
Table 1 –Sprayers characteristics at the treatments

Sprayer	Travel Speed (km h^{-1})	Nozzle Type	Pressure (kPa)	Flow nozzle^{-1} (L min^{-1})	Application rate (L ha^{-1})
Conventional	3.2	D4-DC25*	723.9	1.74	467
	5.6	D6-DC25*	827.3	3.00	
	8.0	D8-DC25*	1103.1	4.35	
Intelligent	3.2	XR 8002**	Varied during spraying	0.68 at 207 kPa	170
	5.6				
	8.0				

*TeeJet disc-core type hollow cone spray nozzles. ** TeeJet flat-fan spray nozzle.

2.3. Target Locations for the Spray Deposition and Coverage, and Drift Test

For the spray deposition and spray coverage tests, artificial targets were attached in seven positions inside the Ash tree canopy and on one position on the trunk of the tree. At each position, one monofilament nylon screen (50 × 50 mm, Filter Fabrics, Inc., Goshen, Ind) and one water sensitive paper (WSP) (26 x 76 mm, Syngenta Crop Protection AG, Basel, Switzerland) were clanged to the tree using binding clips. The deposition to the ground beyond the target tree was quantified using ground targets. Three wooden boards containing the targets were positioned next to each tree. The artificial targets were two plastic plates of 26 x 76 mm and one WSP of 26 x 76 mm, on each wooden board. Figure 2 shows a scheme of the target locations inside the Ash tree canopy and on the ground, beyond each tree.



(a) (b)

Figure 2 - Scheme of targets on Ash tree canopy (Position 1 to 7) and trunk (Position 8) (Figure a), and on ground near the tree (Figure b, upper view).

To quantify the spray drift to the air, collection posts were positioned on five distances from the last sprayed Ash tree row; 5 m, 15 m, 35 m, 65 m and 105 m. At the collection posts, nylon screens of 203 x 203 mm were located at 2.18 m, 2.84 m and 3.51 m height. An average of the three nylon screens was considered on the drift deposition study. The spray drift deposition on the ground on those five distances (5 m, 15 m, 35 m, 65 m, 105 m) was collected using two plastic plates of 96 x 192 mm. The plastic plates were positioned over white paper sheets, next to the collection posts.

2.4. Laboratory Analysis

The 50 x 50 mm nylon screens and the 26 x 76 mm plastic plates were put in 125 mL glass bottles and washed with 50.0 mL of deionized water, to wash the screens free from the tracer. The 203 x 203 mm nylon screens were put in glass bottles and washed with 50.0 mL of deionized water, to extract the tracer. The 96 x 192 mm plastic plates were put on plastic bags and washed with 20.0 mL of deionized water.

The washing solution from nylon screens and plastic plates, containing water and BSF, was poured into cuvettes and read on a fluorimeter (Trilogy Laboratory Fluorimeter, Turner Design, San Jose, CA), at an excitation wavelength of 460 nm. The fluorimeter expresses the result in fluorescence unit. The fluorescence was converted into concentration using a calibration curve. The concentration was then multiplied by the volume of the deionized water used to wash the samples and divided by the spray tank solution concentration (2 g L^{-1}). The result was divided by the area of the targets, resulting in deposition (μL cm^{-2}). The deposition unit in μL cm^{-2} allows an easier comparison of deposition with other research studies, for it does not depend on the concentration of the spray tank mixture.

The WSP were scanned on a hand-held business card scanner (ScanShell 800N, CSSN, Inc., Los Angeles, Cal.) using a resolution of 600 dpi, and then analyzed about the percentage of spray coverage on the software DepositScan (Zhu et al., 2011).

2.5. Statistical Analysis

The statistical analyses were made using the statistical softwares SigmaPlot 12.5, Sisvar, SPSS 20.0 and Microsoft Excel 2010. Previously to the statistical test, all data were tested according the assumptions of normality of error and homogeneity of variance, at 0.05 of significance, using the statistical software SPSS 20.0.

The spray deposition and spray coverage on each position inside the Ash tree canopy and on the ground next to the trees was tested separately through Analysis of Variance (ANOVA), considering a factorial scheme 2 x 3, with three replications in randomized blocks. The first factor was two sprayers (intelligent and conventional) and the second factor was travel speeds (3.2, 5.6 and 8.0 km h^{-1}). The ANOVA allowed investigating the presence of interaction between two factors or the effects of the factors alone on the spray deposition and spray coverage. To compare means it was used Tukey's test.

The spray drift to the air and spray drift to the ground, on five distances, were analyzed as a factorial scheme. The factorial was the same for the spray deposition and coverage on targets located inside the trees and on ground under the trees, with the addition of the distance of the collectors as a third a factor, which characterized a split-plot. The factor distance formed a split-plot with the factorial scheme due to its impossibility of randomization in the field. Thus, a triple factorial 2 x 3 x 5 with three replications composed the ANOVA, for the variables spray drift to the air and to the ground.

The analysis of the spray drift to the air and to the ground according to the distances was made using regression curves. The comparison of spray deposition on each distance on the curves, according to the factors sprayer or travel speed, was made using Tukey's test, when the factor(s) was (were) significant.

A third analysis was made using F test for variance dual comparisons. This test compared the variance of the spray deposition and spray coverage on three axis inside the Ash tree canopy (x, y and z), comparing treatments according to their capacity of producing uniform deposition and coverage on each axis. For this test, the locations 1 to 7 (inside the canopy) were grouped in three axis; x – sprayer travel direction, composed by positions 7, 2 and 5; y – tree height direction, composed by positions 1, 2 and 3, and; z - spray direction, composed by positions 4, 2 and 6.

3. RESULTS AND DISCUSSION

3.1. Spray Deposition and Coverage

It was observed that there was no significant interaction ($p>0.05$) between the factors sprayer and travel speed for the variables spray deposition and spray coverage on targets located inside the Ash trees canopy. The average values of spray deposition and coverage were tested separately using Tukey's. Figure 3 shows the depositions on each position inside the Ash trees canopy, for the trees 1, 2 and 3.

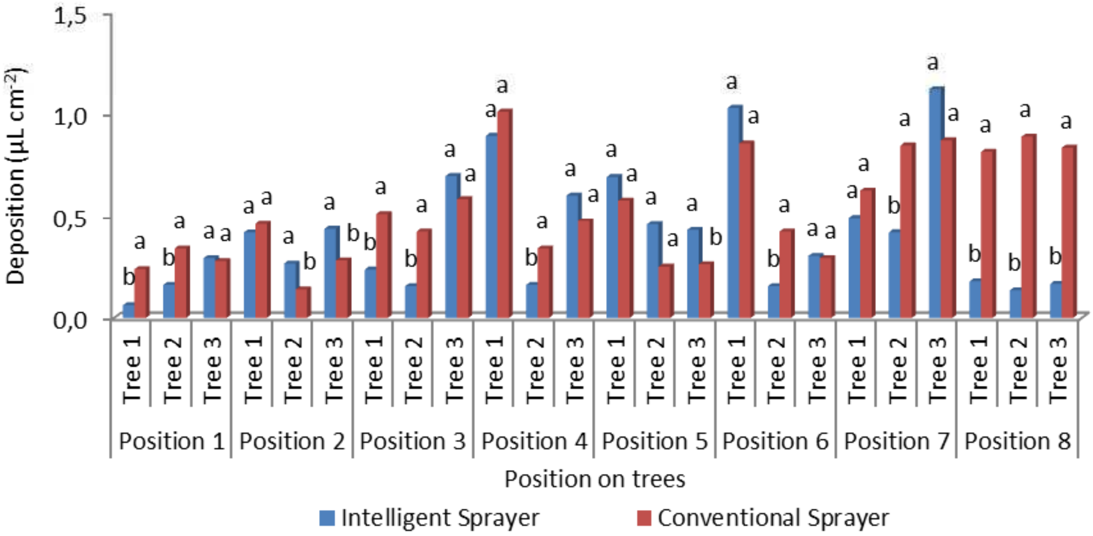


Figure 3 – Deposition (µL cm^{-2}) produced by application with conventional airblast sprayer and air-assisted variable-rate intelligent sprayer, on nylon screen targets inside *Ash* trees.
*Means followed by the same letter, inside tree, do not differ from each other according to the Tukey's test, at 0.05 of significance.

The spray deposition on the target positions inside the Ash tree canopies (position 1 to 7) and at the trunk of the Ash trees (position 8) presented difference in some positions for the conventional and the variable-rate intelligent sprayer application.

At position 8, the spray deposition was higher for the conventional sprayer on all the trees. This position is located in the trunk of the trees, and was expected to receive more spray deposition from the conventional sprayer. The narrow shape of the trunk of the Ash tree results in a lower amount of solution applied, due to a smaller volume detected by the laser sensor of the variable-rate sprayer.

The target position 1, on the top of the canopy, had higher values of deposition with the conventional sprayer on trees 1 and 2. The variable-rate sprayer had difficulty on depositing droplets on the top part of the Ash tree canopy. The average height of the Ash trees of the experiment was 2.7 m, and the top nozzles manifold of the intelligent sprayer was at 2.35 m above ground level with the sprayer engaged to the tractor, but has a laser maximum height measurement capacity of 2.7 m.

The trees 1 and 2 had lower spray depositions on positions 1 and 3 with the variable-rate sprayer. At the extremities of the canopy (top and bottom, respectively position 1 and 3), there's the presence of less foliage, resulting in lower spray application volume by the variable-rate intelligent sprayer on those areas.

This result is similar to Gil et al. (2007), which concluded that the deposition produced by a variable-rate sprayer, equipped with ultrasonic sensor for tree scanning, was significantly lower on the top of vineyards trees than in the rest of the areas, and probably due to a lower position of the nozzle set in relation to the top part of the tree canopy, or to the inclination of the crop structure.

Chen et al. (2013) tested three air-assisted sprayers on apple trees, in three different leafing stages. The authors concluded that the top part of trees had less foliage and thus received greater spray deposits from a conventional air-assisted sprayer and from the ATRU intelligent sprayers, but with the variable-rate function turned off (spraying at a constant rate). In contrast, the variable-rate intelligent sprayer, with the variable-rate function turned on, presented lower spray deposition at this canopy part.

Gil et al (2007), studying variable-rate application on apple trees, stated that the lower amounts of leaves were located on the top and bottom of the canopy, with 21% and 21.2% of the total leaf surface, respectively. This can explain a lower amount of solution applied on the extremities of tree crops.

However, at position 2 (in the middle of the canopy), both sprayers produced equal spray depositions on plant 1, while the variable-rate intelligent sprayer produced higher depositions on plants 2 and 3. The variable-rate sprayer produced higher deposits on the inner part of most trees. Agreeing with the results, Chen et al. (2013) concluded that the spray coverage and deposit on the inner parts of the canopies, from the ATRU variable-rate intelligent sprayer, were consistent regardless of the change in canopy size and foliage density during the tree growing season.

It is important to state that on this experiment, the application rate was 64% lower when applying with the variable-rate intelligent sprayer, maintaining similar depositions inside the Ash tree canopy. Chen et al (2013) related savings from 50-70% in the application rate using the ATRU air assisted variable-rate intelligent sprayer, maintaining consistent spray deposition and coverage. Agreeing with the results, Gil et al (2007) concluded that a variable-rate sprayer equipped with an ultrasonic sensor sprayed on average 58% less liquid when compared to a constant-rate sprayer application, with similar depositions on leaves with both treatments.

The variable-rate sprayer has the capacity to apply the amount of solution that will match the tree structure. This lead to a more effective use of active ingredient and a lower amount of spray volume applied. The reduction in the spray volume could be followed by an equivalent reduction in plant protection products, however, the biological efficacy of a reduced dose of active ingredients needs to be further researched (GIL et al., 2007).

Figure 4 shows the spray coverage on WSP inside the Ash tree canopy (positions 1 to 7) and on the trunk of the tree (position 8), for the trees 1, 2 and 3.

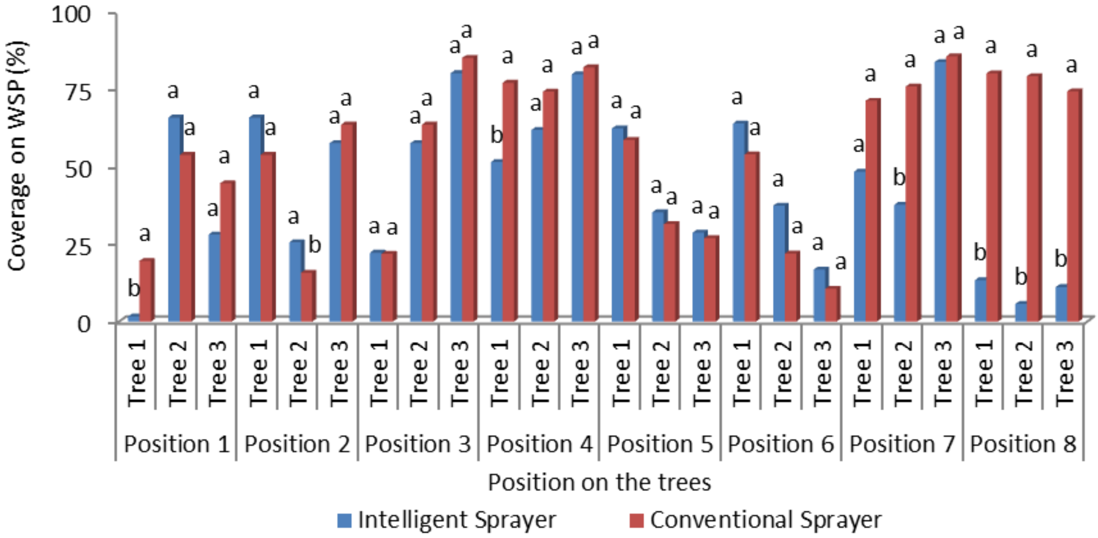


Figure 4 – Spray coverage, produced by spray application with conventional airblast sprayer and air-assisted variable-rate intelligent sprayer, on WSP (%) positioned inside the Ash trees.
*Means followed by the same letter, inside tree, do not differ from each other according to the Tukey's, at 0.05 of significance.

The variable-rate intelligent sprayer produced lower spray coverage three times inside the Ash tree canopy (positions 1 to 7), when compared to the conventional air-assisted sprayer, and one time it produced higher spray coverage. The spray coverage on WSP was statistically equal for both sprayers 16 times inside the canopy. On position 8, all the trees had lower spray coverage when sprayed with the variable-rate intelligent sprayer, due to the location of the target on the trunk, as discussed above.

The spray coverage using the variable-rate intelligent sprayer ranged from 10.00 to 64.43% and from 28.81 to 77.95% using the conventional air-assisted sprayer. The results of spray coverage are higher than the ones found by Chen et al. (2013), which ranged from 36% to 41% using the ATRU variable-rate intelligent sprayer to spray apple trees. Also, the wider range on the spray coverage is due to the location of the WSP on the Ash tree canopy. Position 8 received less spray due to the small area of the Ash tree trunk, where it was positioned, while position 4 showed higher spray coverage due to its location on the outer area of the canopy, close to the sprayer set of nozzles.

The use of water sensitive papers are preconized due to the capability of showing the percentage of the sprayed target covered by the spray application Water Sensitive Papers (WSPs) are the most common artificial targets for spray coverage evaluation. Spray coverage, expressed as a percentage of target area covered by spray, give additional information what portion of protected area is in direct contact with the chemical (HOLOWNICKI et al., 2002).

Figure 5 shows the spray deposition inside the Ash tree canopy at three travel speeds. The values are an average of the conventional airblast sprayer and the variable-rate intelligent sprayer, at each travel speed, due to the no significance of the interaction.

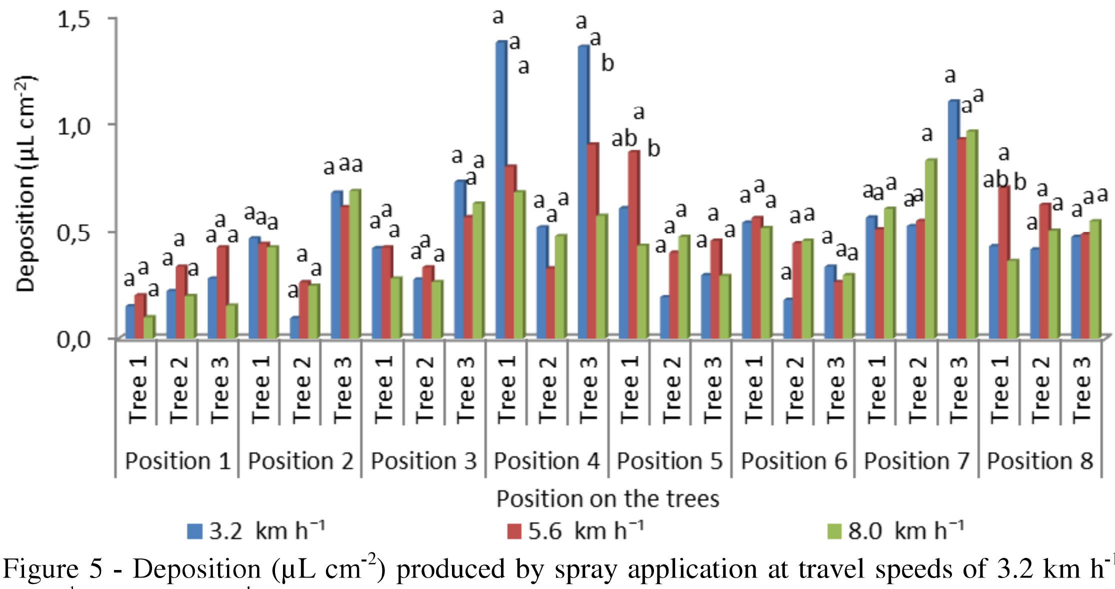


Figure 5 - Deposition (µL cm^{-2}) produced by spray application at travel speeds of 3.2 km h^{-1}, 5.6 km h^{-1} and 8.0 km h^{-1}, on nylon screen targets inside Ash trees.
*Means followed by the same letter, inside tree, do not differ from each other according to the Tukey's, at 0.05 of significance.

The travel speed of 8.0 km h^{-1} produced lower spray deposition on position 4 of tree 3, and on positions 5 and 8 of tree 1. On the positions 5 and 8 of tree 1, the spray deposition at the travel speed of 8.0 km h^{-1} was equal to the deposition at travel speed of 3.2 km h^{-1}, and the average spray deposition at these two travel speeds were lower than the deposition at 5.6 km h^{-1}.

On the other points, the deposition was equal for all speeds, showing the capacity of the sprayers to produce consistent depositions on the Ash tree canopy independently of the travel speed used in the application. The conventional sprayer was adjusted to spray the same rate at all the travel speeds. The variable-rate intelligent sprayer used data from the speed sensor to adjust the spray output to the travel speed of the tractor.

Zhu et al (2014) concluded that changing the travel speed of the ATRU variable-rate intelligent sprayer, in the range from 3.2 to 8.0 km h^{-1}, did not significantly influence the spray deposition quality inside ornamental nursery tree canopies.

Figure 6 shows the spray coverage on WSP inside the Ash tree canopy at three travel speeds. The values represent an average of the conventional air-assisted sprayer and variable-rate intelligent sprayer, at each travel speed.

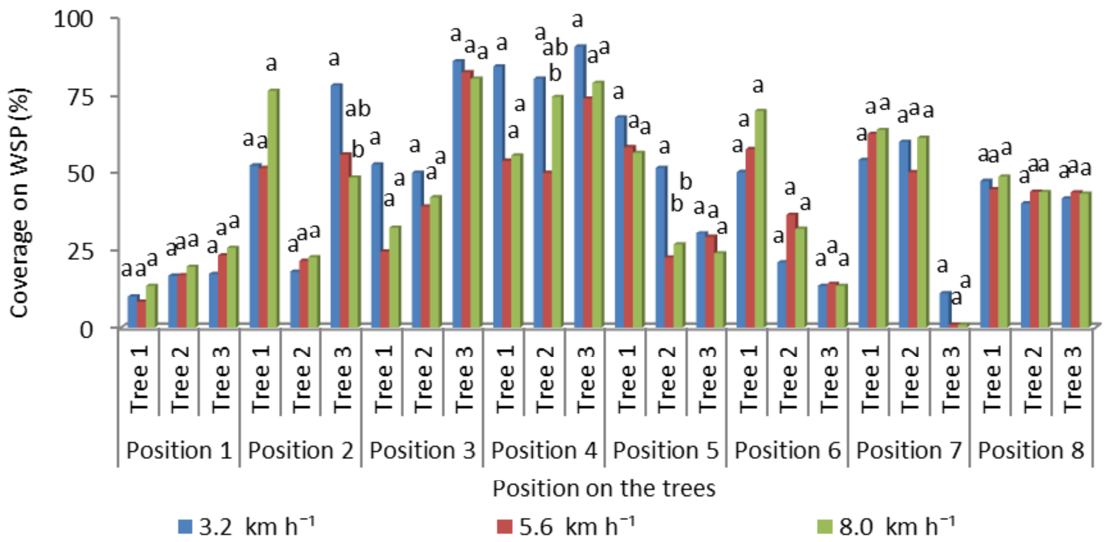


Figure 6 – Spray coverage on WSP (%) produced by spray application at travel speeds of 3.2 km h^{-1}, 5.6 km h^{-1} and 8.0 km h^{-1}, on WSP positioned inside the Ash trees.
*Means followed by the same letter, inside tree, do not differ from each other according to the Tukey's, at 0.05 of significance.

The spray coverage on targets inside the plants was different within the sprayers travel speeds on three positions. The sprayer coverage on WSP was statistically equal on 21 positions. The travel speed 8.0 km h^{-1} had lower spray coverage in two positions, and 5.6 km h^{-1} had it in one.

All travel speeds were capable of producing consistent spray deposition and spray coverage on most positions inside Ash tree canopies. The results show the capacity of the variable-rate intelligent sprayer on producing good spray application on a range of speeds from 3.2 km h^{-1} to 8.0 km h^{-1}, maintaining the efficacy and consistency, as well as the conventional air-assisted sprayer.

Figure 7 shows the spray deposition on ground targets next to the tree row after application using the conventional airblast sprayer and the variable-rate intelligent sprayer (figure on the left), and on three travel speeds (figure on the right); 3.2 km h^{-1}, 5.6 km h^{-1} and 8.0 km h^{-1}.

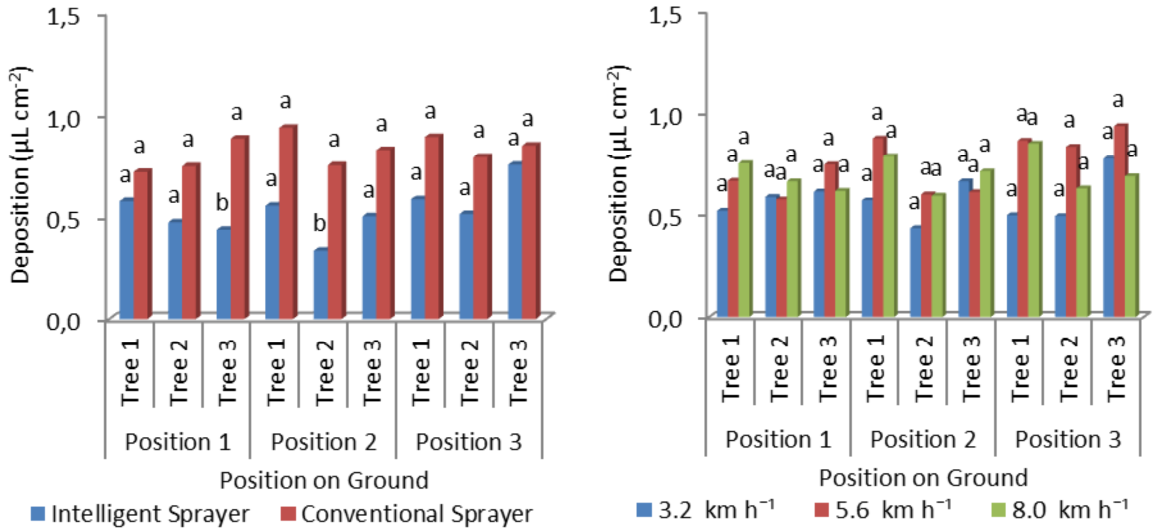


Figure 7 - Deposition (µL cm^{-2}) on targets located on the ground next to the tree row, after spray application with; two sprayers (graph on the left) and; travel speeds of 3.2 km h^{-1}, 5.6 km h^{-1} and 8.0 km h^{-1} (graph on the right).
*Means followed by the same letter, inside tree, do not differ from each other according to the Tukey's test, at 0.05 of significance.

The spray deposition on ground targets was numerically smaller on all the three positions next to of all the trees, when spraying with the variable-rate intelligent sprayer. Nevertheless, only two positions (position 1 on tree 3 and, position 2 on tree 2) had significant lower spray deposition using this sprayer, according to the Tukey's. No statistical difference was observed for spray deposition on the ground after application varying the sprayer's travel speeds.

Results obtained by Gil et al. (2007), studying variable-rate application on vineyard, show that the spray deposition to the ground produced by the variable-rate sprayer was equal or even higher than the conventional air-assisted sprayer. Especially on the targets located near the trees canopy projection area, these authors stated that some leakage produced by the nozzles when the solenoid shut off could be the cause of the higher spray deposition.

On this test, no leakage was observed from the nozzles during their operation. The spray deposition on the ground, produced by both sprayers, was understand to come from the droplets that were intended to stay in the Ash tree canopy, but passed through it without hitting any leaf. Even though, as the application rate was smaller using the variable-rate intelligent sprayer, less spray deposition was observed on the ground, but with no statistical significance.

The spray deposition on the ground was not affected by the sprayer's travel speed, in the range from 3.2 km h^{-1} to 8.0 km h^{-1}. Similar to what was observed on the spray deposition on targets inside the Ash tree canopy, both sprayers could operate with consistent results on the travels speeds tested. This fact shows the capability of the variable-rate intelligent sprayer on adjusting the spray output according to the ground speed.

Figure 8 shows the spray coverage on WSP on ground targets next to the tree row, after application using the conventional airblast sprayer and the variable-rate intelligent sprayer (figure on the left), and on three travel speeds; 3.2 km h^{-1}, 5.6 km h^{-1} and 8.0 km h^{-1} (figure on the right).

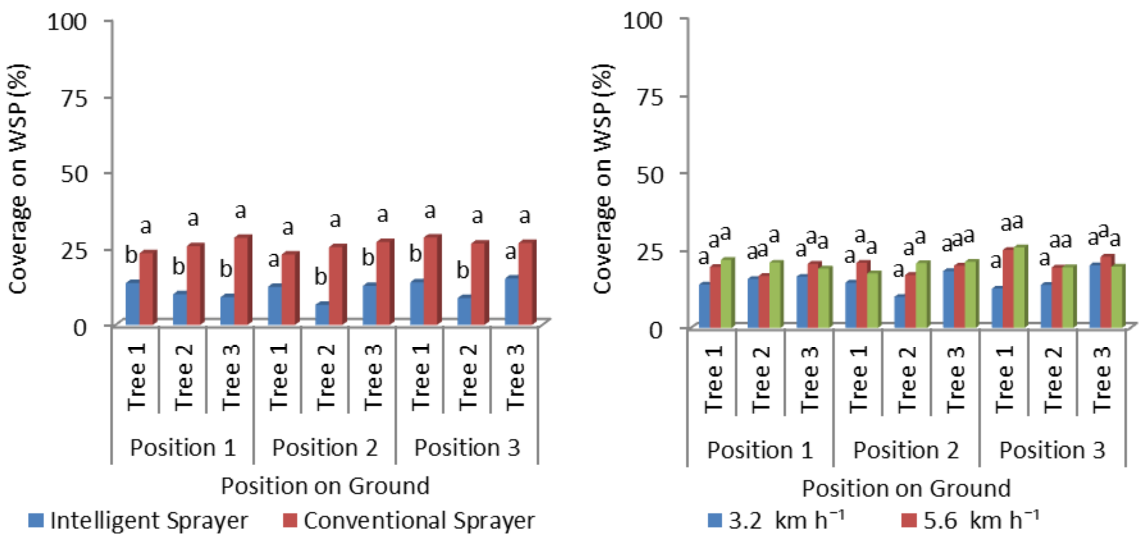


Figure 8 - Spray coverage on WSP (%) located on the ground next to the tree row, after spray application with; two sprayers (graph on the left) and; travel speeds of 3.2 km h^{-1}, 5.6 km h^{-1} and 8.0 km h^{-1} (graph on the right).
*Means followed by the same letter, inside tree, do not differ from each other according to the Tukey's test, at 0.05 of significance.

The spray coverage on WSP located on the ground was significantly reduced by using the variable-rate intelligent sprayer. The coverage was different on seven positions. Two positions had equal coverage (position 2 on tree 1 and, position 3 on tree 3). The spray coverage on WSP on the ground was reduced due to adjust of the spray output to match the canopy characteristics.

Similar to the spray deposition, the spray coverage was not affected by the sprayer's travel speed. Thus, the variable-rate intelligent sprayer had a consistent behavior on all speeds tested.

3.2. Spray Drift to the Air and to the Ground

The drift to the air and the drift to the ground presented a "sprayer x distance" double interaction that was significant. This way, two curves are presented on Figures 9 and 10 to show the spray drift to the air and to the ground, respectively. According to the ANOVA, travel speed didn't affect the drift produced by any of the two sprayers, being both the airborne drift the drift to the ground independent of the sprayer's travel speed.

Figure 9 shows the regression curves of the drift to the air produced by spray application with the conventional sprayer and the air-assisted variable-rate sprayer, on five distances downwind after the last Ash tree row.

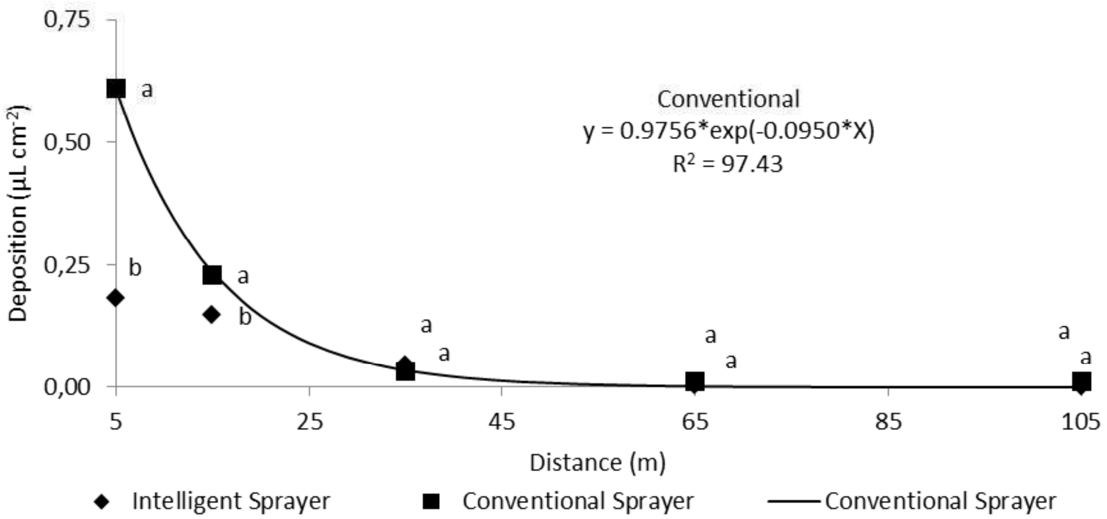


Figure 9 - Drift to the air produced by two sprayers, conventional airblast and air-assisted variable-rate intelligent sprayer, in five distances (5 m, 15 m, 35 m, 65 m and 105 m) from last Ash tree row.
*Means followed by the same letter, inside the same distance, do not differ from each other according to Tukey's, at 0.05 of significance.

The variable-rate intelligent sprayer drift to the air did not adjust any regression curve. The conventional sprayer drift equation adjusted for an exponential decay 2 parameters curve, as show on Figure 9.

The drift caused by conventional sprayer was bigger at 5 m and 15 m. At 35 m, 65 m and 105 m, the airborne drift produced by both sprayers was statistically equal. The concentration in the samples on the last two target locations (65 m and 105 m) were close to the minimum measuring capacity of the fluorimeter.

The major depositions were observed on the screens close to the last tree row, and it was significantly reduced with the use of the variable-rate intelligent sprayer, being this decrease in the deposition of 0.5634 μL cm^{-2} at 5 m and 0.2156 μL cm^{-2}, at 15 m. This represents 92% less drift at 5 m and, 94% at 15 m. The results are in accordance to Chen et al (2013 b), which concluded that the ATRU variable-rate intelligent sprayer reduced the airborne drift in 70% to 85%, at 5 m and 80% to 100%, at 15 m, varying according to apple the tree's leaf density and growth stage.

Figure 10 shows the regression curves related to the drift to the ground produced by spray application with the conventional sprayer and the variable-rate intelligent sprayer, in five distances after the last tree row.

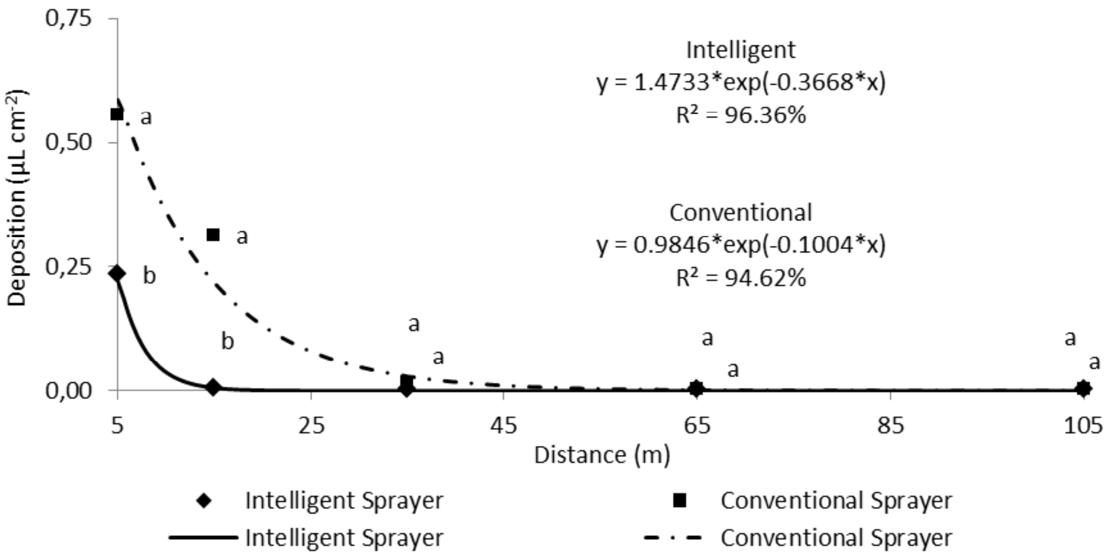


Figure 10 - Drift to the ground produced by two sprayers, conventional airblast and air-assisted variable-rate intelligent sprayer, in five distances (5 m, 15 m, 35 m, 65 m and 105 m) from last Ash tree row.
*Means followed by the same letter, inside the same distance, do not differ from each other according to Tukey's, at 0.05 of significance.

The drift to the ground was reduced at 5 m and 15 m on the spray application using the variable-rate intelligent sprayer. At 35 m, 65 m and 105 m, the drift produced by both sprayers was statistically equal. The percentage of drift reduction on 5 m and 15 m was 58% and 98%, respectively.

The variable-rate intelligent sprayer adjusts the spray output to the canopy characteristics, and interrupts the spray application when no target is detected. The spray application between trees could have contributed to the bigger drift detected using the conventional sprayer.

3.3. Test of Variance (F) for the Axis X, Y and Z

Tables 2 and 3 show the tests of variance (F) made for the axis spray deposition and coverage inside the Ash tree canopies. Figure 2 (left figure) shows the schematic draw of the axis inside the tree canopy. Positions 1, 2 and 3 formed the Y axis (height of the tree direction). Positions 7, 2 and 5 formed the X axis (sprayers speed direction). Positions 4, 2 and 6 formed the Z axis (spray direction).

The test aimed to find differences between the variance of deposition on the axis when spraying with intelligent or conventional sprayer, and also when spraying with different travel speeds. The F test for variance is a dual comparison test, so comparisons were made using all the dual combinations possible between treatments. Variance of the spray deposition and coverage is an indicator of the consistency of these variables, giving information about the quality and uniformity of these features inside the tree canopy, separated by axis.

The variance on the axis was calculated using the values of the three replications of one position, adding to the values of the three replications of the other two positions that formed the axis, in a total of nine values per axis per treatment. This variance was then tested against the variance of the correlated treatment.

Table 2 – F-Test for variance of spray deposition (µL cm^{-2}) on nylon screens positioned on the axes X, Y and Z inside Ash tree canopies, after application using a conventional air-assisted sprayer and a variable-rate air-assisted intelligent sprayer, with travel speeds of 3.2 km h^{-1}, 5.6 km h^{-1}, and 8.0 km h^{-1}.

Treatments - Dual Combinations		Tree 1			Tree 2			Tree 3		
		X	Y	Z	X	Y	Z	X	Y	Z
V1	I*C	ns	ns	*(C)	ns	*(C)	ns	*(I)	*(I)	ns
V2	I*C	ns	ns	ns	ns	ns	ns	ns	ns	ns
V3	I*C	ns	ns	*(I)	*(C)	ns	ns	ns	ns	ns
I	V1*V2	ns	ns	*(V1)	ns	ns	*(V1)	*(V1)	ns	ns
	V1*V3	ns	ns	*(V1)	ns	*(V3)	*(V1)	ns	ns	*(V1)
	V2*V3	ns	ns	ns	ns	ns	ns	ns	ns	ns
C	V1*V2	ns	ns	ns	ns	ns	ns	ns	ns	ns
	V1*V3	ns	ns	ns	ns	ns	ns	ns	ns	ns
	V2*V3	ns	ns	ns	ns	ns	ns	ns	ns	ns

ns – Non significant according to the F test, at 0.05 of significance.
*Significant at 0.05 of significance, according to the F test. Information between parentheses represents the treatment that had the biggest variance: C – Conventional Sprayer, I – Intelligent Sprayer, V1 – Velocity 1 (3.2 km h^{-1}), V2 – Velocity 2 (5.6 km h^{-1}) and, V3 – Velocity 3 (8.0 km h^{-1}).

The variable-rate intelligent sprayer and the conventional sprayer showed three situations each, with higher variance of the deposition inside canopy, when it was compared the sprayers at a determined travel speed. Also, both sprayers had one situation of higher variance on each axis (X, Y, and Z), when compared at the same travel speed. The conventional sprayer presented the higher variance on the axis Z (tree 1) and Y (Tree 2), at 3.2 km h^{-1}, and on X axis (Tree 2), at 8.0 km h^{-1}. The intelligent sprayer presented the higher variance on the axis X (Tree 3) and Y (tree 3) at 3.2 km h^{-1}, and on Z axis (Tree 1), at 8.0 km h^{-1}. The travel speed of 3.2 km h^{-1} had more variance of spray deposition for both sprayers.

On 21 occasions, the difference between the spray deposition variance of the variable-rate intelligent and conventional sprayer was non-significant, meaning that the variance had no statistical difference. Both sprayers could produce depositions very similar according to variance, and demonstrates the capability of the variable-rate intelligent sprayer in producing applications with consistency, similar to commercially available air-assisted sprayers for tree crops.

The spray application with the variable-rate intelligent sprayer, after dual comparisons for travel speed, showed that V1 (3.2 km h^{-1}) had higher variance six times, being five times on Z axis and one on X axis. V3 (8.0 km h^{-1}) had the highest variance one time, and on Y axis.

The spray application with conventional sprayer presented no differences in the variances on dual comparisons of travel speed.

Table 3 - F-Test for variance of spray coverage (%) on WSP positioned on the axes X, Y and Z inside Ash tree canopies, after application using a conventional air-assisted sprayer and a variable-rate air-assisted intelligent sprayer, with travel speeds of 3.2 km h^{-1}, 5.6 km h^{-1}, and 8.0 km h^{-1}.

Treatments - Dual Combinations		Tree 1			Tree 2			Tree 3		
		X	Y	Z	X	Y	Z	X	Y	Z
V1	I*C	ns	ns	ns	ns	*(C)	ns	ns	ns	ns
V2	I*C	ns	ns	ns	*(C)	*(C)	ns	ns	ns	ns
V3	I*C	ns	ns	ns	*(C)	*(C)	ns	ns	ns	ns
I	V1*V2	ns	ns	ns	ns	ns	ns	ns	ns	ns
	V1*V3	ns	ns	ns	ns	ns	ns	ns	ns	ns
	V2*V3	ns	ns	ns	ns	ns	ns	ns	ns	ns
C	V1*V2	ns	*(V1)	ns	ns	ns	ns	ns	ns	ns
	V1*V3	ns	ns	ns	ns	ns	ns	ns	ns	ns
	V2*V3	ns	ns	ns	ns	ns	ns	ns	ns	ns

ns – Non significant according to the F test, at 0.05 of significance.
*Significant at 0.05 of significance, according to the F test. Information between parentheses represents the treatment that had the biggest variance: C – Conventional Sprayer, I – Intelligent Sprayer, V1 – Velocity 1 (3.2 km h^{-1}), V2 – Velocity 2 (5.6 km h^{-1}) and, V3 – Velocity 3 (8.0 km h^{-1}).

At the comparison of sprayers on the same speed, the conventional sprayer had the higher variance of coverage on WSP five times, being two on X axis and three on Y axis. On V1 (3.2 km h^{-1}), conventional sprayer had higher variance one time, and two times the higher variance on both V2 (5.6 km h^{-1}) and V3 (8.0 km h-1). The variable-rate intelligent sprayer had no higher variance of spray coverage on WSP when compared to the conventional sprayer.

There were obtained no differences in the variance of the spray coverage on WSP on the comparison of travel speeds using the variable-rate intelligent sprayer. Yet, the conventional sprayer had higher variance one time on Y axis, spraying at 3.2 km h^{-1}.

4. CONCLUSIONS

The variable-rate intelligent sprayer reduced the application rate in 64%.

Both variable-rate intelligent sprayer and conventional sprayer were able to produce consistent spray deposition and spray coverage inside Ash tree canopies. These variables were predominantly not affected by the sprayers travel speed.

The spray deposition on ground near the application area was similar for conventional and variable-rate intelligent sprayer, and also not affected by travel speed.

The variable-rate intelligent sprayer reduced the drift to the air in 92% and 94%, and the drift to the ground in 58% and 98%, at 5 m and 15 m downwind, respectively.

The variance of spray deposition inside of the three Ash tree canopy axes (x, y and z) was similar between the conventional sprayer and variable-rate intelligent sprayer.

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CHAPTER 3

LABORATORY EVALUATION OF SPRAY OUTPUTS FOR A VARIABLE-RATE INTELLIGENT SPRAYER COUPLED WITH PWM SOLENOID VALVES

Abstract: Variable-rate sprayer can adjust the spray output at real-time, without the need of previous calibration. The spray output is adjusted by solenoid valves, activated through electric current to turn on or shut off. A variable-rate intelligent sprayer implementing a high speed laser scanner was developed for tree crops spraying. It was capable of spraying on 10 increasing percentages of the maximum flow rate (designated duty cycles), and was evaluated on its flow rate under several combinations of working conditions. Tests were realized to evaluate the flow rate and the effect on the pressure with the modulation of the spray output. The first experiment was on a factorial scheme 10 x 40, whith the first factor being the modulation of the flow rate (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%), and the second factor the number of active nozzles (1 to 40). In the first test, the sprayers pressure was set to 50 PSI (344,7 kPa) with all nozzles shut off, at the beginning of the test, and the pressure was not changed through the rest of the test. A second test was made to evaluate the flow rate at a constant pressure of 35 PSI (241 kPa). The second test also had a factorial scheme of 10 x 5, whith the first factor being the modulation rate (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%), and the second factor the number of active nozzles (1, 10, 20, 30, and 40), with three replications. The flow rate was quantified collecting the output water from the nozzles on a previous determined time and weighting it on a precision scale. On the first test, the pressure was observed, and the decay on the pressure with increasing number of active nozzles and duty cycles was studied. It was observed a higher pressure drop with the increasing numbers of active nozzles. The same effect was observed as the modulation of the duty cycles was increased. The pressure decay lead to a lower increase in the flow rate, for both varied and constant pressure conditions. As the number of active nozzles increased, and those operating at higher duty cycles, the increase in the flow rate was smaller, due to the pressure decay. Higher increases in the flow rate were observed for the 35 PSI constant pressure condition test. The smaller increases in the flow rates on varied pressure condition were due to pressure drop. The flow rate of the variable-rate intelligent sprayer, according to number of active nozzles and duty cycle, could be described through a polynomial regression curve, for both varied and constant pressure conditions.

Keywords: pressure decay, air-assisted sprayer, flow-rate.

CAPÍTULO 3

AVALIAÇÃO DA VAZÃO DE UM PULVERIZADOR DE TAXA VARIADA CONTROLADA POR VÁLVULAS SOLENÓIDES DE PULSO MODULADO

Resumo: Pulverizadores de taxa variada podem ajustar a quantidade de calda aplicada em tempo real, sem a necessidade de calibração prévia da máquina. A quantidade aplicada é regulada através de válvulas solenóides, ativadas por corrente elétrica, que condicionam o tempo de abertura destas e a passagem de líquido. Um pulverizador inteligente à taxa variada, equipado com sensor laser de alta velocidade para leitura da copa foi desenvolvido para pulverização de culturas arbóreas. O pulverizador era capaz de pulverizar em 10 porcentagens crescentes da capacidade máxima de vazão ("duty cycles"). A máquina possuia 20 pontas de pulverização em cada lado, totalizando 40 pontas. Avaliou-se a vazão do pulverizador em combinações de número de pontas x "duty cycle", formando diferentes regimes de trabalho. Os testes objetivaram avaliar o efeito de crescentes números de pontas e "duty cycles" sobre a pressão, o que acabaria por afetar a vazão. O primeiro experimento foi em esquema fatorial 10 x 40, sendo o primeiro fator a modulação da taxa da vazão ("duty cycle") (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% , e 100%), e o segundo fator o número de pontas abertas (1 a 40), com três repetições. No primeiro ensaio, a pressão do pulverizador foi ajustada para 50 PSI (344,7 kPa) com todas as pontas desligadas, sendo que esta não foi alterada durante o teste. Um segundo teste foi realizado para avaliar a vazão em condição de pressão constante à 35 PSI (241 kPa). A pressão era reajustada antes do início de cada medição, com todas as pontas desligadas. O segundo teste foi em esquema fatorial de 10 x 5, sendo o primeiro fator a taxa de modulação da vazão ("duty cycle") (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% e 100%) e o segundo fator o número de pontas abertas (1, 10, 20, 30 e 40), com três repetições. A vazão foi quantificada coletando-se a água pulverizada pelas pontas num tempo previamente determinado e pesando-a numa balança de precisão. No primeiro teste, anotou-se o comportamento da pressão à medida que se aumentava o número pontas abertas e o "duty cycle". Observou-se uma maior diminuição da pressão à medida que se aumentava o número de pontas abertas. Efeito semelhante foi observado à medida que a modulação dos ciclos de trabalho aumentava. A diminuição da pressão levou a um menor aumento da vazão, tanto para a condição de pressão variada como para à pressão constante. À medida que o número de pontas abertas aumentou, e estas trabalhando em maiores "duty cycles", o aumento na taxa de fluxo foi menor, devido ao decaimento da pressão. Aumentos mais elevados na vazão foram observados para o teste de condição de pressão constante de 35 PSI. Os aumentos menores na vazão na condição de pressão variada foram devido à maior queda de pressão. A vazão do pulverizador inteligente de taxa variada, de acordo com o número de pontas abertas e o "duty cycle", foi descrita através usando curva de regressão polinomial, para ambas as condições de trabalho.

Palavras-chave: queda de pressão, pulverizador hidropneumático, vazão.

1. INTRODUCTION

Successful use of pesticide sprayers to ensure a bountiful and high quality of plant products is of great importance in crop production. Unfortunately, conventional pesticide sprayers are not suited to the different types, sizes, and shapes of plant canopies, and are prone to losses from spray drift to the ground and air. There are also concerns for potential damage to humans and the environment from off-target loss of pesticides and other agricultural chemicals.

Great variations in the canopy architecture of tree crops occur during a growing season. When applying sprays to a tree, the main targets are leaves, branches and trunks, and their quantity should be one of the major factors affecting the amount of applied spray mixtures. This quantity is difficult to determine instantaneously without sensors. Therefore, the dosage of chemicals for applications can easily be over or under estimated for use in conventional constant-rate sprayers.

Researchers have tried to adjust spray application volume to match plant structure characteristics (FOX et al., 2008; GILES et al., 2011; WEI, SALYANI, 2004; ROSELL et al., 2009; LLORENS et al., 2011; JEON, ZHU, 2012; CHEN et al., 2012). Efforts to lower product dosage based on a leaf area index showed the promise of suppressing diseases (SIEGFRIED et al., 2007). A tree-row-volume (TRV) method was developed to help growers estimate the spray application volume (MORGAN, 1964; BYERS et al., 1971; SUTTON, UNRATH, 1988). These TRV estimations accounted for variations in canopy height, depth, and density, yielding a solution quantity that corresponded to the crop needs. Even though TRV measurements provide an approximation of canopy characteristics such as foliage density, they are not real-time measurements of each individual tree. TRV measurements are only an average representation of the crop sample. Alternatively, the unity canopy row (UCR), which was defined as a volume of canopy 1.0 m high, 1.0 m wide and 100.0 m in length, was proposed to estimate spray application rates (FURNESS et al., 1998). However, neither TRV nor UCR has been widely adopted due to their complexity.

If canopies with different surface areas and/or volumes are sprayed with constant rate applications, they are likely to receive different spray doses. Foliage density also affects the spray penetration (WALKLATE, 1996). Unfortunately, it is difficult to determine the optimal application rates required to achieve effective doses, distributions, and biological responses in crop canopies of different sizes and densities. Furness et al.

(1998) presumed the effect of the nature of the leaf surface and density of the canopy differences on the retention volume of sprays on crops. The maximum amount of water a canopy could hold would be a function of these canopy parameters, which should be determined for each crop and its growth stage to achieve optimum spray application rates.

The development of variable-rate sprayers capable of delivering variable amounts of pesticide to match crop structures has recently gained more attention. Giles et al. (1989) developed an experimental air-blast sprayer using ultrasonic sensors to detect the presence of plants and the canopy height and width. Solenoid valves were used to completely open or close nozzles, achieving the variable-rate function. Reduced spray solution use ranging from 28% to 52% was reported and strongly related to the target architecture of peach and apple trees.

Variable-rate applications reduced spray solution use by more than 50% with ultrasonic sensors and the deposition quality was equal to or even better than constant rate applications (GIL et al., 2007; LLORENS et al., 2010; JEON et al., 2011b). This was achieved because the nozzles were shut off when ultrasonic sensors detected empty spaces between plants (GILES et al., 1989; JEON, ZHU, 2012). However, ultrasonic sensors have a wide divergence angle and low measurement resolution, making them suitable only for point measurements (JEON et al., 2011a; ROSELL et al., 2012). In comparison, laser scanning sensors can produce high resolution and accurate measurements of tree plant presence, size, shape and canopy volume (CHEN et al., 2012, PALLEJA et al., 2010; LIU, ZHU, 2016).

An experimental intelligent sprayer was developed with the integration of a high-speed laser scanning sensor to discharge spray based on plant presence and architecture to reduce spray volume and reduce spray off-target losses (CHEN et al., 2012, 2013a, 2013b). The sprayer was designed to discharge 0.06 to 0.13 L of liquid spray per m^3 of foliage at an average operating pressure of 242 kPa. The amount of liquid sprayed was a function of canopy volume measured in real time. The variable-rate function was achieved by an automatic controller to manipulate the duty cycle of each pulse-width-modulated (PWM) solenoid valve coupled to each nozzle.

When the PWM duty cycle was between 20% and 100%, flat-fan nozzles operated at a constant pressure had minimum droplet size variations (GILES, 1997; GU et al., 2011) and consistent spray patterns (GILES, COMINO, 1990). However, variations in flow rates discharged from PWM-controlled nozzles at different pressures were observed during the laser-guided sprayer development (SHEN et al., 2017). The variations in flow rates were a consequence of pressure fluctuations on nozzles when the sprayer discharged variable outputs with varied number of active nozzles at different PWM duty cycles.

The pressure fluctuation consequently provokes nozzle flow rate fluctuation, causing inaccurate spray outputs with respect to canopy structure volume. A potential solution to this problem is to develop a computer program for a close-loop feedback control system to control actual duty cycles and flow rates for active nozzles. The feedback control system requires information on how the interrelationships among the flow rate, pressure, number of active nozzles and PWM duty cycles interact. In addition, with records of spray outputs discharged from each nozzle, the amount of sprays applied can be calculated to serve as an indicator for sprayer operators to know when to refill the tank or how much volume of tank mixture was applied. However, these functions and their interrelations are not yet elucidated.

Therefore, investigation of the flow rate variations during variable rate applications became a priority. The objectives of this research were to determine variations in the total flow rate of multiple PWM controlled nozzles operated simultaneously and to establish predictable spray output functions to improve future intelligent spray accuracy.

2. MATERIALS AND METHODS

Experiments were conducted using the USDA-ARS ATRU phase I experimental intelligent sprayer employing a laser scanning sensor, developed for orchard and nursery applications (Shen et al., 2017). There were 40 nozzles evenly distributed on eight air-assisted five-port manifolds on two sides of the sprayer. The nozzle tips were flat-fan TeeJet XR8004 (Spraying Systems Inc., Wheaton, IL). Details of each nozzle assembly in the five-port manifold were given by Zhu et al. (2006).

The flow rate was regulated separately for each nozzle by PWM solenoid valves (Capstan Ag Systems, Inc., Topeka, KS) connected to the water line upstream from the nozzles. A microcontroller unit operating at 10 Hz drove the solenoid valves to activate each nozzle with opening times ranging from zero to 100 ms as duty cycles (LIU et al., 2013).

The variable rate functions were controlled through software on the computational system of the intelligent sprayer, which triggered the microcontroller unit. This software received signals from the laser unit and calculated the required spray volume using the recommendation of 0.06 L of water per 1.0 m^3 of foliage.

The variable rate spray out was achieved automatically in real time while the sprayer was moving and spraying in the field. However, for this test, the variable rate function was achieved with manual input of PWM duty cycles through a touch screen located in the tractor cabin. The duty cycle for each nozzle was given according to the modulation rate HEX code, which was the code that specified the duty cycle for one specific nozzle. These codes were manually entered through an interface on a touch screen used to access the sprayer operational software. In this way, each single nozzle or a group of nozzles could be opened or closed simultaneously with any duty cycles chosen for each nozzle independently.

2.1. Test 1 – Varied Pressure

The first experiment was conducted with a factorial scheme 10x40 (or 400 treatments) at an operating pressure initially set at 345 kPa (table 1). The first factor was the duty cycle (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%), and the second factor was the number of active nozzles (from 1 to 40). For this experiment, the operating pressure varied with both number of active nozzles and PWM duty cycle. However, no adjustments to the pressure were made when number of active nozzles and PWM duty cycle were changed during the test. Actual pressure was recorded for each measurement. Water was used as the spray solution. Prior to each measurement, all nozzles were shut down and the pressure was adjusted to 345 kPa. With this initial pressure setting, the operating pressure fluctuated back and forth when the sprayer was running. Each test treatment was repeated three times.

Rubber tubes were connected to the nozzles to guide spray to a specially built cone-shaped catch basin to collect the discharged water. The collected water was immediately channeled to a 10.0 L bucket. Measurement of flow rate was accomplished by collecting water for a predetermined time. A stop-watch was used to count the time. Different collection times were used to match bucket capacity. The collection times were 30 s for 10% and 20% duty cycles, 20 s for 30% duty cycle, 15 s for 40% to 80% duty cycles, and 10 s for 90% and 100% duty cycles. Shorter times for higher nozzle flow rates made it easier to maneuver the bucket and avoided spill of collected water. A scale with 1 g resolution (Sartorius IS 150 IGG-S0CE, Goettingen, Germany) was used to weigh the collected water. Volume of the collected water was calculated from water mass and density (ρ = 1000 kg m^{-3}), and then flow rate in L min^{-1} was calculated from dividing the volume of water by collection time.

The operating pressure in the spray line for each flow rate measurement was recorded on a pressure gauge located 1.25 m upstream of nozzles through 6.4-mm diameter tubes. It is important to note that the recorded pressure was higher than the actual pressure acting on nozzles due to pressure drop in the tubes.

2.2. Test 2 – Constant Pressure

The second test was conducted on the sprayer to evaluate its total flow rate at constant 242 kPa pressure throughout the experiment. This test had a factorial scheme of 10x5 (or 50 treatments). The first factor was the duty cycle (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%), and the second factor was the number of active nozzles (1, 10, 20, 30, and 40). Pressure was adjusted to 242 kPa for each setting prior to each test run. The same method to measure the total flow rate described in the first test was used in the second test. This test was used to be a reference for test 1 to determine changes in spray outputs without constant pressure acting in the spray line.

3. RESULTS AND DISCUSSION

The operating pressure in the spray line dropped considerably when either the number of active nozzles or duty cycle increased under the varied pressure condition (table 1). The most notable pressure drop, with duty cycle increased from 10% to 100%, was observed when all 40 nozzles were open at the same time. For examples, the spray line pressure was 345 kPa when there were no nozzles activated, and it was still 345 kPa at 10% duty cycle but dropped to 324 kPa at 100% duty cycle when one nozzle was activated. When there were 40 nozzles activated, the pressure dropped from 345 to 283 kPa at 10% duty cycle and further dropped to 104 kPa at 100% duty cycle. For hydraulic nozzles, variations of the operation pressure in spray lines would affect the nozzle flow rates (Womac, 2001; Nuyttens et al., 2007).

Table 1. Operating pressures in the spray line obtained from test 1 with changes in number of active nozzles ranging from 1 to 40 for duty cycles (DC) of 10% and 100%. Initial pressure was set at 345 kPa.

Number of active nozzles	Pressure (kPa) 10% DC	Pressure (kPa) 100% DC	Number of active nozzles	Pressure (kPa) 10% DC	Pressure (kPa) 100% DC
1	345	324	21	311	173
2	338	311	22	311	166
3	338	297	23	311	159
4	338	283	24	311	152
5	331	276	25	311	152
6	331	262	26	304	145
7	331	255	27	304	138
8	331	248	28	304	138
9	324	242	29	297	131
10	324	228	30	297	131
11	324	221	31	297	124
12	324	214	32	290	117
13	324	207	33	290	117
14	317	207	34	290	110
15	317	200	35	290	110
16	317	193	36	290	110
17	317	193	37	290	110
18	317	186	38	283	104
19	317	186	39	283	104
20	317	179	40	283	104

Figure 1 shows the total flow rates discharged with 10, 20, 30 and 40 active nozzles for the duty cycles ranging from 10 to 100% under both varied pressure (test 1) and 242 kPa constant pressure (test 2) conditions. The total flow rates from test 1 and test 2 were very close with 10 and 20 active nozzles for duty cycles from 10% to 100%, but were considerably different for 30 and 40 active nozzles especially when duty cycles were over 80%. For example, at 90% duty cycle, the difference in total flow rate between test 1 and 2 was 0.71 L min^{-1} (6.3% difference) with 10 active nozzles, -0.82 L min^{-1} (4.3% difference) with 20 active nozzles, -6.86 L min^{-1} (21.9% difference) with 30 active nozzles, and -10.74 L min^{-1} (27.6% difference) with 40 active nozzles, respectively. The absolute difference in total flow rates between test 1 and 2 increased dramatically as the number of active nozzles increased. The reason was that the operating pressure in spray line dropped considerably under the test 1 condition when the number of active nozzles increased while it was maintained at 242 kPa in test 2. This could be explained by Bernoulli's equation where the flow rate is the proportional to the square root of pressure.

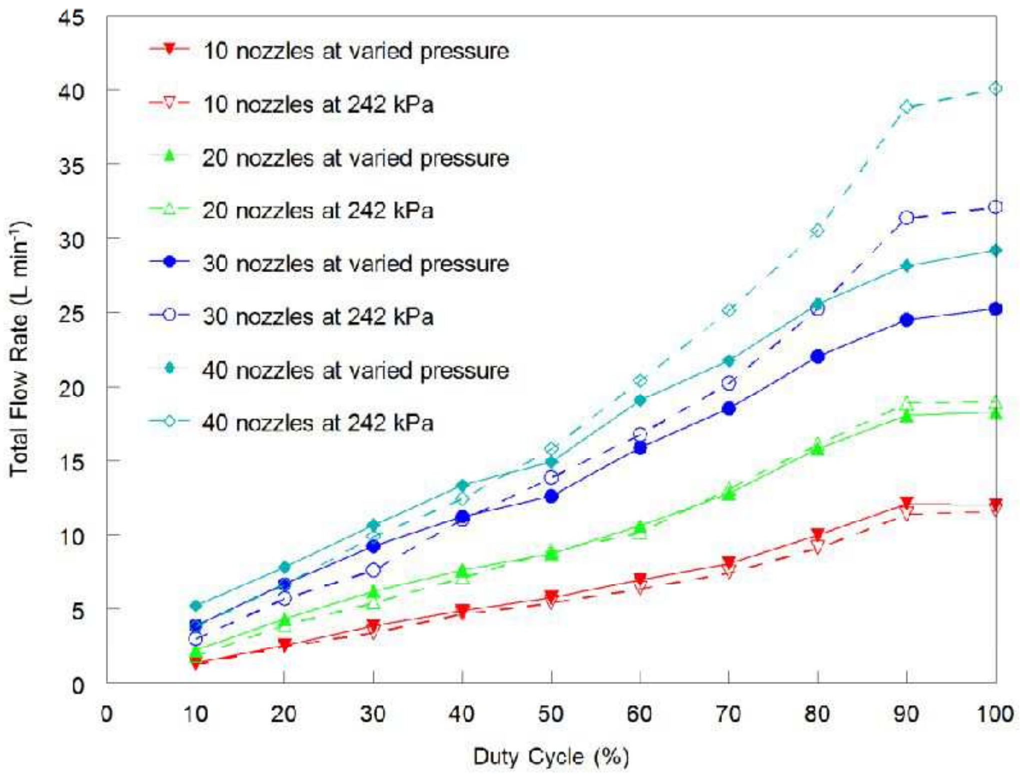

Figure 1. Total flow rates discharged from the sprayer with 10, 20, 30 and 40 active nozzles for the duty cycles ranging from 10% to 100% under both varied pressure (test 1) and 242 kPa constant pressure (test 2) conditions.

Observations of curves in figure 1 indicate a linear relationship between the total flow rate and duty cycle ranging from 10% to 90% for a given number of active nozzles. Table 2 shows the linear regression equations for the total flow rate and duty cycle for 10, 20, 30 and 40 active nozzles, respectively.

Table 3. Linear regression equations for flow rate (Z) in function of duty cycle (X), with 10, 20, 30 and 40 active nozzles at duty cycles ranging from 10% to 90% under varied pressure (test 1) and 242 kPa constant pressure (test 2) conditions.

Number of active nozzles	Linear regression equation			
	Test 1		Test 2	
	Equation	r^2	Equation	r^2
10	Z = 0.126X - 0.12	0.982	Z = 0.117X - 0.07	0.978
20	Z = 0.190X + 0.12	0.984	Z = 0.205X - 0.73	0.980
30	Z = 0.253X + 1.21	0.992	Z = 0.338X - 1.91	0.974
40	Z = 0.288X + 1.88	0.994	Z = 0.417X - 2.66	0.966

The slopes in the linear regression equations represented the magnitude of the increase in the flow rate with the increase in the duty cycle. Under the varied pressure condition (test 1), the slope was 0.126, 0.190, 0.253 and 0.288 for 10, 20, 30 and 40 active nozzles, respectively. It was increased by 50.8% when the number of active nozzles increased from 10 to 20, and by 51.2% when the number of active nozzles increased from 20 to 40. Under the constant pressure condition (test 2), the increase in the slope was of 75.7% from 10 to 20 active nozzles and 103.2% from 20 to 40 active nozzles. The increase in the slope due to the increased number of active nozzles was higher under the constant pressure condition than that under the varied pressure condition. The total flow rate increased with each 10% step increase in duty cycle under both test conditions; however, this flow rate increase was slower in the varied pressure condition than in the constant pressure condition.

Even though the spray line pressure varied with the number of active nozzles in test 1, the total flow rate still increased as the number of active nozzles at a given duty cycle (fig. 2). Obviously, this total flow rate increase with increased number of active nozzles was also true for test 2 under the 242 kPa constant pressure condition (fig. 3).

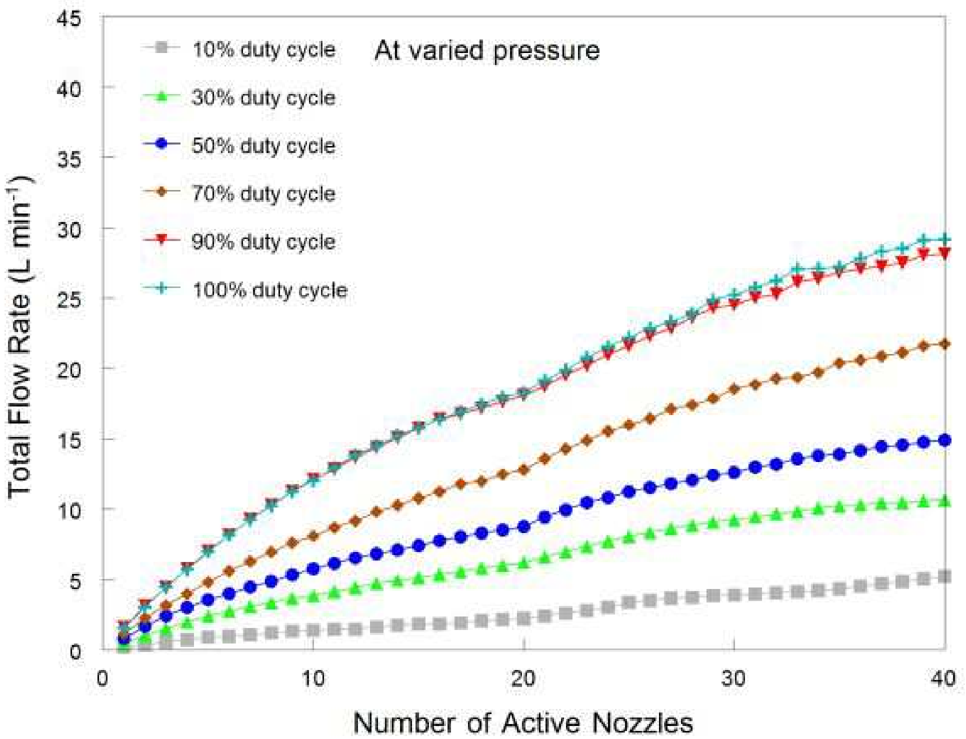

Figure 2. Total flow rate (L min^{-1}) according to the number of active nozzles operated at 10%, 30%, 50%, 70%, 90% and 100% duty cycles under the varied pressure condition (test 1).

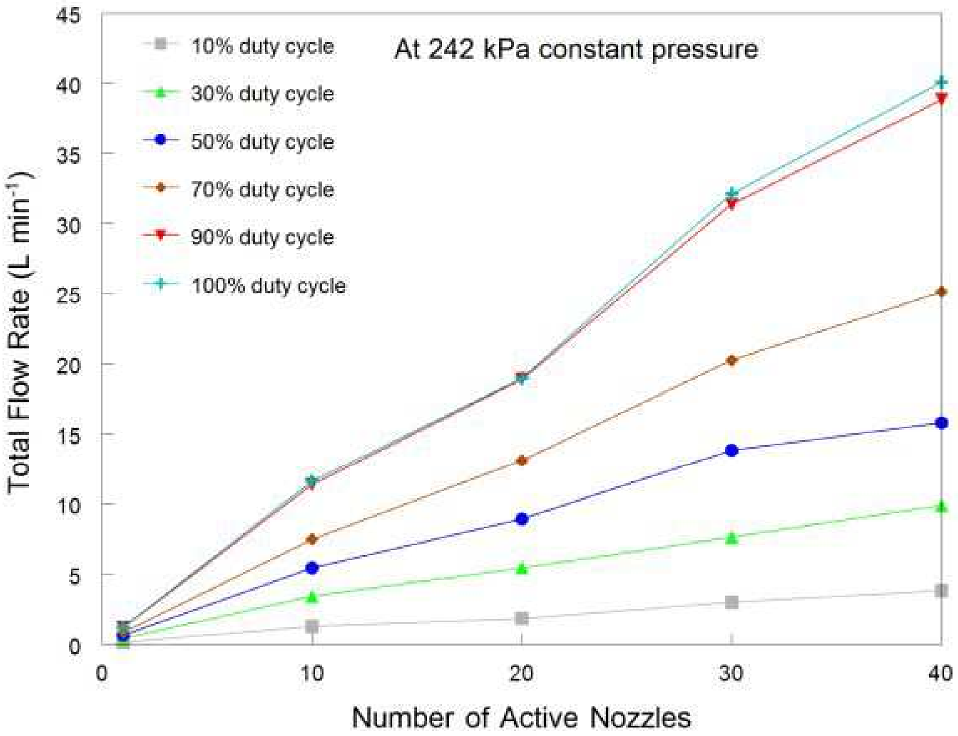

Figure 3. Total flow rate (L min^{-1}) according to the number of active nozzles operated at 10%, 30%, 50%, 70%, 90% and 100% duty cycles under the 242 kPa constant pressure condition (test 2).

Correspondingly, linear regression equations for the total flow rate and number of active nozzles at each duty cycle ranging from 10 to 100% were established and are shown in table 3.

Table 3. Linear Regression equations for total flow rate (Z) with number of active nozzles (Y) at each duty cycle ranging from 10% to 100% under varied pressure (test 1) and 242 kPa constant pressure (test 2) conditions.

Duty cycle (%)	Linear regression equation			
	Test 1		Test 2	
	Equation	r^2	Equation	r^2
10	Z = 0.124Y + 0.11	0.988	Z = 0.092X + 0.18	0.990
20	Z = 0.192X + 0.65	0.990	Z = 0.162X + 0.55	0.979
30	Z = 0.260X + 1.14	0.986	Z = 0.235X + 0.63	0.992
40	Z = 0.320X + 1.47	0.990	Z = 0.307X + 0.97	0.973
50	Z = 0.349X + 1.93	0.988	Z = 0.394X + 0.99	0.982
60	Z = 0.450X + 1.99	0.992	Z = 0.507X + 0.67	0.992
70	Z = 0.514X + 2.56	0.988	Z = 0.625X + 0.76	0.996
80	Z = 0.601X + 3.48	0.980	Z = 0.766X + 0.95	0.994
90	Z = 0.648X + 4.65	0.972	Z = 0.971X + 0.72	0.994
100	Z = 0.677X + 4.42	0.976	Z = 1.001X + 0.59	0.994

Similar to the regression equations shown in table 2, the slope in the linear regression equations in table 3 represents the magnitude of the increase in the total flow rate with the increase in the number of active nozzles. Under varied pressure condition (test 1), the slope increased by 81.8% when duty cycle increased from 20% to 50%, and by 85.7% when duty cycle increased from 50% to 90%. In contrast, under the 242 kPa constant pressure condition (test 2), the slope increased by 143.2% when duty cycle increased from 20% to 50%, and by 146.4% when duty cycle increased from 50% to 90%.

When there was one active nozzle operated at 20% duty cycle, the total flow rate was 0.41 L min^{-1} under varied pressure condition and was 0.30 L min^{-1} under the 242 kPa pressure condition. In contrast, when there were 40 active nozzles operated at 90% duty cycle, the total flow rate was 28.12 L min^{-1} under the varied pressure condition and was 38.86 L min^{-1} under the 242 kPa constant pressure condition. Thus, the difference in flow rates changed considerably at higher duty cycles with more active nozzles. Under an ideal condition such as test 2, which maintained a constant pressure for operation, variable flow rates of nozzles were obtained by manipulating only duty cycles. However, test 1 was the realistic operation. Under this realistic condition, the total flow rate from the sprayer varied with number of active nozzles due to the pressure variation.

Based on the linear equations between the flow rate and duty cycle as well as number of active nozzles (table 2 and 3), regression equations of flow rate with two variables (duty cycle and number of active nozzles) were established using the statistical software Dell Statistica (Version 13, Dell Inc., Plano, TX, USA) for both varied and constant pressure conditions. For the varied pressure condition, the regression equation was,

$$Z = 0.0422X + 0.0305Y + 0.00697XY, \quad r^2 = 0.996 \tag{1}$$

For the 242 kPa constant pressure condition, the regression equation was,

$$Z = 0.0124X - 0.0961Y + 0.0108XY, \quad r^2 = 0.981 \tag{2}$$

Where, Z is total flow rate discharged from the sprayer (L min^{-1}), X is duty cycle ranging from 20% to 90%, and Y is number of active nozzles ranging from 1 to 40. Coefficients of determination for both equations were greater than 0.980.

It was observed that the difference in total flow rates between 90% and 100% duty cycles in both varied and constant pressure conditions were very small compared to lower duty cycles (figs. 1, 2). The flow reached closer to the maximum capacity at 90% duty cycle, not being capable of discharging more water at 100% duty cycle (Liu et al., 2013). A large variability in the flow rate was also observed at 10% duty cycle. Gu et al. (2011), evaluating the PWM solenoid valve controlled nozzles, reported the similar inconsistency in droplet sizes at 10% duty cycle. Therefore, the 10% and 100% duty cycles were not considered in the regression equations.

Table 4 shows absolute and relative errors of total flow rates predicted by the regression equations, comparing to the measured values under varied and constant pressure conditions, for number of active nozzles ranged from 1 to 40 and duty cycles ranged from 20% to 90%. The negative values presented that the predicted values were greater than the measured values.

The highest absolute and relative errors were found near the extremities of the equations (1 and 40 nozzles and 20% and 90% duty cycles). For example, under the varied pressure conditions, the largest absolute error was 2.84 L min^{-1} occurring with one active nozzle at 90% duty cycle. Largest relative error was 207.9% occurring with one active nozzle at 30% duty cycle. Similarly, under the 242 kPa constant pressure condition, the largest absolute error was 3.91 L min^{-1} occurring with 30 active nozzles at 90% duty cycle. The largest relative error was 75.0% occurring with one active nozzle at 70% duty cycle. The most agreeable predictions for the flow rates occurred in the middle ranges of numbers of active nozzles and duty cycles. Within these ranges, it was possible to use the equations to predict and manage spray outputs of variable-rate sprayers with different numbers of active nozzles and duty cycles. To further improve the accuracy of predicting spray outputs, a two-variable matrix for the measured total flow rates with duty cycles and numbers of active nozzles should be established and saved as a database in the computer. During sprayer operation, the database could be used to incorporate actual duty cycle and number of active nozzles to make a close-loop feedback control system to obtain the total flow rate.

Table 4 - Absolute and relative errors of total flow rates predicted from regression equations (1) and (2) according to number of active nozzles and duty cycle at varied pressure (test 1) and 242 kPa constant pressure (test 2) conditions.

Test	DC (%)[a]	Absolute error (L min^{-1})[b]					Relative error (%)[c]				
		Number of active nozzles					Number of active nozzles				
		1	10	20	30	40	1	10	20	30	40
1	20	-0.61	0.03	0.12	0.75	0.20	149.3	1.3	2.7	11.2	2.5
	30	-1.02	0.21	0.14	0.78	-0.19	207.9	5.4	2.3	8.5	1.8
	40	-1.22	0.11	-0.23	0.29	-0.72	156.1	2.2	3.0	2.5	5.4
	50	-1.65	-0.14	-0.94	-0.86	-2.35	196.8	2.4	10.7	6.8	15.8
	60	-1.98	-0.06	-0.89	-0.11	-1.38	198.1	0.9	8.4	0.7	7.2
	70	-2.31	-0.05	-0.51	0.03	-1.94	199.3	0.6	4.0	0.2	8.9
	80	-2.58	0.72	0.70	1.01	-1.33	187.3	7.2	4.4	4.6	5.2
	90	-2.84	1.74	1.14	0.98	-1.98	176.1	14.3	6.3	4.0	7.0
2	20	-0.07	1.07	1.29	1.87	1.61	22.4	42.4	32.7	32.7	24.2
	30	-0.15	0.79	0.52	0.41	0.38	33.5	22.9	9.4	5.4	3.8
	40	-0.32	0.86	-0.09	0.46	-1.53	62.0	18.1	1.2	4.1	12.3
	50	-0.39	0.38	-0.58	-0.11	-2.61	57.8	7.0	6.5	0.8	16.5
	60	-0.55	0.13	-1.63	-0.57	-2.47	74.4	1.9	16.0	3.4	12.1
	70	-0.66	0.02	-0.99	-0.46	-2.20	75.0	0.2	7.5	2.3	8.7
	80	-0.74	0.45	-0.25	1.17	-1.27	72.7	4.9	1.5	4.6	4.2
	90	-0.78	1.50	0.22	3.91	2.62	63.7	13.2	1.2	12.5	6.7

[a] DC presents duty cycle.
[b] Absolute error = measured value - predicted value.
[c] Relative error = (measured value - predicted value) ×100 / measured value.

4. CONCLUSIONS

For a given duty cycle under both varied and constant pressure conditions during sprayer operation, total flow rates increased linearly with an increase in the number of active nozzles coupled with PWM solenoid valves. The magnitude of flow rate increase for the varied pressure condition decreased as the number of active nozzles increased due to considerable pressure drops in the spray line. Total flow rates also increased linearly as the duty cycle increased from 20% to 90% and remained little change when of the duty cycle increased from 90% to 100%.

Two-variable linear regression equations for the total flow rate with number of active nozzles ranging from 1 to 40 and duty cycles ranging from 20% to 90% were established to predict spray outputs under varied and constant pressure conditions. Coefficients of determination (r^2) for the two regression equations were greater than 98%. Except for the extremities of the number of nozzles (1 and 40 active nozzles) and duty cycle (20% and 90%), the calculated flow rate from regression equations agreed well with the measured values.

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