American Society of Agricultural and Biological Engineers

An ASABE Meeting Presentation

Paper Number: 061125

Dynamic air velocity and spray deposition inside dense nursery crops with a multi-jet air-assist sprayer

Heping Zhu, Agricultural Engineer, USDA/ARS, ATRU, Wooster, OH, zhu.16@osu.edu

Richard C. Derksen, Agricultural Engineer, USDA/ARS, ATRU, Wooster, OH.

Charles R. Krause, Plant Pathologist, USDA/ARS, ATRU, Wooster, OH.

H. Erdal Ozkan, Professor, FABE, The Ohio State University, Columbus, OH.

Ross D. Brazee, Agricultural Engineer, USDA/ARS, ATRU, Wooster, OH.

Robert D. Fox, Agricultural Engineer, USDA/ARS, ATRU, Wooster, OH.

Karl Losely, President, Herman Losely & Sons, Inc., Perry, OH.

Written for presentation at the
2006 ASABE Annual International Meeting
Sponsored by ASABE
Oregon Convention Center
Portland, Oregon
9 - 12 July 2006

Mention any other presentations of this paper here, or delete this line.

Abstract. *New sprayers are needed to deliver droplets uniformly within dense nursery crops to obtain healthy and marketable plants in the nursery industry. An air-assist sprayer with five-port nozzles was developed and investigated to improve spray penetration into dense nursery canopies. Spray deposits at top, middle and bottom of canopies were characterized using fluorescence detection, and were compared at three nozzle heights in a commercial nursery field. Dynamic air velocities corresponding to the deposit sampling locations inside and outside the canopy were measured at the time when the sprayer passed over the canopies. Air jet velocity profiles from nozzle outlets to 0.79 m below the nozzles were determined experimentally and mathematically. The measured air jet velocity decreased from 40.1 to 19.4 m/s when the distance from the orifice increased from 0.33 to 0.79 m. The peak velocities at the top and middle elevations for both inside and outside the canopy decreased as the nozzle height above the ground increased, but the peak velocities at the bottom elevation for both situations were not significantly decreased as the nozzle height increased. The average period of time for dynamic air velocities higher than 1 m/s inside the canopy was 1.9 s at 2.5 cm, 3.8 s at 25 cm and 1.1 s at 46 cm. The mean spray deposit inside taxus canopies with leaf area index of 5.96 increased in an exponential function as the peak air velocity increased. The spray penetration capability and spray deposition uniformity inside taxus canopies were greatly improved with the five-port air assist sprayer.*

Keywords. *Dynamic air velocity, New sprayer, Nursery production, Pesticide, Spray deposition.*

The authors are solely responsible for the content of this technical presentation. The technical presentation does not necessarily reflect the official position of the American Society of Agricultural and Biological Engineers (ASABE), and its printing and distribution does not constitute an endorsement of views which may be expressed. Technical presentations are not subject to the formal peer review process by ASABE editorial committees; therefore, they are not to be presented as refereed publications. Citation of this work should state that it is from an ASABE meeting paper. EXAMPLE: Author's Last Name, Initials. 2006. Title of Presentation. ASABE Paper No. 06xxxx. St. Joseph, Mich.: ASABE. For information about securing permission to reprint or reproduce a technical presentation, please contact ASABE at rutter@asabe.org or 269-429-0300 (2950 Niles Road, St. Joseph, MI 49085-9659 USA).

Introduction

Due to the large number of species in nursery production, commercially available sprayers have limited capacity for treating specific nursery species. To control insects and diseases inside dense nursery canopies, existing spray techniques have used either excessive or inadequate pesticide delivery to target areas, resulting in increased cost and contamination of the environment. Sprayers commonly used for field crops are unable to deliver sufficient pesticide to the inner or lower dense nursery canopies where insects and diseases frequently attack. In many cases, high application rates are used to increase the amount of pesticide deposited inside dense canopies, but the spray deposits at the top of plants are saturated. Due to limitation of proper pesticide delivery systems for dense nursery crops, large amounts of pesticide are wasted or improperly applied. Growers are seeking new sprayers or customized delivery systems that can operate economically and effectively with minimum canopy damage and optimum pest control.

To be marketable, many nursery plants are required to have full canopy shapes from the top to the bottom near the ground. Therefore, applying pesticides in nursery crops requires extra care. Some research on spraying nursery stock has been conducted, but literature is limited on results of spray trials. Spray deposition within nursery crop canopies varied significantly with types of sprayers and plant species. Bache and Johnstone (1992) noted that more precise knowledge of fungicide coverage and plant canopy penetration is required to maximize effectiveness of chemical and biological crop management strategies. Krause et al. (2004) reported that spray deposition at different elevations in Honey Locust trees treated with a conventional axial fan sprayer had much less variation than in Canadian Hemlock trees treated with an over-the-row sprayer. Average spray deposit at the top of Canadian Hemlock tree canopies was 14 times higher than that at the middle and the bottom of canopies while about one third of the total spray passed through the first row of Honey Locust trees with the axial fan sprayer (Zhu et al., 1997). The tower sprayer with cross flow fans provided less variation in vertical spray distribution in tree canopies than the traditional air-assist, orchard sprayers (Derksen et al., 2004).

Air sprayers are used widely to apply pesticide to trees and dense field crop canopies. The air jet deflects foliage and delivers spray droplets through the canopy, assisting droplet impingement on target foliage. To maintain air jet integrity in wind conditions and transport droplets uniformly throughout the plant foliage, adequate air volume is required in the canopy region. However, the mass flow rate of the sprayer jet at its outlet greatly influences the jet velocity distribution at considerable distances from the outlet (Reichard et al., 1979; Fox et al., 1982). The amount of spray delivered over a given distance is proportional to the power of the air stream (Fleming, 1962). Brazee et al. (1981) developed air jet models and concluded that air jets from low-velocity, high-air-flow rate sprayers produced greater maximum velocities in the main region of the jets than higher-velocity, lower-air flow rate sprayers having equal air power at the outlet.

Mention of proprietary product or company is included for the reader's convenience and does not imply any endorsement or preferential treatment by either USDA/ARS or The Ohio State University.

Randall (1971) reported that a minimum air speed of 12.2 m/s was required for spray to penetrate beyond the outer canopy of apple trees.

Hydraulic nozzles, due to their simplicity, are widely used in the field applications for controls of weeds, insects and fungi, but the deposition uniformity inside short, dense canopies is very poor (Zhu et al., 2004b). Air-assist sprayers have potential to economically and effectively deliver pest control agents inside short, dense canopies without additional labor or machinery costs.

Zhu et al. (2004a) investigated a specially designed five-port air assisted sprayer to improve spray penetration into canopies of taxus, a very dense nursery crop. The hypothesis of the sprayer design was that spray penetration into dense nursery crops can be improved by dividing a conventional large diameter air jet to several small diameter air jets arranged in a flat-fan shape. Small air jets, due to high speed, can carry spray droplets deeper into dense canopies and at the same time the adjacent air jets will create eddies to spread droplets in surrounding areas within canopies. Due to their flat-fan pattern arrangement, small air jets can cover a much wider spray width than a conventional large diameter air jet. In contrast, using a conventional large diameter air jet may easily damage part of canopies directly beneath the single air jet outlet due to high air volume and speed. The previous study (Zhu et al., 2004a) indicated the five-port air-assist sprayer improved spray penetration into taxus canopies. This study continued the concept of dividing a large air jet to several small diameter air jets to form a flat-fan air pattern to increase spray penetration and spray width for dense nursery crops.

The objectives of this research were to: (1) further investigate the five-port, air-assist sprayer to improve spray penetration into short dense canopies by modifying nozzle design and changing nozzle heights; and (2) determine the relationship between spray deposits and air velocities at different levels within taxus canopies by changing the nozzle height above the top of canopy.

Materials and Methods

Five-port sprayer

A boom-type, high-clearance, over-the-row sprayer (Hagie Manufacturing Company, Clarion, IA) was modified to become an air assisted, high-clearance, over-the-row sprayer. The original boom-type hydraulic nozzles on the sprayer were converted to five-port, air assisted nozzles. A hydraulic-driven centrifugal fan with 0.56-m diameter housing was mounted at 0.6 m above a trapezoid shape air distributor to deliver air to the five-port air assisted nozzles. The nominal fan speed was 9000 RPM. The centrifugal fan provided a high volume of air flow and high air pressure. The trapezoid shape air distributor served as a manifold between the fan and three five-port nozzles. Each nozzle was connected to the trapezoid air distributor with a 10-cm diameter pipe. The three five-port nozzles were mounted 0.61 m apart under the trapezoid distributor to direct fan pattern sprays covering a 1.82 m wide row of plants during spray application. The centrifugal fan, trapezoid shape air distributor, and three five-port nozzles were mounted on a metal frame to form a spray application system. A hydraulic motor was used to drive the metal frame to adjust the nozzle height. The pump and controller delivering liquid to nozzles was the same as used for boom-type nozzles. The fan had high and low speed control with a hydraulic power switch. All controller switches were set inside the driver cab with the spray application system mounted in front of the cab.

The five-port nozzle consisted of a five-port air manifold (Montana Industrials, Dal Negro, Brazil), distributed by Pickin' Patch Inc. (Plymouth, IN), and five liquid dischargers. The internal geometric construction of the five-port air manifold is shown in Figure 1. The manifold was cast with five ports at 15° radial separation, each with an inside diameter of 3.6 cm.

The liquid discharger was a modified flat fan nozzle tip and was mounted at the centerline of each port of the five-port air manifold. The nozzle tip orifice was in the same plane as the port outlet. In the previous study (Zhu et al., 2004a), the liquid discharger at the center of each air port was 0.60-cm diameter copper tubing with a flattened outlet as its orifice. A precision orifice controlled total flow to the manifold that distributed liquid to each port. The design with the flattened-tubing orifice was simple but resulted in large variations in the spray pattern under each five-port nozzle. Liquid flow rate from individual ports was nonuniform, and the main spray stream from each port was not wide enough to cover the target unless the nozzle height was sufficient. Increasing the nozzle height caused air velocity loss within the canopy and also increased drift potential.

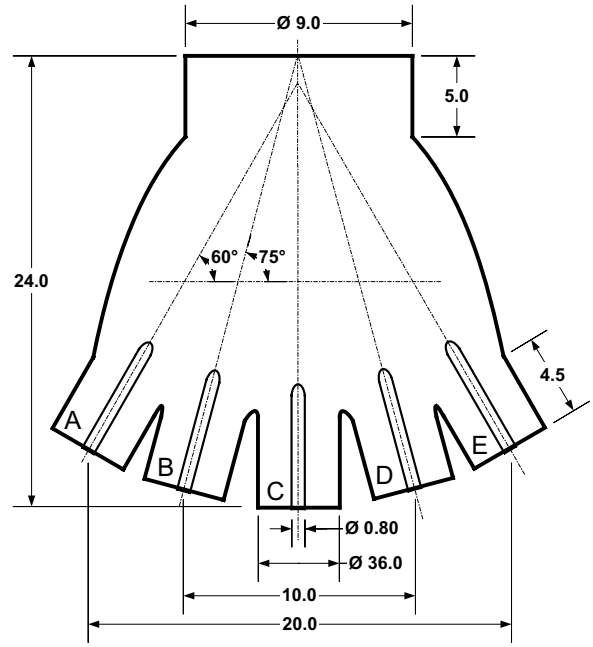

Figure 1. Internal structure of a five-port air manifold with dimensions in centimeters.

In this study, the flattened tubing discharger was replaced with a modified flat fan nozzle tip to improve the accuracy of flow rate control and increase spray uniformity across the spray pattern width. The nozzle tip was modified from a brass tip, a part of a TeeJet 11003VB flat fan nozzle (Spraying Systems, Wheaton, IL) by reducing the exterior surface of the brass tip without changing internal structures (Fig. 2). The modified nozzle tip was1.40 cm long and 1.42 cm outside diameter. A 0.635-cm diameter and 9.5-cm long copper tube was bent to a 45° angle to connect the nozzle tip to the outer casting body of the five-port air manifold. The tubing was soldered to the modified nozzle tip with their centerlines aligned. With the modified liquid dischargers, liquid flow rates were discharged equally from the five ports, and the spray pattern across 60 cm width became uniform 15 cm below the five-port nozzle.

Figure 2. A modified liquid discharger for a five-port nozzle.

Field test

Taxus (*L.C. Bobbink*), a common dense nursery crop, was selected for evaluation of canopy penetration capability of the sprayer. At the time of the experiment, average plant height was 50 cm, average circumference was 196 cm, and edges of adjacent plants nearly overlapped. Spray deposits at three heights inside taxus canopies and three nozzle heights above the ground were evaluated with the air assisted sprayer equipped with three five-port nozzles (Fig. 3) in two trials. The three heights inside canopies were 2.5, 25 and 46 cm above the ground, representing target positions at the bottom, middle and top of the canopy, respectively. The three nozzle heights were 60, 70 and 80 cm from the orifice at the center port of each nozzle to the ground, or 12, 22, and 32 cm above the top of canopies, respectively. The three five-port nozzles directed fan pattern sprays downward toward three rows of taxus plants (Fig. 3). The center port of each five-port nozzle was directly above the midline of each canopy row in a 1.8 m wide and 76 m long test plot.

A plot with three rows of taxus canopies was divided into 9 sections to test the spray penetration with the three nozzle heights. The sprayer was operated at 140 kPa and 4.8 km/h travel speed from north to south. The total flow rate from each five-port nozzle at 140 kPa was 4.47 L/min, producing 900 L/ha application rate for each test. A spray mixture containing water and Brilliant Sulfaflavine (MP Biomedicals, Inc., Aurora, OH) at a concentration of 2 g/L was used for the two trials.

Figure 3. Spray penetration test in a nursery crop, taxus field with an air assist sprayer containing three 5-port nozzles.

During the tests, the average wind velocity was 2.4 m/s for Trial 1 on a sunny day and 1.1 m/s for Trial 2 on a cloudy day. Wind direction was from south to north in both trials. In Trial 1, the ambient temperature was 18 °C and relative humidity was 39%. In Trial 2, the ambient temperature was 16 °C and relative humidity was 83%.

One canopy in each row of a section, a total of three canopies in each section, was randomly selected to locate artificial targets for collection of spray deposits. The targets were 2.5 cm by 7.5 cm sheet-metal plates placed at the top (46 cm), middle (25 cm) and bottom (2.5 cm) of each canopy. Plates were mounted horizontally with their longer dimension normal to the stake and with 120° radial separation from each other. The midpoint of each plate was 11 cm from the stake. The stake was placed as near to the plant trunk as possible. The plates were collected 15 minutes after spraying and stored in 125-ml wide-mouth glass bottles in non-transparent boxes. These samples were stored in a refrigerator and analyzed within 24 hours.

Spray deposits on sample plates were washed and dissolved in 20 ml of purified water (prepared with Mega-pure System, Model MP-12A, Barnstead International, Dubuque, IW). Then, a 4 ml sample solution was placed in a cuvette for determination of peak fluorescent intensity with a Model LS 50B Luminescence Spectrometer (Perkin-

Elmer Limited, Beaconsfield, Buckinghamshire, England) at an excitation wavelength of 460 nm. If a sample concentration fell outside the calibration range, it was further diluted and measured again. Data were analyzed by one way ANOVA and differences among means were determined with Duncan's New Multiple-Range Test using the ProStat version 3.8 (Poly Software International, Inc., Pearl River, NY). All significant differences were determined at the 0.05 level of significance.

Static air jet velocity modeling and measurement

Since each air jet was discharged from a circular port, air velocity at the midline of an axially symmetric jet could be expressed from the theory of turbulent jets (Abramovich, 1963) as

$$u_m(x) = u_0 \cdot \Delta u_m(x) \tag{1}$$

where

$$\Delta u_m(x) = \begin{cases} 1, & x \le x_t \\ F(x), & x > x_t \end{cases} \tag{2}$$

$$F(x) = \frac{r_0 \cdot \Phi(\zeta)}{c_m \cdot (x - x_0)} \sqrt{\frac{n_2 - n_1 \cdot m}{A_1 \cdot (1-m)^2}} \tag{3}$$

and

$$\Phi(\zeta) = \frac{[4 + (\frac{3}{\alpha}) + 2 \cdot \zeta] \cdot (1 + \sqrt{1+\zeta}) + 8}{\frac{3}{\sqrt{\alpha}} \cdot \sqrt{1+\zeta} \cdot (1 + \sqrt{1+\zeta})} \tag{4}$$

The effective jet velocity transition length x_t was defined approximately by the equation,

$$x_t = x_0 + \frac{r_0 \cdot \Phi(\zeta)}{c_m} \sqrt{\frac{n_2 - n_1 \cdot m}{A_1 \cdot (1-m)^2}} \tag{5}$$

The parameters in Eqs. (3) and (5) are:
u_0, mean air velocity at the jet outlet;
u_h, effective ambient air velocity outside the jet, 12 m/s;
$m = u_h/u_0$, 0.142;
r_0, jet outlet diameter, 0.01905 m; and
x_0, apparent main region origin relative to jet outlet (usually near zero for an axial jet), -0.1 m.
Other parameters are:
$\alpha = A_2/A_1$, 0.519;
$\zeta = \mu/\alpha$, $\mu = m/(1-m)$, 0.319;
$n_1 = 0.5$;
$n_2 = 0.2$;
c_m = main region empirical jet coefficient, 0.22;
$A_1 = 0.258$; and
$A_2 = 0.134$.

The parameters n_1 and n_2 are integrated measures of velocity non-uniformity and other fluid conditions at the jet outlet. The values for A_1 and A_2 account for the cross-

sectional velocity profile in the main region of the jet. Thus, the simplified numerical air jet velocity relations were,

$$u_m(x) = \begin{cases} u_0, & x \le 0.11 \\ \dfrac{0.211 \cdot u_0}{x + 0.1}, & x > 0.11 \end{cases} \tag{6}$$

To verify the accuracy of the air jet velocity modeling expressed by equation (6), static air velocity profiles at 40 points at locations from the five-port nozzle outlets to 0.79 m below the middle port were measured inside a building. To determine the variation of air velocity from the three five-port nozzle system, air velocity at outlets of all three nozzles were measured. Points having air velocities over 45 m/s were measured with a No.167 pitot tube (Dwyer Instruments, Inc., Michigan City, IN). Points having air velocities below 45 m/s were measured with a Model 8386A Air Velocity Meter (TSI Incorporated, St. Paul, MN). The sprayer was mounted over a concrete floor at a height of the nozzle orifice 0.9 m above the floor. The fan was operated at 9000 rpm. The measured air velocities were converted to standard conditions, defined as 21.1°C and 101.4 kPa at 0% relative humidity.

Field dynamic air velocity measurement

To correlate canopy spray deposits to air speed, dynamic air jet velocities were measured at three heights (2.5, 25, and 46 cm above the ground) inside a taxus canopy when the five-port air assisted sprayer was passing over the canopy at the 4.8 km/hr speed with three nozzle heights (60, 70 and 80 cm) above the ground. Three air velocity probes located at the three elevations inside the canopy were Model 1210-60, 0.15-mm cylindrical, hot-film, constant temperature anemometer (CTA) sensors (TSI Incorporated, St. Paul, MN) controlled by a Model 1050B anemometer (TSI Incorporated, St. Paul, MN). Each CTA sensor was enclosed in a screen guard to protect it from damage by moving foliage. Output signals from the anemometer were recorded with a 14-channel, Model 3500, magnetic tape recorder (Sangamo Electric Company, Springfield, IL). The CTA sensors at three elevations inside a taxus canopy were positioned at different distances from the canopy main stem in the plant row centerline so they would not interfere with each other. The sensors were calibrated with a Model 1125 calibrator (TSI Inc., Shoreview, MN). After air-velocity signals were recorded on a magnetic tape in the field, a Keithley Model KPCI-3108 data acquisition board (Keithley Instruments, Inc. Cleveland, OH) was used in the laboratory to convert analog velocity signals from the magnetic tape to digital format, acquired and stored at a rate of 2,000 samples per second.

In order to compare air velocities at three levels inside the canopy, velocities at the same levels were measured outside the canopy with the three CTA sensors as the sprayer passed over the sensors for each of the three nozzle heights used.

Air velocity measurement for every condition was repeated five times. During measurement in the field, the average wind velocity was 2.2 m/s from south direction, the ambient temperature was 14 °C, and relative humidity was 85%.

Because dynamic air jet velocity data were acquired at a rate of 2000 per second and was repeated five times for every condition in the field, it was impossible to have

identical air velocity profiles for the five replications. A method was devised to obtain an averaged air-velocity transient (pulse) for the five air velocity profiles inside and outside the taxus canopy as the sprayer passed over the CTA sensors.

A total of $\boldsymbol{K}$ sets of air velocity samples (vectors) were taken with $\boldsymbol{W_{j,k}}$, $\boldsymbol{j}$=0, 1, …, $\boldsymbol{J}$, and $\boldsymbol{k}$=0, 1, …, $\boldsymbol{K}$. Since velocity observations $\boldsymbol{W_{j,k}}$ were taken at time intervals $\boldsymbol{\Delta t}$ = 0.0005 s, the Nyquist frequency, $\boldsymbol{f_n}$, with

$$f_n = \frac{1}{2(\Delta t)} \tag{7}$$

was 1000 Hz, a value sufficient to assure $\boldsymbol{f_n}$ enclosed the frequency bandwidth of the velocity samples.

The first step in analysis of the samples was to compute a set of smoothed average velocity vectors using the "supsmooth" routine available with Mathcad® (Mathsoft Engineering & Education, Inc., Cambridge, MA),

$$S_{j,k} = smoothed(W_{j,k})$$

The next step was to shift the smoothed velocity pulses so the peaks, max($\boldsymbol{S_{j,k}}$), for each $\boldsymbol{k}$ were coincident. This was done by determining the smallest index, min($\boldsymbol{j_{max}}$), $\boldsymbol{k}$ for the max($\boldsymbol{S_{j,k}}$) of each of the $\boldsymbol{k}$ vectors, giving new indices,

$$i = j - \min(j_{\max}), k \tag{8}$$

which yielded a new set of smoothed velocity transients for which the peak velocities were coincident,

$$V_{i,k} = S_{j-\min(j\max),k} \tag{9}$$

It was then possible to obtain an average velocity pulse

$$U_i = \frac{1}{k}\sum_k V_{i,k} \tag{10}$$

At this point samples could be truncated, so that

$$i = 0,1,2,...N \tag{11}$$

where N must be a power of 2 to enable later transformation to the frequency domain by the Fast Fourier Transform (FFT).

The vectors for fluctuating velocities were calculated as

$$w_{i,k} = W_{i,k} - S_{i,k} \tag{12}$$

The frequency spectrum for the $\boldsymbol{k}$ velocity vectors was calculated as

$$f_{q,k} = FFT(w_{i,k}), \qquad q = 0,1,...\frac{N}{2} \tag{13}$$

An average spectrum was then calculated as

$$F_q = \frac{1}{K}\sum_k f_{q,k} \tag{14}$$

By inverse FFT(IFFT), a resultant vector of fluctuating velocity was then

$$u_i = IFFT(f_{q,k}), \qquad i = 0,1,...N \tag{15}$$

The resultant total velocity was

$$V_{T,i} = U_i + u_i \tag{16}$$

In this study, K=5, Δt=1/2000 or 0.0005 s, and J=13896.

Leaf Area Index measurement

Following the measurement of dynamic air velocities inside the canopy, leaf area index (LAI) of three taxus canopies were measured using an LAI-2000 plant canopy analyzer (LI-COR®, Inc., Lincoln, Nebraska) with two sensor modes. The instrument recorded the attenuation of diffuse sky radiation at five angles simultaneously as it passed through the canopy and gave an estimate of the foliage amount in that canopy per unit ground area. A dimensionless unit was used for leaf area index, which was m^2 foliage area/m^2 ground area. Three canopies were randomly selected from those used in the spray deposition tests. Before the measurement, about 10 cm of soil and debris were removed from beneath each canopy for the convenience of positioning the lower optical sensor close to the bottom of the canopy. The upper sensor was set about 1.2 m above the ground. Both sensors were leveled. For each canopy, eight measurements of LAI at eight orientations in an octagon shape were conducted. The sky was fully covered by clouds at the moment of measurement. The LAI sensor was also calibrated under fully-cloudy conditions.

Results and Discussion

Static air jet velocity from nozzle port

The average axial air jet velocity near the outlets of five ports was 81.8 m/s for the middle five-port nozzle, and 74.3 m/s for both left and right side nozzles under the trapezoid air distributor (Fig.4). The average outlet velocity from the middle nozzle was about 9% higher than that from the two adjacent nozzles. Unequal air paths from the distributor to the three nozzles might cause the variation in mean velocities from the three five-port nozzles. The middle nozzle was closer to the manifold than the two side nozzles. However, the variation of the exit air velocity of the five ports on each individual five-port nozzle was very low. For example, the standard deviation of the outlet velocity from five ports on left, middle and right five-port nozzles was 3.6, 5.1, and 3.5 m/s, respectively. Therefore, the sprayer produced reasonably uniform air output from each of three nozzles.

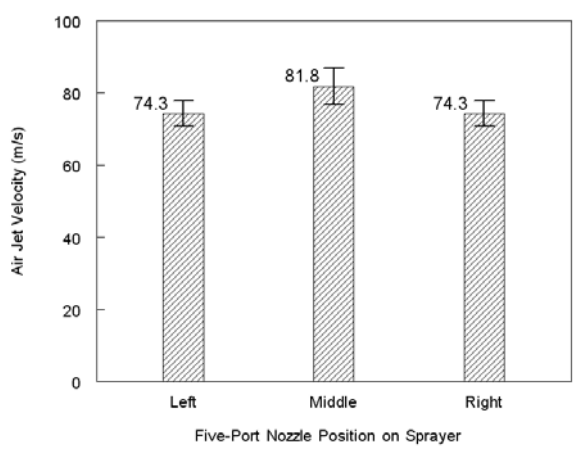

Figure 4. Average air jet velocity near outlets of five ports for three nozzles, 0.61 m apart, located at left, middle and right side in front of the sprayer. Error bars represent standard deviations of means.

Air velocities across the fan pattern at the same distance from the nozzle outlets were not consistent because the five air jets were separately discharged from five ports on each nozzle

(Fig. 5). For example, the average midline air velocity from the five ports of the nozzle was 40.9 m/s at 0.33 m downstream from the nozzle while the average velocity across the fan pattern at 0.33 m distance was 33.4 m/s. The difference between the two average velocities decreased as the downstream distance from the nozzle increased. For example, the difference between the two average velocities was about 1.9 m/s at 0.56 m from the nozzle, and was 0.7 m/s at 0.79 m from the nozzle. Air velocities across the level at 0.79 m from the nozzle were nearly constant. Therefore, variations of air velocities across the same level above the ground decreased as distance from the nozzle increased.

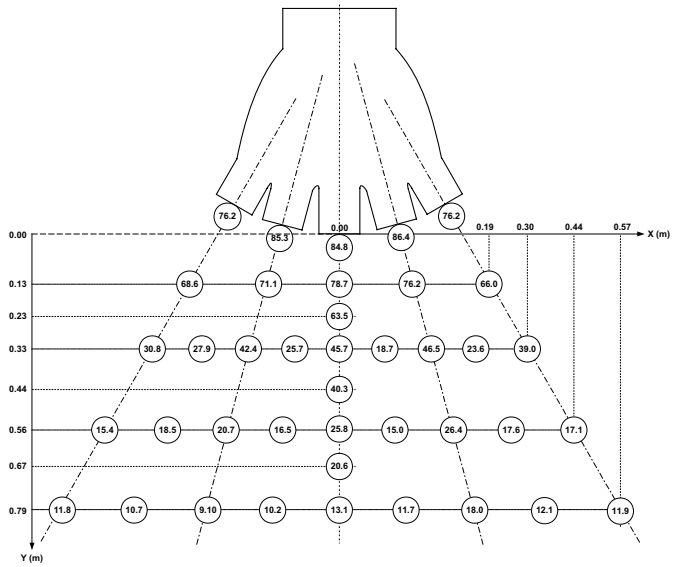

Figure 5. Axial air velocities at positions below the five outlets of the five-port nozzle. Values in circles are air velocities in m/s.

Figure 6 shows the comparison of experimentally determined axial air velocities at various distances from the nozzle orifice with values predicted by Eq. (6) with an assumption of $\boldsymbol{u_0}$ = 81.8 m/s which was the average of outlet velocities from the five ports of the middle nozzle under the trapezoid air distributor. The calculated air jet velocity from Eq. (6) agreed very well with the measured velocity. The slope of the linear regression equation for the calculated and measured velocities was 1.08 with r^2 = 0.98. An equilateral hyperbola relationship was used to represent the midline air velocity in the jet main region as a function of distance from the nozzle orifice. The air jet velocity decreased as the distance from nozzle outlets increased due to jet entrainment, divergence and turbulent dissipation. For example, the air velocity decreased from 40.1 to 19.4 m/s (or 51.3%) when the distance from the orifice increased from 0.33 to 0.79 m. In field conditions, the air velocity profiles differed from that measured under indoor conditions, as discussed in the following section.

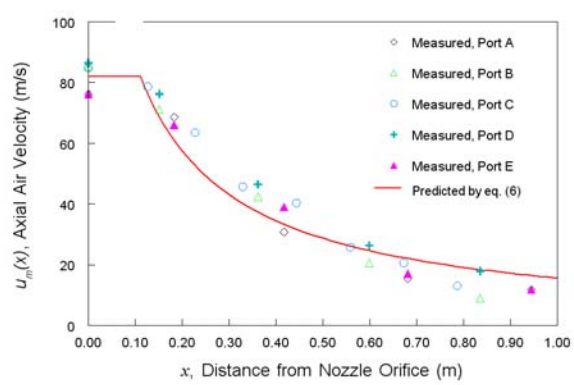

Figure 6. Comparison of measured axial air velocity at different distances from the five outlets of the five-port nozzle with predicted velocity.

Dynamic air velocity profile inside and outside the taxus canopy

Instantaneous air velocity profiles inside the taxus canopy (Fig. 7) and outside the canopy (Fig. 8) at heights of 2.5, 25, and 46 cm above the ground appeared as pulse transients when spray nozzles mounted 70 cm above the ground passed over the sensors at a travel speed of 4.8 km/hr. Duration of velocity transients inside the canopy was shorter than outside the canopy.

Calculated with equation (10), data in Table 1 shows average peak air velocities inside and outside the canopy at heights of 2.5, 25, and 46 cm above the ground when spray nozzles mounted at 70 and 80 cm above the ground passed over the sensors at 6.4 km/hr. The average peak velocities at three heights inside the canopy were considerably lower than the velocities at the same heights outside the canopy for all three nozzle heights. The peak velocities at the top and middle elevations for both inside and outside the canopy decreased as the nozzle height above the ground increased. However, the peak velocities at the bottom elevation for both situations did not drastically decrease as the nozzle height increased. Due to interception of airflow by dense canopies, rates of decrease in peak velocities from 46 cm to 25 cm and 2.5-cm elevations inside the canopy were considerably higher than outside the canopy. When the nozzle height was 60 cm above the ground, the peak air velocities inside the canopy decreased 4.9 times from 46 cm to 2.5 cm elevation and 1.8 times from 46 cm to 25 cm elevation. For the same

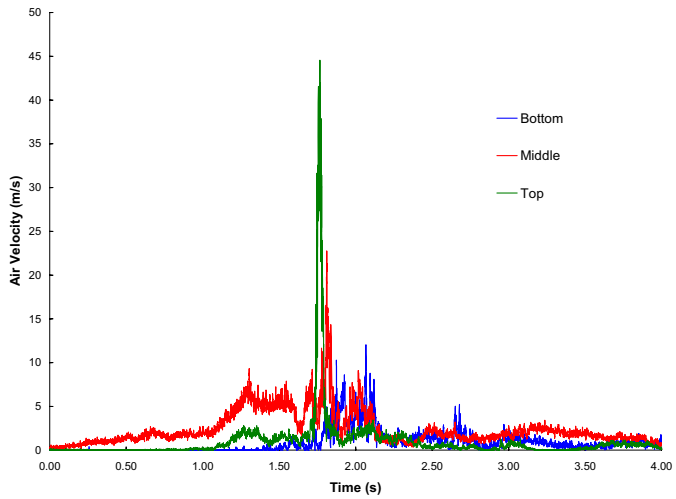

Figure 7. Real-time instantaneous air velocity profiles at the top, middle and bottom of a taxus canopy when the sprayer with the nozzle height 25 cm above the canopy passed over the canopy at 6.4 km/h.

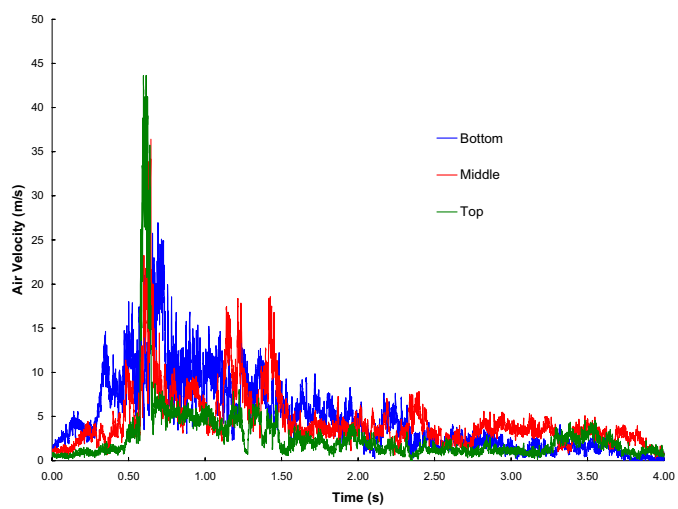

Figure 8. Real-time instantaneous air velocity profiles at three different heights outside the canopy when the sprayer with the nozzle height 25 cm above the canopy passed over the CTA anemometer sensors at 6.4 km/h.

conditions, the peak air velocities outside the canopy decreased 2.1 and 1.2 times, respectively. The average peak air velocity at the bottom of canopy was 9.3 m/s for the three nozzle heights when the air jet velocity near the port outlets was 81.8 m/s. The velocity decreased 8.8 times from the nozzle outlet to the bottom of canopy. Taxus canopies acted as a porous filter function in degrading air velocity.

The taxus plant has one of the densest canopies in nursery production. The average leaf area index of the taxus canopies during the test was 5.93. With the value of leaf area index, the ratio of air velocities between heights of 46 cm and 2.5 cm inside the canopy was 5, 4.3 and 4.6 for the nozzle height of 60, 70, and 80 cm, respectively. The average peak air velocity at 2.5 cm outside the canopy for the three nozzle heights was three times the velocity at the same height inside the canopy. Therefore, the peak air velocity at the bottom of the canopy was reduced three times due to the interception of dense canopies with the leaf area index of 5.93.

Data in Table 2 shows the period of time that air velocity at three heights inside and outside the canopy was higher than 1 m/s when the sprayer passed over sensors using three different nozzle heights. Equation (16) was used to average velocity profiles from five replications to determine the time period for each treatment. At the three nozzle heights, the average time period for air velocities higher than 1 m/s inside the canopy was 1.9 s at 2.5 cm, 3.8 s at 25 cm, and 1.1 s at 46 cm, respectively. With the same conditions, the average period of time outside the canopy was 3.6 s at 2.5 cm, 4.6 s at 25 cm and 2.9 s at 46 cm, respectively. The airflow inside the canopy degraded faster than that outside the canopy.

Spray deposition

In the two trials, spray deposits at the top of canopies were not significantly different for three nozzles on the sprayer, and also were not significantly different in most cases for three nozzle heights with two trials (Table 3). This result was true for spray deposits at both middle and bottom of canopies (Tables 4 and 5). Therefore, the three five-port nozzles could deliver equal amounts of spray deposit into canopies although there was about 6% variation in air jet velocities near the three-nozzle outlets (Fig. 9). Data in Figure 8 illustrated

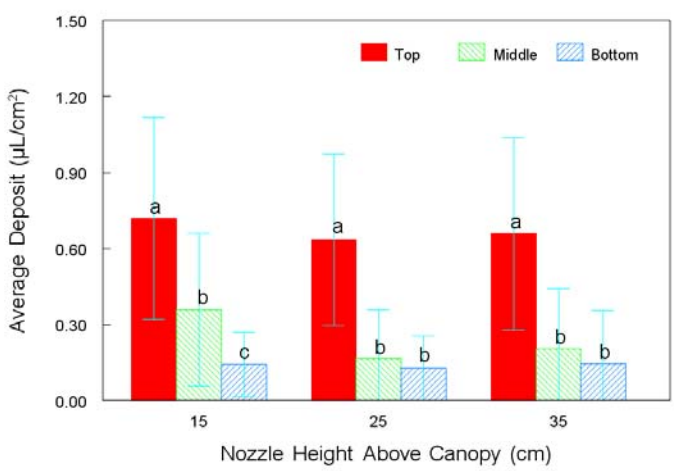

Figure 9. Average spray deposits at the top, middle and bottom of taxus canopies with three different nozzle heights above the ground. Letters a, b, c in bars represent significant difference ($p<0.05$) among spray deposits at three heights inside canopies with the same nozzle height. Error bars represent standard deviations of means.

average spray deposits at 2.5, 25 and 46 cm inside canopies were 0.143, 0.358 and 0.718 μL/cm^2 for the nozzle height of 12 cm above the canopy; 0.127, 0.165, and 0.635 μL/cm^2 for the nozzle height of 22 cm above the canopy; and 0.146, 0.206, and 0.659 μL/cm^2 for the nozzle height of 32 cm above the canopy, respectively. For the three nozzle heights, the top of canopies received 2.8 and 4.8 times greater average spray deposits over the middle and bottom of canopies, respectively. For a boom sprayer with conventional hydraulic flat fan nozzles, spray deposits on the top of peanut canopies were 10.5 times higher than at the middle position and 62 times higher than at the bottom positions (Zhu et al., 2002). Therefore, spray penetration capability and spray deposition uniformity inside taxus canopies were greatly improved with the five-port air assist sprayer.

There was no significant difference in deposits at the middle of canopies between heights of 22 and 32 cm, but the deposit at the middle of canopies with the nozzle height of 12 cm was significantly higher than that at the other two nozzle heights (Fig. 9). The change in nozzle height above canopies from 22 cm to 32 cm did not produce significant difference in spray deposition at the bottom of taxus canopies with the five-port air assisted sprayer.

For water droplets, the critical relative velocity at which the droplet will continue to breakup is given by the equation (Lefebvre, 1989),

$$U_R = \frac{784}{\sqrt{D}} \qquad (17)$$

where U_R is the critical relative velocity in m/s and D is droplet diameter in micrometers. The average exit air velocity from the three five-port nozzles was 76.8 m/s. From Equation (17), the critical droplet diameter from the sprayer would be approximately 104 μm or smaller. The average spray deposit at the bottom of canopies at a nozzle height of 22 cm above the canopy was 0.127 μL/cm^2, which was equivalent to the volume of 216 droplets with 104-μm diameter in a square centimeter. Therefore, a sufficient number of droplets was delivered to the bottom of taxus canopies for the nozzle heights between 12 and 32 cm above canopies with the five-port sprayer at 900 L/ha application rate.

Almost equal peak air velocities at the bottom of canopies were obtained for the three nozzle heights, which corresponds to nearly equal spray deposits at the bottom of canopies for the three nozzle heights

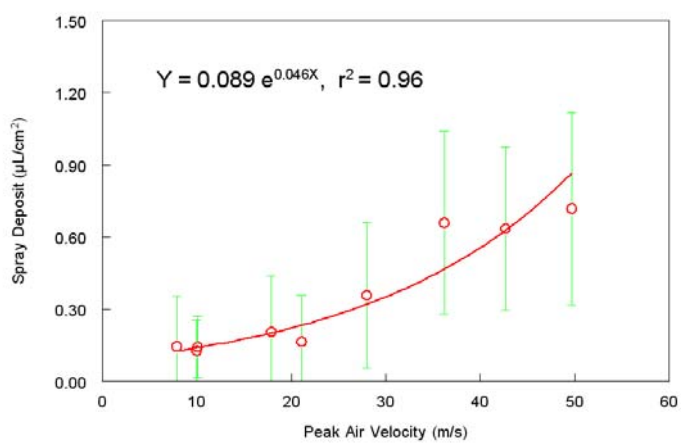

Figure 10. Effect of average peak air velocity inside the canopy on spray deposition within canopies. Error bars represent standard deviations of means.

evaluated. There was good correlation between peak air velocity and average deposits inside taxus canopies (Fig. 10). For the leaf area index of 5.93, the mean spray deposit inside taxus canopies increased as the peak air velocity increased in an exponential function with a coefficient of determination of 0.96. Strong air jets with a fan-pattern curtain from the five-port nozzle assisted in disturbing dense canopies and assisted droplets in reaching the bottom of the taxus canopy.

Conclusions

1. The specially designed five-port air assist sprayer had great spray penetration capability and spray deposition uniformity inside taxus canopies. The average spray deposit at the bottom of canopies with nozzle height of 22 cm above the canopy was 0.127 $\mu L/cm^2$ that was equivalent to the volume of 216 droplets having 104 μm diameters.
2. Decreasing the nozzle height from 32 to 12 cm above the top of taxus canopies did not increase spray deposits and peak dynamic air velocities at the bottom of taxus canopies for the five-port air assist sprayer. However, decreasing nozzle height above the top of canopies from 22 to 12 cm significantly influenced the amount of spray deposits at the middle of canopies.
3. The axial air velocity model (Equation (6)) agreed well with experimental values; decreasing as an equilateral hyperbolic relationship with distance from jet outlet.
4. There was good correlation between the amount of spray deposits and peak air velocity inside the canopy. Spray deposits inside taxus canopies increased exponentially as the peak air velocity at the deposition sampling location increased.
5. For taxus canopies with the leaf area index of 5.93, the peak air velocity at the bottom of the canopy was reduced three times compared to the velocity at the same location outside canopies.

Acknowledgements

Technical assistance was provided by K. Williams, D. Troyer, A. Doklovic, B. Nudd, H. Guler, L. Morris and L. Horst. The authors acknowledge helpful discussions and editorial suggestions by Dr. Loren E. Bode of the University of Illinois.

References

Abramovich, G.N. 1963. The theory of turbulent jets. The M.I.T. Press, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Bache, D.H. and D.R. Johnstone. 1992. *Microclimate and spray dispersion*. Ellis Horwood, New York, 239 pp.

Brazee, R.D., R.D. Fox, D.L. Reichard, F.R. Hall. 1981. Turbulent jet theory applied to air sprayers. *Transactions of ASAE.* 24(2): 266-272.

Derksen, R.C., C.R. Krause, R.D. Fox, R.D. Brazee, and R. Zondag. 2004. Spray delivery to nursery trees by air curtain and axial fan orchard sprayers. *Journal of Environmental Horticulture.* 22(1): 17-22.

Fleming, G.A. 1962. The relationship of air volume, air velocity and droplet size to the efficiency of spray transport in airblast spraying. Cornell University, Ph.D. Thesis (University Microfilm Cat. No. 6202451). 66pp.

Fox, R.D., R.D. Brazee, D.L. Reichard, F.R. Hall. 1982. Power in an air sprayer jet. *Transactions of ASAE.* 25(5): 1181-1184, 1188.

Krause, C.R., H. Zhu, R.D. Fox, R.D. Brazee and R.C. Derksen, L.E. Horst, R.H. Zondag. 2004. Detection and quantification of nursery spray penetration and off-target loss with electron beam and conductivity analysis. *Transactions of ASAE.* 47(2): 375-384.

Lefebvre, A.H. 1989. Atomization and Sprays. Hemisphere Publishing Corporation. New York, NY.

Randall, J.M. 1971. The relationship between air volume and pressure on spray distribution on fruit trees. *Journal of Agricultural Research.* 16(1):1-31.

Reichard, D.L., R.D. Fox, and R.D. Brazee. 1979. Air velocities delivered by orchard air sprayers. *Transactions of ASAE.* 22(1): 69-74, 80.

Zhu, H., R.C. Derksen, C. R. Krause, R.D. Brazee, R.D. Fox, H.E. Ozkan. 2004a. Spray deposition in taxus and air velocity profile for a five-port, air-assist sprayer. *ASAE Paper No. 041032.* ASAE, St. Joseph, MI.

Zhu, H., J.W. Dorner, D. L. Rowland, R.C. Derksen, and H. E. Ozkan. 2004b. Spray penetration into peanut canopies with hydraulic nozzle tips. *Biosystems Engineering* 87(3): 275-283.

Zhu, H., C.R. Krause, R.D. Fox, R.D. Brazee and R.C. Derksen. 1997. Techniques for assessing spray drift and canopy penetration in nurseries. *ASAE Paper No. 975006.* ASAE, St. Joseph, MI.

Zhu, H., D. L. Rowland, J.W. Dorner, R.C. Derksen, and R.B. Sorensen. 2002. Influence of plant structure, orifice size and nozzle inclination on spray penetration into peanut canopy. *Transactions of the ASAE* 45(5): 1295-1301.

Table 1. Average peak air velocities calculated from equation (10) at three different heights inside and outside the canopy when the sprayer passed over sensors with three different nozzle heights above the canopy. Standard deviations are given in parentheses.

Nozzle Height (m)	Sensor height (cm)	Air velocity (m/s)		
		Outside canopy	Inside canopy	Ratio
15	2.5	30.6 (6.8)	10.1 (2.8)	3.0
25	2.5	27.8 (4.2)	10.0 (1.9)	2.8
35	2.5	26.6 (2.3)	7.9 (1.1)	3.4
15	25	56.1 (8.1)	28.0 (11.6)	2.0
25	25	48.3 (8.0)	21.1 (2.6)	2.3
35	25	42.6 (11.0)	17.9 (3.9)	2.4
15	46	65.7 (6.2)	49.7 (11.7)	1.3
25	46	53.8 (12.5)	42.7 (4.3)	1.3
35	46	50.9 (5.5)	36.2 (8.1)	1.4

Table 2. Period of time that air velocities at three different levels within a canopy was higher than 1 m/s when the sprayer was passing over the canopy at three different nozzle heights above the canopy.

Nozzle height (cm)	Sensor height (cm)	Period of time (s)	
		Outside canopy	Inside canopy
15	2.5	3.61	1.56
25	2.5	3.87	2.57
35	2.5	3.47	1.65
15	25	3.88	3.81
25	25	5.31	3.82
35	25	4.76	3.80
15	46	2.57	0.69
25	46	3.50	1.65
35	46	2.59	1.01

Table 3. Mean spray deposits at the top of taxus canopies (46 cm height inside canopies) with three five-port nozzles in two trails when nozzle discharge height above the top of canopies was 15, 25 and 35 cm, respectively. Standard deviations are given in parentheses.

Trial No.	Nozzle on sprayer	Mean Spray Deposit ($\mu L/cm^2$)		
		15 cm	25 cm	35 cm
1	Left	0.78 (0.32)aA[a]	0.92 (0.45) aA	0.20 (0.30) aA
1	Middle	0.89 (0.55) aA	0.47 (0.47) aA	0.56 (0.14) aA
1	Right	0.79 (0.71) aA	0.63 (0.22) aA	0.71 (0.41) aA
2	Left	0.58 (0.50) aA	0.86 (0.42) aA	0.63 (0.44) aA
2	Middle	0.56 (0.24) aA	0.42 (0.04) aA	0.88 (0.42) aA
2	Right	0.70 (0.14) aAB	0.51 (0.07) aA	0.97 (0.19) aB

[a] Means in a row followed by different uppercase letters are significantly different ($p<0.05$). Means in a column followed by different lowercase letters are significantly different ($p<0.05$).

Table 4. Mean spray deposits at the middle of taxus canopies (25 cm height inside canopies) with three five-port nozzles in two trails when nozzle discharge height above the top of canopies was 15, 25 and 35 cm, respectively. Standard deviations are given in parentheses.

Trial No.	Nozzle No.	Mean Spray Deposit ($\mu L/cm^2$)		
		15 cm	25 cm	35 cm
1	Left	0.58 (0.61) aA[a]	0.09 (0.08) aA	0.26 (0.33) aA
1	Middle	0.22 (0.12) aA	0.20 (0.20) aA	0.26 (0.14) aA
1	Right	0.65 (0.16) aA	0.24 (0.17) aB	0.16 (0.07) aB
2	Left	0.21 (0.16) aA	0.03 (0.02) aA	0.07 (0.05) aA
2	Middle	0.17 (0.11) aA	0.16 (0.12) aA	0.14 (0.11) aA
2	Right	0.33 (0.10) aA	0.27 (0.40) aA	0.35 (0.48) aA

[a] Means in a row followed by different uppercase letters are significantly different ($p<0.05$). Means in a column followed by different lowercase letters are significantly different ($p<0.05$).

Table 5. Mean spray deposits at the bottom of taxus canopies (2.5 cm height inside canopies) with three five-port nozzles in two trails when nozzle discharge height above the top of canopies was 15, 25 and 35 cm, respectively. Standard deviations are given in parentheses.

Trial No.	Nozzle No.	Mean Spray Deposit ($\mu L/cm^2$)		
		15 cm	25 cm	35 cm
1	1	0.17 (0.15) aA[a]	0.23 (0.18) aA	0.30 (0.26) aA
1	2	0.19 (0.13) aA	0.26 (0.14) aA	0.21 (0.22) aA
1	3	0.22 (0.21) aA	0.07 (0.08) abA	0.01 (0.00) aA
2	1	0.08 (0.03) aA	0.08 (0.05) abA	0.09 (0.10) aA
2	2	0.05 (0.03) aA	0.10 (0.07) abA	0.24 (0.36) aA
2	3	0.15 (0.15) aA	0.02 (0.01) bA	0.02 (0.01) aA

[a] Means in a row followed by different uppercase letters are significantly different ($p<0.05$). Means in a column followed by different lowercase letters are significantly different ($p<0.05$).