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Distribution Pattern Variability of Granular VRT Applicators

John P. Fulton
Auburn University

Scott A. Shearer
University of Kentucky

Stephen F. Higgins
University of Kentucky, shiggins@bae.uky.edu

Dennis Wayne Hancock
University of Kentucky, hancock.dennis@gmail.com

Timothy S. Stombaugh
University of Kentucky, tim.stombaugh@uky.edu

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Distribution Pattern Variability of Granular VRT Applicators

DISTRIBUTION PATTERN VARIABILITY
OF GRANULAR VRT APPLICATORS

J. P. Fulton, S. A. Shearer, S. F. Higgins, D. W. Hancock, T. S. Stombaugh

ABSTRACT. *Granular applicators equipped with variable-rate technology (VRT) have gained popularity in recent years as a result of increased interest in variable-rate application. The purpose of this investigation was to characterize distribution patterns at varying rates for different granular applicators. Uniform-rate (UR) tests were conducted to assess the accuracy of variable-rate application from four granular applicators: two spinner-disc spreaders (A and B), and two pneumatic applicators (C and D). Pattern results indicated a consistent triangular pattern for spinner spreader B and consistent patterns for the pneumatic applicators (C and D). However, applicator D produced pattern variations at the center and right side. Simulated overlap analysis generated CVs <20% for applicators B and C. Applicator A performed well at the two lower rates (CVs <19%) but not at the highest rate (CV = 27%). Pattern unevenness for applicator D produced CVs between 25% and 34%. The spinner-disc spreaders over-applied, while the pneumatic applicators under-applied at the margins, suggesting an adjustment to the effective swath spacing or spinner-disc speed is needed to improve application accuracy. Further, overlap plots indicated pattern variability even when acceptable CVs were attained for applicators B and C. Therefore, it is recommended that CVs accompany simulated overlap pattern plots to ensure proper calibration of VRT equipment. Swath spacing analysis indicated that three of the four applicator spacings could be changed from the recommended value to improve application uniformity. Pattern comparisons showed that pattern shifts occurred for applicator A (P = 0.0092) with increasing application rate but not for applicators B, C, and D. These results demonstrate potential application errors with VRT and the need for proper calibration to maintain acceptable performance. Further, this investigation demonstrates the need for a VRT equipment testing standard.*

Keywords. Granular fertilizer, Pneumatic applicator, Potassium, Precision agriculture, Site-specific management, Spinner-disc spreader, Variable-rate application.

The use of variable-rate technology (VRT) has grown with the development of precision agriculture (PA), leading farmers to focus on site-specific nutrient management. Fertilizer dealers and custom applicators are providing variable-rate (VR) services to farmers, and this represents an additional cost because of the added equipment and software required to perform VR application. The rationale behind VRT is to apply only what is needed based on local fertility levels and anticipated crop needs. This assumes that soil fertility levels vary at some manageable scale. Traditional uniform-rate (UR) application tends to over- and under-apply, while VRT can result in more efficient use of inputs. While VRT may be a viable option for managing nutrient inputs, an understanding of application errors associated with VRT equipment is essential. Quantification of these errors will help to determine whether or not VRT is an improved alternative to UR application.

Yule et al. (1996) reported that site-specific farming (SSF) allows for the application of "economic optimum dressing" where allocation of inputs is based on site-specific information. However, the assumption is that SSF can be correctly executed with existing technology and that spatial data authenticates crop and field conditions. To capture some of the unexpected profits from PA technology and improve its performance, the operation of equipment must be precise (Mowitz, 2003). This requires that VRT equipment is in proper working order, calibrated correctly, and consistently applies the specific rate for a specific site. In the Midwest, granular materials are typically applied with spinner-disc and pneumatic applicators. Spinner-disc spreaders tend to be the most common type of granular applicators, likely due to the lower capital investment relative to air-boom applicators, which are popular among companies providing custom application services.

Granular materials are quite variable in terms of material density, particle size, and moisture content. This variability has the potential to introduce additional error with regard to the uniformity of application. Many believe that air-boom technology offers more uniform product distribution across the swath when compared with spinner-disc spreaders. In

The authors are **John P. Fulton, ASABE Member Engineer,** Assistant Professor, Department of Biosystems Engineering, Auburn University, Auburn, Alabama; and **Scott A. Shearer, ASABE Member Engineer,** Professor, **Stephen F. Higgins,** Research Specialist, **Dennis W. Hancock,** Research Specialist for Precision Agriculture, and **Timothy S. Stombaugh, ASABE Member Engineer,** Assistant Extension Professor, Department of Biosystems and Agricultural Engineering, University of Kentucky, Lexington, Kentucky. **Corresponding author:** John P. Fulton, Auburn University, 200 Corley Bldg., Auburn, AL 36849; phone: 334-844-3541; fax: 334-844-3530; e-mail: fultojp@auburn.edu.

either system, application variability exists due to the inherent variability of granular products. Thus, application precision is affected by both application equipment and the inherent variability of the product.

ASAE Standard S341.2 (*ASAE Standards*, 2000) provides a uniform procedure for testing, assessing, and reporting broadcast spreader performance. The standard outlines a methodology to assess the distribution pattern from a broadcast spreader using a 1-D row of collection trays. While the standard addresses uniform application, the methodology does not accommodate testing of VRT-equipped spreaders. Fulton et al. (2001) suggested modifications to ASAE Standard S341.2 to include a 2-D array of collection pans to assess VR application of granular products. The modified plot layout provides a means to characterize distribution patterns while also evaluating distribution patterns and rate response during rate changes. Capturing rate changes within the collection pan matrix also allows for quantification of system latency for VRT equipment.

The coefficient of variation (CV) provides a means to quantify application variability and accuracy. ASAE Standard S341.2 (*ASAE Standards*, 2000) requires CVs to be reported when testing applicators, and CV is indicative of spread uniformity. Further, manufacturers and companies providing custom application services have adopted CVs as a descriptive term to describe equipment's application accuracy. Lower CVs indicate uniform distribution patterns. Parish (1991) showed that CVs increased for a spinner-disc spreader from 10% to the upper 20s or lower 30s when moving from operating on a smooth surface to a rough surface. They used ryegrass seed and three different-sized fertilizers. Sogaard and Kierkegaard (1994) reported that CVs in the range of 15% to 20% are typical of field tests for spinner-disc spreaders, while Smith et al. (2000) acknowledged that CVs are higher for field operation compared to laboratory-derived CVs. Smith et al. (2000) also indicated that CVs around 15% or less should be a desirable goal for any liquid or granular application, especially for laboratory or controlled testing. However, granular applicator users and manufacturers have commonly accepted CVs ≤20% as an acceptable level for pattern uniformity.

Fulton et al. (2001) demonstrated distribution variability at different rates from a single spinner spreader. They cited that distribution variability and the resultant patterns changed with different application rates, indicating the possibility of compounding the application errors for VRT application with spinner spreaders. However, they only tested one spinner-disc spreader while focusing on modeling the distribution patterns during rate changes and at uniform rates. Distribution pattern comparisons were not performed for the tested application rates.

Pattern shifts during the rate changes (Fulton et al., 2001; Olieslagers et al., 1997) and system latency (Fulton et al., 2001) causing delayed rate changes create other sources of application error in VR application. The problem with pattern shifts is not as easily rectified but needs to be addressed to maintain distribution uniformity at various application rates. Glover and Baird (1970) indicated the need for setup adjustments in applicator hardware when changing the product or target application rate to preserve acceptable performance. Similar adjustments may be required as application rate ranges change from product to product.

Research suggests that dynamic weighing of the fertilizer spreader to automatically calibrate the flow control device during fertilizer application (van Bergeijk et al., 2001) is needed to maintain proper deposition of granular material from a VRT system. However, accurate metering is independent of accurate distribution of material from an applicator. The resulting mass flow must be correctly distributed for site-specific application of fertilizers (van Bergeijk et al., 2001). Asymmetrical irregularities in distribution data can occur (Roth et al., 1985). Currently, no research has been conducted to quantify and compare distribution patterns at different application rates from VRT applicators. Therefore, the goal of this investigation was to assess and quantify the variability of distribution patterns from typical granular VRT application equipment. Pattern characterization is essential to evaluate potential application errors. Further, this distribution data can be utilized to model the overall accuracy of VRT application (Fulton et al., 2003). The specific objectives were to: (1) characterize the distribution patterns from spinner-disc and pneumatic applicators at different application rates, (2) evaluate the accuracy of these applicators under simulated field operation, and (3) assess the consistency of the distribution patterns from the various applicators.

MATERIALS AND METHODS

Four granular applicators were used for this investigation. Applicators A and B utilized spinner discs to distribute material and relied on pattern overlap from adjacent passes to achieve uniform application. Applicators C and D are pneumatic (boom) applicators that do not require overlapping passes, except for the extreme outside distributors. Pneumatic applicators are designed to uniformly meter from ducts that are uniformly distributed across the boom. The operating parameters, such as swath spacing and nominal ground speed, were varied in accordance with manufacturer's specifications.

For each applicator, a total of four tests was conducted at different uniform rates using murate of potash (KCl) (table 1). The tests were performed using the modified ASAE Standard S341.2 (*ASAE Standards*, 2000) using the same pans, and following the same test protocol outlined by Fulton et al. (2001). The test site was flagged to indicate collection pan positions (fig. 1) and desired applicator path.

All application equipment was calibrated before performing any of the UR tests using murate of potash (KCl). Fulton et al. (2001) provided testing and calibration details for applicator A. They followed the manufacturer's recommendations for calibration using potash (KCl). Calibration for applicators B and C consisted of following the manufacturers' recommendations provided in the operator manuals. An application rate of 224 kg/ha (200 lb/ac), the midpoint of 112 kg/ha (100 lb/ac) and 336 kg/ha (300 lb/ac), was used for calibration. A single row of pans was used for calibration

Table 1. Various applicator nomenclature and testing characteristics.

Applicator	Type	Test Speed, km/h (mile/h)	Swath Spacing, m (ft)
A	Spinner	20.4 (12.7)	16.0 (52.5)
B	Spinner	14.5 (9.0)	18.3 (60.0)
C	Pneumatic	9.4 (5.8)	12.2 (40.0)
D	Pneumatic	12.9 (8.0)	21.3 (69.9)

Figure 1. Material collection and example test site layout.

(*ASAE Standards*, 2000). Adjustments were made according to manufacturers' specifications until the desired application rate, 224 kg/ha (200 lb/ac), and distribution pattern uniformity were achieved. For applicator D, the organization supplying the equipment performed the calibration procedure prior to testing. Several pan tests (single-row) were conducted prior to the more extensive UR pattern testing to double-check the distribution pattern and ensure that each machine was operating within specifications.

Several application rates were selected for performing the uniform-rate (UR) tests. Applicator A was tested at 56.0 and 168.1 kg/ha (50 and 150 lb/ac) (Fulton et al., 2001) with the distribution pattern at 112.1 kg/ha (100 lb/ac) established by Fulton et al. (2003). The rates selected for applicators B and C were 56.0, 112.1, 224.2, and 336.2 kg/ha (50.0, 100.0, 200.0, and 300.0 lb/ac, respectively). Applicator D was tested at 112.1, 224.2, 336.2, and 448.3 kg/ha (100.0, 200.0, 300.0, and 400.0 lb/ac, respectively). These application rates are based on the maximum application rates for potassium from the University of Kentucky's Lime and Fertilizer Recommendations (AGR-1, 2002) along with the Tri-State Fertilizer Recommendations for Corn, Soybeans, Wheat, and Alfalfa (Tri-State, 2000). The low application rate of 56 kg/ha (50 lb/ac) was chosen to determine if applicators B and C would perform accurately at a low application rate. Many spinner-disc spreader manufacturers do not recommend applying fertilizers below 112 kg/ha (100 lb/ac). However, some farmers implementing VRT on these applicators intend to apply at rates below those recommended. At the

request of the owners, applicator D was not tested at the 56.0 kg/ha (100.0 1b/ac) rate but rather at 448.3 kg/ha (400.0 lb/ac).

The collection pan matrices for applicators B, C, and D were developed based on the 2-D pan matrix used by Fulton et al. (2001; fig. 2). The 0.0 m (0.0 ft) transverse distance represents the pans that were straddled during a test run. The width of the pan layouts was based on the effective application and overlap widths for each applicator (table 1). Transverse pan spacing was adjusted to ensure that the total material distribution width was captured. The length of each test matrix was determined by estimating the time for rate changes. This time was obtained through discussions with experienced VRT equipment operators for the equipment tested. The goal was to capture the rate change within the test matrix. In addition, it was essential for each operator to attain a constant ground speed prior to entering the test pan matrix.

Test pattern data were collected for applicator A using a fixed 13 × 13 matrix (169 total pans; Fulton et al., 2001). As the result of the earlier study, it was decided that more transverse pans (17 versus 13) were required to better characterize the distribution patterns from the applicators. The number of longitudinal rows was set at 12 to provide a sufficient number of replications for characterizing the UR distribution patterns for applicators B, C, and D. The final number of pans for the UR tests for these applicators was established at 204.

Upon completion of each test, the KCl particles in each pan were placed in individual plastic bags, sealed, and labeled according to location (fig. 1). A digital scale was used to measure the mass of each sample under laboratory conditions. For each UR test, the mean at each transverse pan position was computed to generate the single-pass distribution patterns for applicators A, B, C, and D. The 95% confidence interval (CI) was also computed for each distribution pattern. Surface plots were generated for these three applicators using the software package Surfer (Surfer, 2003) to facilitate visualization of pattern variability. Since a 2-D matrix of collection pans was used rather than a 1-D row, a 3-D representation or surface can be used to illustrate the distribution patterns from a granular applicator. The traditional illustration is a 2-D plot, as recommended by *ASAE Standards* (2000). Additionally, 3-D representations
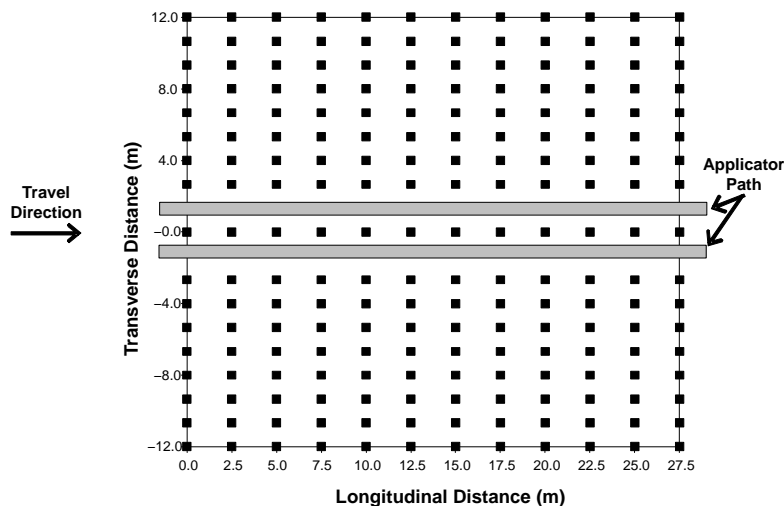

Figure 2. Collection pan matrix used for single-pass UR tests of applicator D.

can provide more insight into distribution issues, if any exist, that could be undetectable by plotting distribution patterns two-dimensionally. Similar results for applicator A for the single-pass analysis were previously reported by Fulton et al. (2001) and thus are not included here.

The resulting single-pass distribution patterns were then used to create the simulated overlap distribution patterns using the progressive method outlined in *ASAE Standards* (2000) to assess application uniformity. For comparison, the 112.1 kg/ha (100.0 lb/ac) distribution pattern established by Fulton et al. (2003) for applicator A was included in this overlap analysis. This overlap pattern provides a means to estimate how single-pass distribution pattern variations affect overall application uniformity, assuming parallel passes at the specified swath width. Overlap patterns were created using the manufacturer-recommended swath spacing reported for each applicator. The mean application rate for the overlap patterns was computed by taking the mean of all points in the pattern. Ideally, the overlap data should produce a horizontal line, indicating uniform distribution of material. In this article, the desired application levels are indicated with dashed lines to illustrate deviations in the estimated overlap application levels.

CVs were calculated using the computed overlap data to assess application variability for each of the applicators at each rate. The CVs were computed using two approaches: one to report accuracy (CV_{acc}), and the other to represent precision (CV_{prec}). For accuracy, the desired level was used as the mean when calculating the sample standard deviation (eq. 1), whereas the mean of the computed overlap pattern was used as the mean in the sample variance calculation (eq. 2) for precision:

$$STD\_DEV_{acc} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - Desired\_Rate)^2}{n-1}} \quad (1)$$

$$STD\_DEV_{prec} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - Mean\_Overlap\_Rate)^2}{n-1}} \quad (2)$$

where y_i is the computed overlap application rate for a transverse location, n is the total number of transverse rows or sampling positions, *Desired_Rate* is the desired application rate level, and *Mean_Overlap_Rate* is the computed mean overlap application rate for a specific uniform rate test. The associated CVs were computed by dividing each standard deviation by the mean overlap application rate and multiplying by 100.

Accuracy represents how the resulting distribution pattern deviates from the desired application rate (pattern variability about the desired application rate, which is shown as a dashed line in the figures). The CV_{prec} relates only to pattern repeatability or simply pattern uniformity across the effective swath width (variability about the mean of the application pattern). Thus, an applicator may have a small CV_{prec}, indicating that the overlap pattern is uniform, but the CV_{acc}

could be large, indicating that the overlap pattern deviated from the desired rate. Computing only the CV_{acc} for UR application, in accordance with *ASAE Standards* (2000), may not be appropriate for VRT application. Generation of both CVs is needed for VRT, as it is important to specify both accuracy and precision as rates change during application. A small setup adjustment of applicators to provide acceptable performance at one rate could negatively impact pattern uniformity at another. Similarly, setup adjustment at one rate could increase the difference between the desired and actual application rate at other rates. For this investigation, CVs ≤20% were considered acceptable and were used in the analyses.

Three distribution patterns for applicator A (Fulton et al., 2003) were included in the overlap analyses: 56.0 and 168.1 kg/ha (50.0 and 150.0 lb/ac) (Fulton et al., 2001), and 112.1 kg/ha (100.0 lb/ac) (Fulton et al., 2003). Although only two of the rates used for the simulated overlap analysis for applicator A were equal to the four used for the other two applicators, the results for applicator A can provide insights into trends and potential errors for this type of applicator. Further, an optimal swath spacing analysis was performed, as outlined by *ASAE Standards* (2000), to determine if the swath spacing could be changed to help improve application uniformity.

The characterized distribution patterns for each applicator were standardized based on the mean application rate calculated for the simulated overlap analysis. Pattern standardization allows for quantifiable comparisons between the characterized patterns for each applicator. An ANOVA was conducted using the GLM procedure in SAS (SAS, 2001), enabling comparisons between rates across all positions (rate), transverse positions across all rates (position), and rates within each position (rate*position). The presence of pattern shifts is indicated by a significant interaction between rate and position.

RESULTS AND DISCUSSION

SINGLE-PASS ANALYSIS

Figures 3 through 6 depict the distribution patterns along with the 95% CIs for applicators A, B, C, and D, respectively. A distinctive feature in these figures is the apparent symmetry about the center of the patterns for applicators A, B, and C, but not for D. Symmetry is a desirable feature in that similar distribution is occurring on either side of the spinner-disc spreader. This symmetry is desirable, as these applicators rely on overlap from adjacent passes to achieve uniformity. For applicator B, there seems to be a slight pattern peak shift for the 112.1 kg/ha (100.0 lb/ac) rate test where the maximum occurred at the −2.3 m (−7.5 ft) position rather than at the center. Applicator B's central peak becomes more prevalent as the application rate increases. The 56.0 and 112.1 kg/ha (50.0 and 100.0 lb/ac) tests for applicator C appear rather uniform, with more variability occurring at the higher rate tests. For the most part, the distribution patterns show consistency from side to side for applicators B and C, which coincide with the results reported by Fulton et al. (2001) for applicator A.

The patterns produced by applicator B could be described as "triangular" shaped. This shape coupled with the correct swath spacing generates a uniform distribution of material
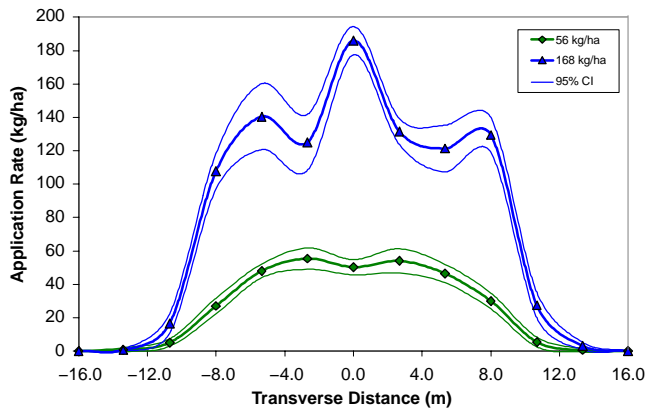
Figure 3. Characterized distribution patterns for applicator A (Fulton et al., 2001).
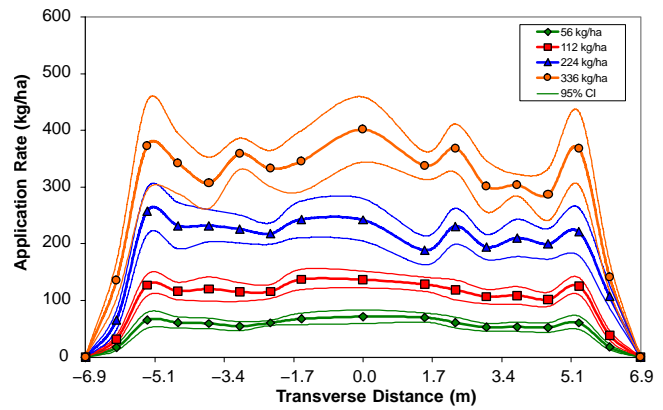

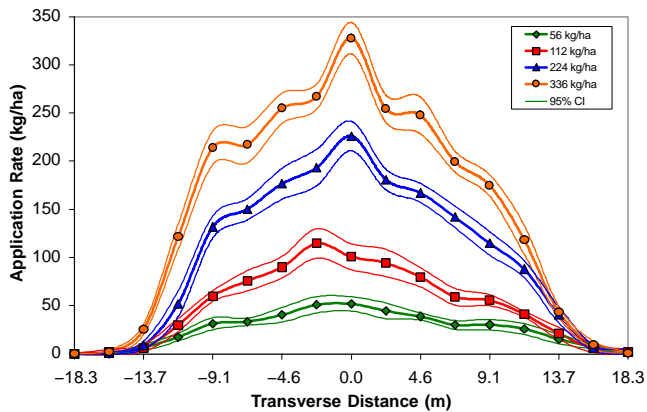**Figure 5. Characterized distribution patterns for applicator C.**

Figure 4. Characterized distribution patterns for applicator B.
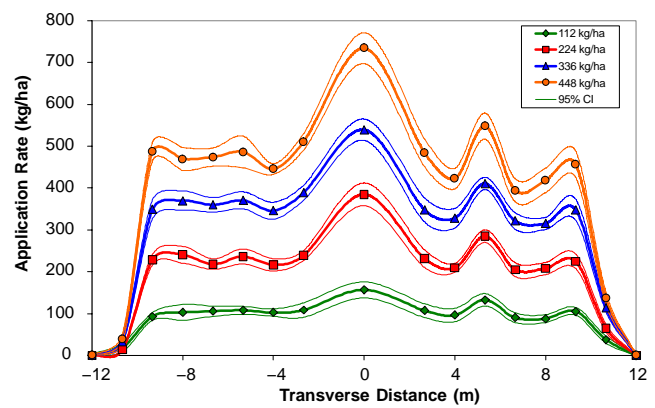

Figure 6. Characterized distribution patterns for applicator D.

for overlapping passes. These results vary from the W- and M-shaped patterns observed for applicator A (Fulton et al., 2001) at the uniform low and high test rates, respectively.

A distribution problem for applicator D is readily apparent for the center and right boom sections (fig. 6). This problem was consistent from pattern to pattern, increasing in magnitude with application rate. The cause for this problem is unknown, but it appears to be a metering issue because the mean pattern results on either side of the peaks, at the center, and at the 5.33 m (17.5 ft) positions are similar to the results for the left boom. If it was a deflector or delivery duct problem, then points on either side of the peaks would be dissimilar. Therefore, more material is likely being metered into the distribution ducts that feed the distributors at these locations.

The 95% confidence intervals reveal that applicator B (fig. 4) and applicator D (fig. 6) are consistent with regard to variability about the mean application rates. However, applicator C demonstrated variability about the mean patterns, especially at the 224.2 and 336 kg/ha (200.0 and 300.0 lb/ac) rates (fig. 5). The smaller CIs for applicators B and D are desirable because they indicate that these applicators produce consistent patterns independent of test rate. However, even though the patterns are consistent, pattern problems resulting from metering or distribution irregularities can have a profound effect on application accuracy.

Distribution surface graphs generated for applicators B, C, and D further demonstrate the aforementioned results (figs. 7

through 9). These surfaces highlight the spread variability of each applicator and permit a quick visual comparison between the applicators. The surface plot for applicator B shows more variability at the lower two test rates (figs. 7a and 7b) with more consistency at the higher test rates (figs. 7c and 7d). The surface plots for applicator C demonstrate the most variability of the three applicators (fig. 8), with many peaks and depressions for all tests. These results would tend to indicate that adjustments are needed to this applicator to increase pattern uniformity. The surface plot produced for applicator D (fig. 9) shows the repeatability of these patterns, with the most variability occurring at the lowest test rate (fig. 9a). Figure 9 also distinctly highlights the central and ride-side pattern problem with applicator D. These surfaces provide a 3-D representation of the distribution patterns, which can be used to quickly assess pattern variability and determine the need for adjustments to improve the quality of application.

OVERLAP ANALYSIS

The overlap estimates for applicator A (fig. 10) were similar to those generated for applicator B (fig. 11). At the two higher rates, the points nearest the margins of the spread width exceeded the desired level for both spinner spreaders. This needs to be corrected to provide a more uniform distribution of material at the high application rates. For both applicators, material from the outside of the pattern must be redistributed towards the center to fill the valleys shown for the higher two application rates. The trend for these two applicators is that the patterns deviate more from the desired
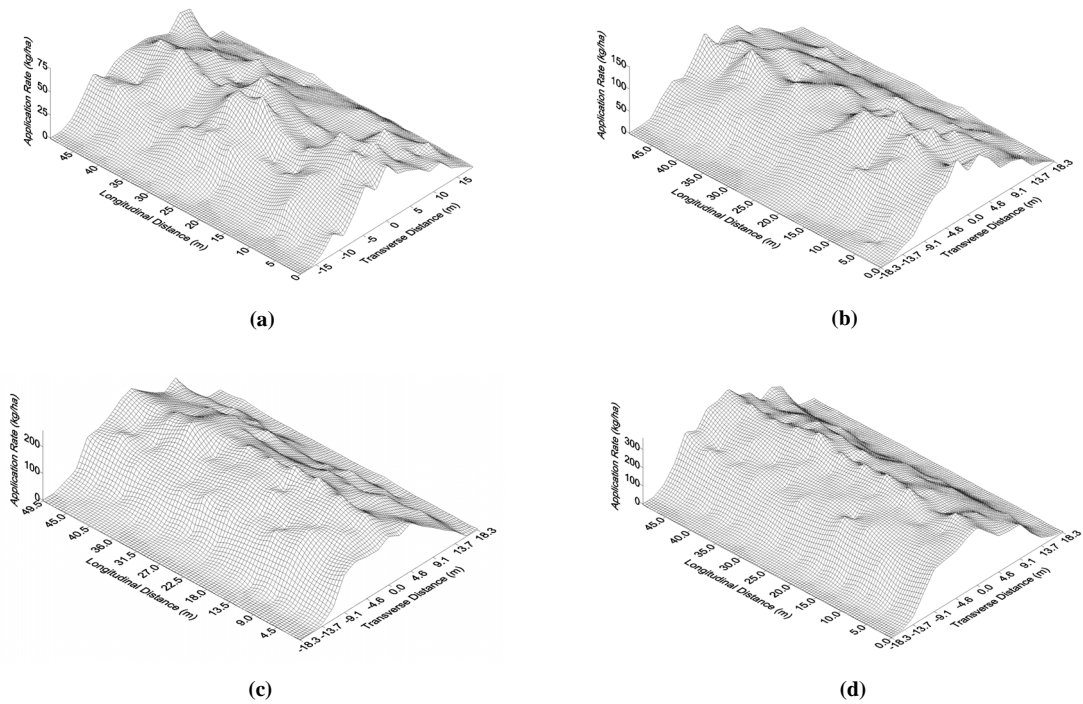
Figure 7. Uniform application rate surfaces for applicator B: (a) 56.0 kg/ha (50 lb/ac), (b) 112.1 kg/ha (100 lb/ac), (c) 224.2 kg/ha (200 lb/ac), and (d) 336.2 kg/ha (300 lb/ac).
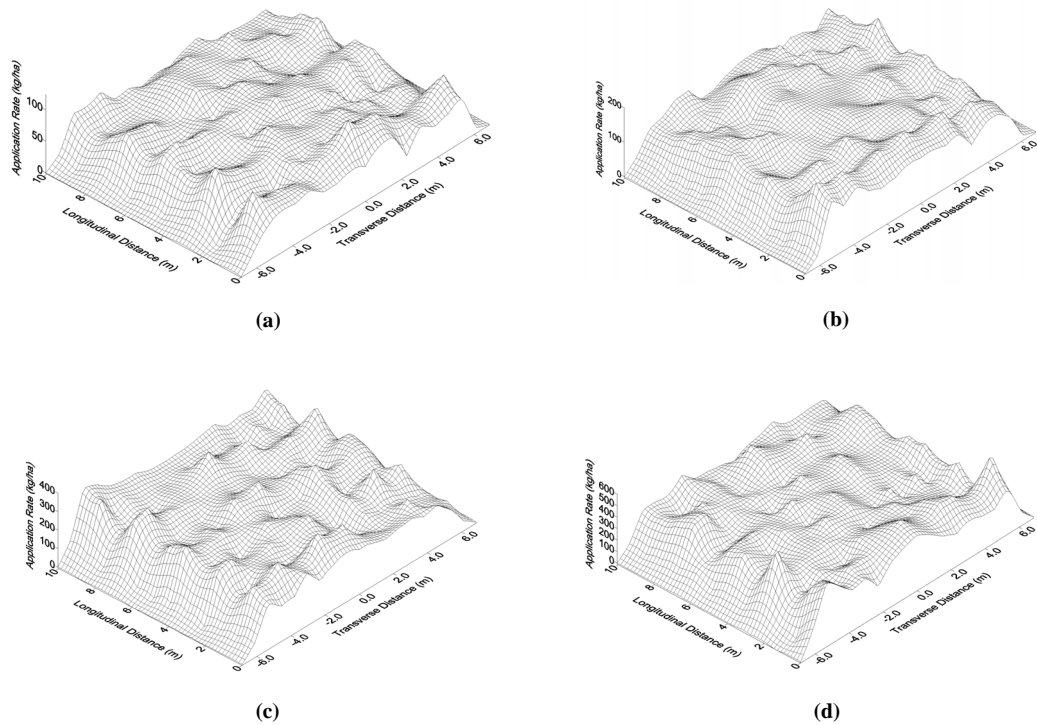

Figure 8. Uniform application rate surfaces for applicator C: (a) 56.0 kg/ha (50 lb/ac), (b) 112.1 kg/ha (100 lb/ac), (c) 224.2 kg/ha (200 lb/ac), and (d) 336.2 kg/ha (300 lb/ac).

level with an increase in application rates. The 56 kg/ha (50 lb/ac) test for applicator A and the 56 and 112 kg/ha (50 and 100 lb/ac) tests for applicator B produced the most uniform results, with small deviations from the desired level and patterns that are rather horizontal.

Overlap analysis results for applicator C illustrate considerable pattern irregularities about the desired level (fig. 12).

The overlap pattern at all four rates fluctuates about the desired level except at either margin of the pattern. As with the spinner spreader, more variability in the pattern occurred with an increase in application rate. A common feature with all four patterns is the under-application at the margins of the spread width, ±6.10 m (±20.0 ft), and over-application at the centers, 0.0 m (0.0 ft). Adjustments to the hardware of
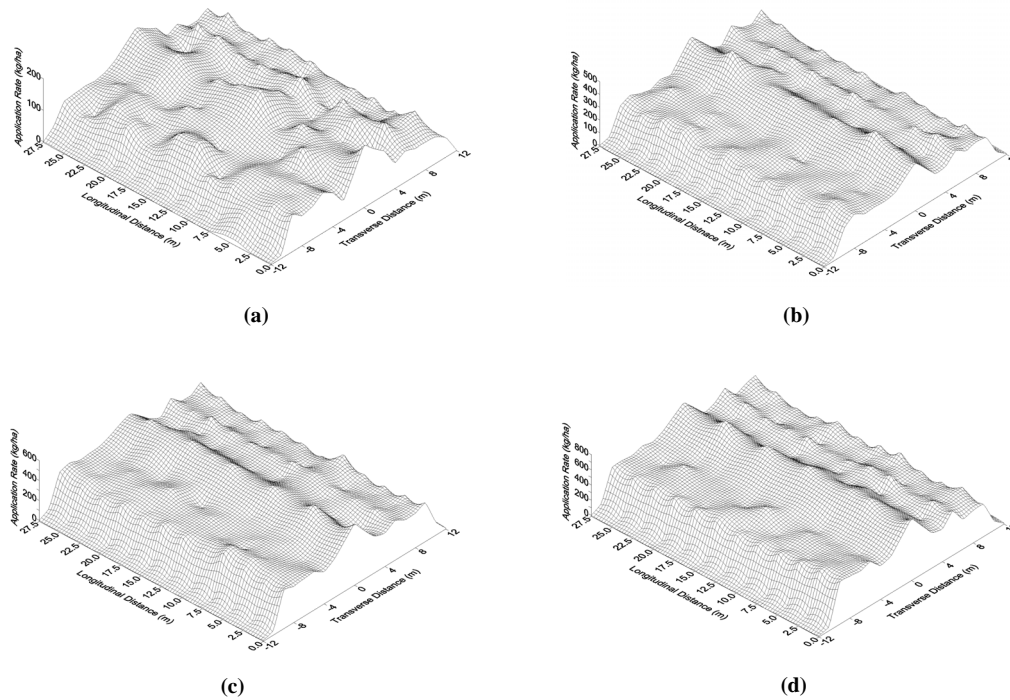
(a)

(b)

(c)

(d)

Figure 9. Uniform application rate surfaces for applicator D: (a) 112.1 kg/ha (100 lb/ac), (b) 224.2 kg/ha (200 lb/ac), (c) 336.2 kg/ha (300 lb/ac), and (d) 448.3 kg/ha (400 lb/ac).

applicator C to improve distribution could minimize this observed overlap variability. Overall, mean pattern values indicate that applicator C applies near the desired levels.

Overlap patterns for applicator D exhibit distribution variability as a result of pattern problems similar to those of applicator C (fig. 13). The left boom produced uniform distribution of material close to the desired level. The center and 5.33 m (17.5 ft) positions generated significant application errors. Similar to applicator C, the margins of the spread width on all the patterns received rates below the desired, suggesting a needed reduction in swath spacing. Correction of these under- and over-application issues could produce a uniform overlap pattern for applicator D. As with the other applicators, increasing the application rate increases pattern variability for applicator D.

Table 2 provides summary statistics for the simulated overlap patterns. The CVs for applicator A were <20% for the lower two rates but >20% at the 168.1 kg/ha (150.0 lb/ac) rate. The 56.0 kg/ha (50.0 lb/ac) test produced the best results for all the rates and applicators tested, with a CV equal to 5.8%. The precision and accuracy CVs differed slightly, yet applicator A requires improvement (CV >27%) at the 168.1 kg/ha (150.0 lb/ac) level. A reduction in the mean application rate would help slightly, but the main cause of error is the resulting W-shaped distribution pattern, which generates peaks at the center and tails of the overlap pattern (fig. 10). These peaks result in application rates in excess of the desired level. The overlap pattern also exhibits valleys that are below the desired level. The desirable action would be to smooth this pattern out by depositing material from the peaks into the
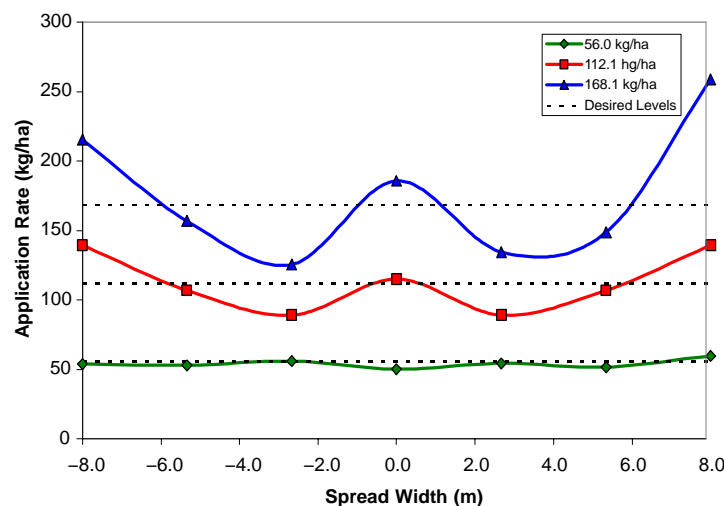

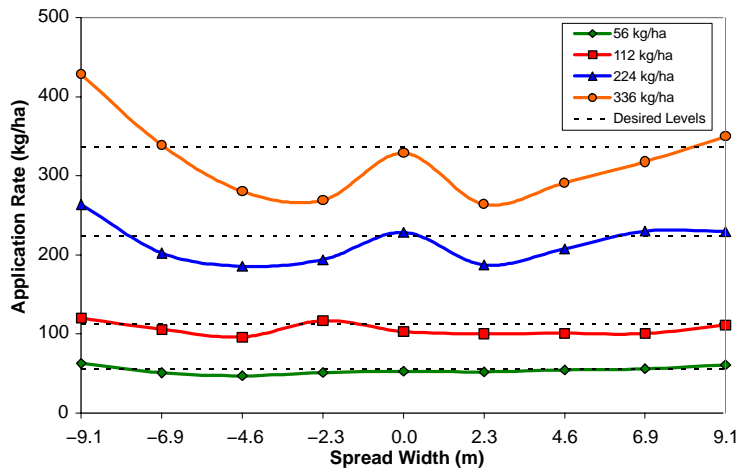**Figure 10. Simulated overlap distribution pattern for applicator A.**

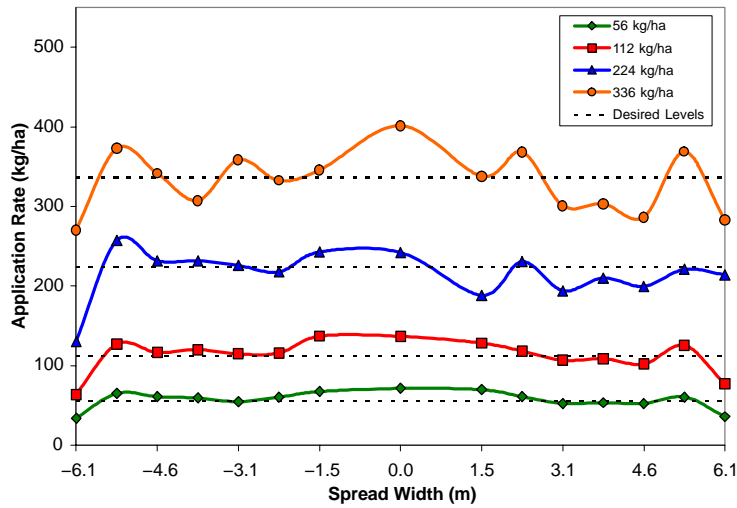**Figure 11. Simulated overlap distribution pattern for applicator B.**

Figure 12. Simulated overlap distribution pattern for applicator C.
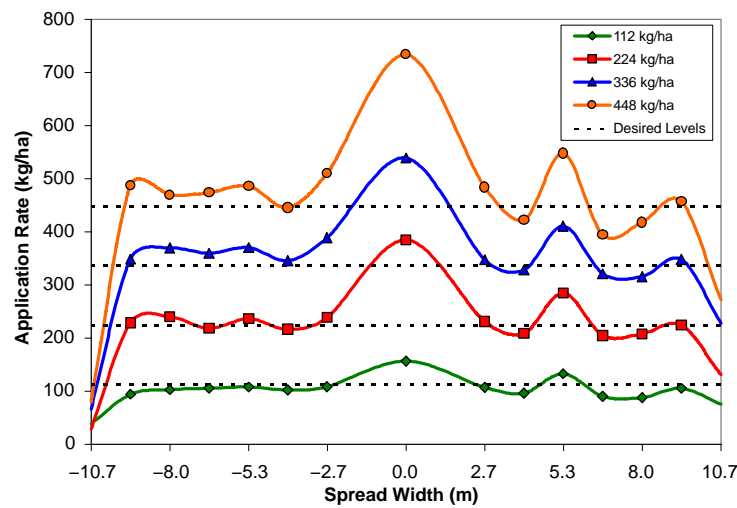
Figure 13. Simulated overlap distribution pattern for applicator D.

valleys. This reallocation of material can be achieved by adjusting the rear divider, which is positioned between the apron chain/belt and spinner discs, either forward or rearward as recommended by the manufacturer. This divider controls

where the flow of material from the chain or belt contacts the spinner discs, thus influencing material distribution.

Applicator B performed the best, with all CVs below 20% and three tests producing CVs less than 15%. The 56 and

Table 2. Simulated multiple pass summary statistics (progressive method).

	Applicator A				Applicator B			
Desired Rate, kg/ha (lb/ac)	Mean, kg/ha (lb/ac)	Difference, kg/ha (lb/ac)	CV_{prec} (%)	CV_{acc} (%)	Mean, kg/ha (lb/ac)	Difference, kg/ha (lb/ac)	CV_{prec} (%)	CV_{acc} (%)
56.0 (50.0)	54.2 (48.4)	−1.8 (−1.6)	5.8	6.8	54.2 (48.4)	−1.8 (−1.6)	9.2	9.9
112.1 (100.0)	112.3 (100.2)	0.2 (0.2)	18.6	18.6	106.1 (94.7)	−6.0 (5.4)	7.8	9.8
168.1 (150.0)	175.2 156.3)	7.1 (6.3)	27.4	27.8	––	––	––	––
224.2 (200.0)	––	––	––	––	214.3 (191.2)	−9.9 (−8.8)	12.0	13.0
336.2 (300.0)	––	––	––	––	318.6 (284.3)	−17.6 (−15.7)	16.1	17.2

	Applicator C				Applicator D			
Desired Rate, kg/ha (lb/ac)	Mean, kg/ha (lb/ac)	Difference, kg/ha	CV_{prec} (%)	CV_{acc} (%)	Mean, kg/ha (lb/ac)	Difference, kg/ha	CV_{prec} (%)	CV_{acc} (%)
56.0 (50.0)	55.2 (49.2)	−0.8	18.9	19.5	––	––	––	––
112.1 (100.0)	105.4 (94.0)	−6.7	17.9	19.5	100.9 (90.0)	−11.2 (−10.0)	25.5	28.0
224.2 (200.0)	212.5 (189.6)	−11.7	14.0	18.6	219.2 (195.6)	−5.0 (−4.5)	34.0	34.1
336.2 (300.0)	320.6 (286.0)	−15.6	11.6	12.1	339.3 (302.7)	3.1 (2.8)	29.3	29.3
448.3 (400.0)	––	––	––	––	445.5 (397.5)	−2.8 (−2.5)	31.3	31.3

112 kg/ha (50 and 100 lb/ac) tests produced CVs less than 10%. However, since the accuracy CVs are slightly higher than those for precision, and the applicator tended to under-apply for all tests, increasing the mean application rate by 5% should result in lower CVs. This rate adjustment could be accomplished by making a 5% change to the calibration number within the controller. While the deviation was consistently low at each rate, it was not measured during calibration. The main difference between calibration and test methodology for all applicators was that a 1-D array of collection pans was used during calibration, as recommended by the manufacturer.

Applicator C applied at slightly lower rates than desired, with the differences increasing at higher rates. The accuracy CVs are higher than for precision, but both decreased with an increase in application rate. All computed CVs are within an acceptable range (<20%), with the 336 kg/ha (300 lb/ac) rate producing CVs below 15%. Although applicator C performed satisfactorily, an adjustment to the controller to increase the application rate by approximately 5% would improve the accuracy CVs. The under-application issue should have been resolved at calibration; however, this issue was not detected at that time. The precision CVs represent pattern repeatability, meaning that setup variables other than a controller adjustment are needed to generate more uniform patterns.

The poor precision of applicator D (CV_{prec} ranging from 25% to 34%) resulted from the identified distribution pattern issue. Applicator D also tended to under-apply, except for the 336 kg/ha (300 lb/ac) test. Since the precision and accuracy CVs were similar, the pattern problem is the predominate application error. The narrow CIs about each spread pattern indicate that resolving distribution pattern uniformity would improve the performance of applicator D, likely producing CVs well below 20%.

Applicators A, B, and C performed at acceptable levels with respect to pattern precision and accuracy at the lower two rates. Applicator A at the higher rate, and applicator D at all rates, will require adjustments to improve application performance to within a desirable level. It was observed that the overlap plots (figs. 10 through 13) tended to show more pattern variation than the CVs, meaning that the CVs can be used to quantify distribution variability, but overlap plots are needed to draw meaningful conclusions about the spread quality. Calculation of only CVs without graphically displaying the results could be misleading in pattern uniformity evaluation. Plots can better illustrate where patterns can be corrected to improve distribution. Similarly, determination of precision and accuracy CVs are indicative of possible error sources.

Off-target application can usually be corrected through calibration. However, alteration of distribution patterns may require considerable effort, including design changes at the point of material metering and distribution. The existence of pattern shifts will require simultaneous adjustments of the hardware during rate transitions (Fulton et al., 2001; Olieslagers et al., 1997). Such adjustments to the hardware, even if minor, could potentially generate additional distribution and metering errors, which would interfere with the goal of precise and accurate application rates, relative to the desired values, for VRT equipment.

The under-application occurring at the margins of the overlap pattern for applicators C (fig. 12) and D (fig. 13) could be resolved by reducing the swath spacing. Optimal swath spacing analysis for applicators C and D supports this notion. Reducing the swath spacing to 11.8 m (38.7 ft) produces CV_{prec} values around 15% for all rates, improving the overall application uniformity. Similarly, increasing the overlap for applicator D by decreasing the swath spacing to 20.0 m (65.6 ft) would enhance application quality, producing CV_{prec} values in the range of 18% to 20% for all rates. Increasing the swath spacing for applicators A and B would cause the opposite effect at the tails. The lowest CV_{prec} values for applicator B were attained using the recommended 18.3 m (60.0 ft) swath spacing. However, the swath spacing could be increased up to 22.6 m (74.1 ft) and still yield CV_{prec} values less than 20%. Varying swath spacing results existed for applicator A. The lowest CV_{prec} (5.8%) for the 56 kg/ha (50 lb/ac) rate occurred at the recommended swath spacing of 16.0 m (52.5 ft). Increasing the swath spacing to 18.7 m (61.4 ft) would reduce the CV_{prec} to 14.0% and 16.3% for the 112 and 168 kg/ha (100 and 150 lb/ac) test rates, respectively, but increase it by over threefold to 19.6% for the 56.0 kg/ha (50 lb/ac) test rate. Thus, a swath spacing of 18.7 m (61.4 ft) could be selected, but it would have a profound influence on distribution uniformity at the 56.0 kg/ha (50.0 lb/ac) level.

Figure 14. Standardized distribution patterns for applicator A.

Figure 16. Standardized distribution patterns for applicator C.

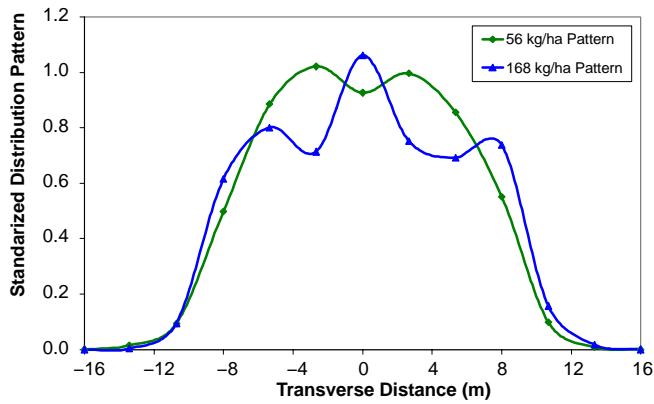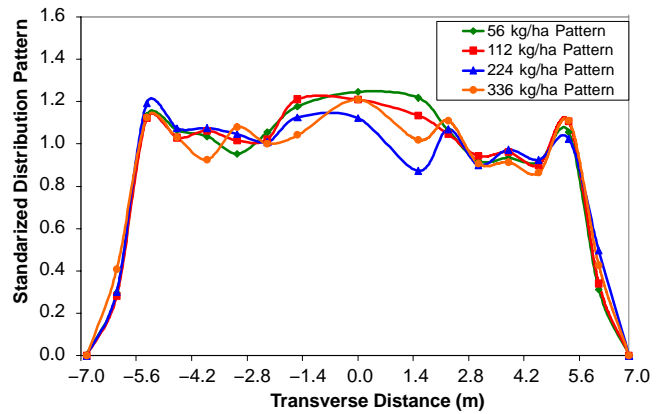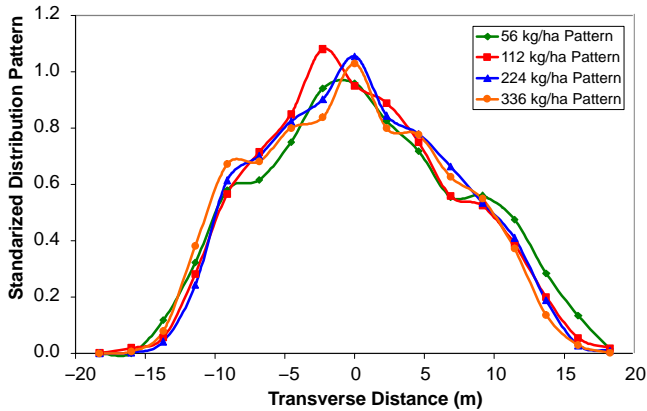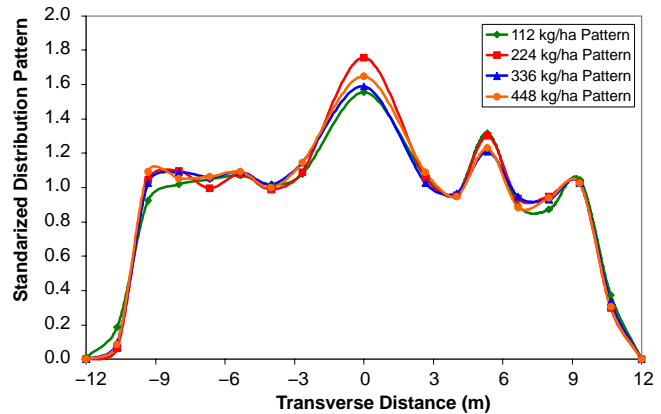**Figure 15. Standardized distribution patterns for applicator B.**

Figure 17. Standardized distribution patterns for applicator D.

DISTRIBUTION PATTERN COMPARISON

To facilitate comparisons between distribution patterns of the applicators tested, and at different application rates, the data were standardized based on the mean of the simulated overlap analysis for each application rate (table 3). For example, the overlap results for applicator B at the 56 kg/ha (50 lb/ac) test were divided by 54.2 kg/ha (48.4 lb/ac) to produce the standardized rate at this test level. Figures 14 through 17 are plots of the standardized patterns for applicators A, B, C, and D, respectively. As shown in the standardized pattern plots, applicator D patterns were the most consistent, applicator B and C patterns were fairly consistent, but a noticeable pattern shift was exhibited for applicator A.

There was a significant difference in the standardized amount applied for applicator A as judged by the interaction with rate (P = 0.0092) and position (P < 0.0001). The differences between the transverse positions are to be expected when evaluating the distribution pattern of a spinner-disc spreader, since the relative application rates decrease from the center towards the margins of the pattern. More importantly, however, a significant (P < 0.0001) pattern shift with rate change was confirmed for applicator A. These results reinforce the findings regarding pattern shifts reported by Fulton et al. (2001). Pattern shifts are undesirable in that they affect overall application uniformity; further, they require several tests for characterizing distribution patterns. Caution should be taken when calibrating an applicator exhibiting this attribute, as no single rate would be truly indicative of performance at other rates. Since no technology

Table 3. ANOVA results for the various applicators.

Applicator	Source	DF	SS	P-value
A	Rate	1	0.106	0.0092
	Position	12	63.46	<0.0001
	Rate*position	12	2.08	<0.0001
	Error	312	4.8083	
B	Rate	3	0.006	0.9250
	Position	16	95.245	<0.0001
	Rate*position	48	1.340	<0.0001
	Error	748	9.0606	
C	Rate	3	0.017	0.9440
	Position	16	120.554	<0.0001
	Rate*position	48	1.9354	0.6773
	Error	748	33.6453	
D	Rate	3	0.01573	0.8068
	Position	16	163.5132	<0.0001
	Rate*position	48	0.9404	0.1537
	Error	748	12.0411	

currently exists to correct pattern shifts simultaneously with rate changes, this spreader should be initially calibrated at the median rate of the expected application range for which the applicator is predominately operated. Once an acceptable distribution is reached, then distribution tests should be performed at low and high rates within the anticipated operating range.

In contrast, applicator B did not show a significant (P > 0.05) rate effect. However, as with applicator A, applicator B demonstrated a significant (P < 0.0001) position interac-

tion. These differences are again attributable to the distribution pattern characteristics of a spinner spreader. There was also a significant (P < 0.0001) interaction between rate and position, indicating a possible pattern shift for applicator B. Based on observation of the patterns, no discernible trend exists for this interaction in differing rates, indicating that a single pattern test, within normal operating ranges, may be sufficient to characterize the distribution pattern of this applicator. Therefore, these results indicated that no pattern shift occurred with applicator B.

Similar to applicator B, the pneumatic applicators (C and D) showed no significant (P > 0.05) rate effect. The pneumatic applicators also shared the spinner-disc spreaders significant (P < 0.0001) position effect. In contrast to the spinner-disc spreaders, the pneumatic applicators exhibited no significant (P > 0.05) interaction between rate and position that would indicate pattern shifts. However, only applicator A illustrated a pattern shift based on these results.

The results from the pneumatic applicator tests indicate that application rate as a function of position varied (P < 0.0001 for position). While this is to be expected for spinner-disc spreaders, such variability across the pattern of pneumatic applicators is undesirable. However, for both pneumatic applicators, the standardized rate applied across all positions was very consistent (P > 0.05 for rate). The absence of distribution pattern shifts can be expected within the rate ranges tested for these applicators. Again, such consistency in the distribution patterns of the pneumatic applicators is desirable, as it implies that a single pattern test can be conducted for distribution pattern characterization and/or calibration.

These data indicate that pattern shifts occurred for applicator A. To minimize errors, careful calibration is needed of an applicator either exhibiting or expected to exhibit this attribute. These results suggest that one test may be sufficient to characterize the distribution patterns of pneumatic applicators, while more intensive testing might be required for spinner-disc spreader pattern characterization. Specifying only one test for pneumatic applicators reduces calibration time.

CONCLUSIONS

Collection pan tests were conducted to assess distribution pattern variability for four different VRT granular applicators. The following conclusions could be drawn from the results, which highlight some of the potential variations between VRT applicators and the need for standard testing protocol for this type equipment:

- Pattern characterization results indicated that applicators B (spinner disc) and C (pneumatic) produced consistent, symmetric patterns for all test rates. However, applicator C exhibited high variability about its mean distribution patterns. The most consistent patterns (smallest CIs) were generated by applicator D (pneumatic), but this applicator exhibited distribution problems at the center and right boom sections, causing asymmetry in its pattern.
- Simulated overlap pattern analysis produced mixed results from the VRT applicators. Two of the four applicators (B and C) produced CVs <20% for all tests. Applicator A performed well at the two lowest test

rates (CVs <19%) but not for the high test rate (CV = 27.4%). The overlap patterns highlighted the distribution pattern problem for applicator D, producing CVs >25%. The simulated overlap plots illustrated that pattern adjustments could be made to improve material distribution for all applicators. Hence, both distribution plots and CVs must be generated at calibration to properly assess application quality of VRT equipment.

- Determination of the optimal swath spacing for each applicator showed that the recommended swath spacing for applicator B produced the lowest CVs. The swath spacing for the pneumatic applicators (C and D) can be reduced from the manufacturers' recommended values to improve application uniformity. However, a swath spacing of 18.7 m (61.4 ft) could be selected over the recommended 16.0 m (52.5 ft) spacing for applicator A to improve CVs at the two higher test levels, but this comes at a cost by generating a CV three times greater, but less than 20%, for the low test rate.
- Distribution pattern comparisons revealed that only applicator A produced a pattern shift. Therefore, a more intensive testing regime is required to quantify distribution patterns over a range of rates for applicators producing pattern shifts. In contrast, a single-pass pan test would suffice for characterizing the expected distribution patterns for applicators exhibiting consistent patterns, such as applicators B, C, and D.

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