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SIMULATION OF FIXED– AND VARIABLE–RATE APPLICATION OF GRANULAR MATERIALS

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ABSTRACT. *Research has shown that application errors exist with variable–rate technology (VRT) systems. Consequently, using prescription maps for economic and agronomic analyses can generate misleading results. The intent of this article was to develop and validate a spatial data model for generating "as–applied" maps to support the advancement of precision agriculture practices. Previous research modified ASAE Standard S341.2 to include a 2–D matrix of collection pans to assess fixed–rate and variable–rate (VR) deposition of granular fertilizers and agricultural lime from a spinner disc spreader. The "as–applied" spatial data model uses GIS functionality to generate "as–applied" surfaces by merging distribution patterns and a spatial field application file (FAF) into an "as–applied" surface representing the actual distribution of granular fertilizer or agricultural lime across a field. To validate the "as–applied" spatial data model, field studies were conducted by randomly placing collection pans across two fields. Murate of potash was then applied using a VR spinner spreader. The "as–applied" spatial data model was used to predict the amount of material each pan should have received. Comparisons were made between the actual and predicted application rates for two fields, with R^2 values of 0.45 (field A) and 0.58 (field B) computed. However, R^2 values of 0.16 (field A) and 0.21 (field B) were observed when comparing the actual application rates and prescription maps. These low R^2 values indicated poor application by the spinner spreader but demonstrated that the "as–applied" model did a better job of representing the distribution of murate of potash when contrasted with the prescription maps. "As–applied" surfaces provide a means for evaluating fixed–rate and VR application of granular products while enhancing researchers' ability to compare VR management approaches.*

Keywords. *As–applied surfaces and maps, Distribution patterns, Fertilizer and lime application, Modeling, Potash, Precision agriculture, Spinner disc spreader.*

Variable–rate technology (VRT) used in conjunction with the global positioning system (GPS) has become a common practice implemented by precision agriculture (PA) practitioners. VRT appears to provide a method for improving input use efficiency by applying near–optimum rates based on local soil conditions and crop requirements. This reduction of over– and under–application of inputs enhances productivity and profitability while reducing environmental impacts. These positive outcomes are predicated on the accuracy of VRT equipment. However, many studies have shown that errors exist in VRT systems. GPS receivers exhibit position and latency errors. VRT controllers have limited response time and steady–state rate error. Consequently, the use of prescription maps for economic and agronomic analysis can generate misleading results. Some errors can be minimized through software corrections and hardware calibration.

Of more critical importance to application accuracy is the deposition or application consistency of product across the application width of the machine. Manufacturers and producers have acknowledged the existence of deposition variability. However, producers continue to use the equipment despite these errors.

Today, many software and hardware manufacturers offer two–way communications between VRT software and VR controllers. The software packages not only send the desired application rate to the VR controller, but they also record the actual application data returned by the VR controller. This application data represents a spatial application quantity point file describing the location and amount of product that passes through the metering device. The main limitations of these data sets are that they do not represent actual product distribution after it leaves the metering devices. In particular, they do not account for possible distribution pattern inaccuracies at various application rates, over– and under–lap on parallel passes, the offset distance between the GPS antenna and the point of application, and system latency. These application errors are evident on spinner spreaders applying granular material. Consequently, even the use of the logged field application data for economic and agronomic analysis

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can generate misleading results. Therefore, a better quantification of spatial material deposition in the field is necessary for accurate economic and agronomic analyses.

Objectives

While VRT equipment offers a method to better match nutrient application rates to localized soil conditions, limitations of the distribution equipment often result in application errors. The goal of this project was to develop a method to post–process field application files (FAF) to create accurate "as–applied" surfaces. The specific objectives were:

- To generate an "as–applied" surface for granular fertilizer and agricultural lime using the distribution patterns determined by Fulton et al. (2001) and the FAF logged during field application with a VR spinner disc spreader.
- Validate the "as–applied" surface generating spatial data model.
- Compare the "as–applied" surface to the desired prescription surface.
- Assess the effect of GPS receiver offset distances and receiver latency on the accuracy of the spatial data model.

Background

Application accuracy of VR spinner spreaders is typically quantified by the coefficient of variation (CV). Lower CVs indicate uniform distribution patterns. Spinner spreaders tend to exhibit CVs varying from 5% to 10%; however, terrain irregularities can greatly increase CVs to the upper 20s or lower 30s (Parish, 1991). Sogaard and Kierkegaard (1994) reported that CVs in the range of 15% to 20% are typical of field tests for spinner spreaders.

Over– and under–lap on parallel passes creates application errors. Dorr and Pannel (1992) reported that 10% of a field had either over– or under–lapping patterns. This result indicates that operator pass–to–pass consistency is important. Marchenko and Chernikov (1977) determined varying swath width for spreaders under normal operation, which creates potential application errors by not maintaining the correct pass–to–pass distance. Similarly, vehicle speed (Parish and Chaney, 1986; Parish, 1987) and rough terrain (Parish, 1991) affect the performance of a spreader. Parish (1991) showed that the CV increased from 10% to 30% when moving from operating on a smooth surface to a rough surface. Thus, several factors influence the quality of application of spinner spreaders under fixed application.

Problems with VR spinner spreader application include distribution pattern shifts during rate changes (Fulton et al., 2001; Olieslagers et al., 1997) and delayed rate changes due to system latency. System latency can be improved with the "look–ahead" feature provided in most software packages. The problem with pattern shift is not as easily rectified. Solutions will likely involve modification of the spreader hardware, i.e. adjustment of divider position simultaneously with apron chain speed adjustments to maintain the desired distribution pattern.

Fulton et al. (2001) modeled fixed and VR application of murate of potash. They established a 2–D array of pans that was used to collect the spread of murate of potash over the test area. Single–pass tests were performed to facilitate model development for fixed and VR application. Through this testing, they were able to mathematically describe both fixed– and variable–rate distribution patterns at a low rate (56.0 kg/ha), high rate (168.1 kg/ha), and a rate change from low to high. These relationships can form the basis for creating an "as–applied" surface.

Methodology

Three fields located in Shelby County, Kentucky, were used to collect experimental data during application of murate of potash applied using the same spinner spreader used by Fulton et al. (2001). Field A (9.6 ha) was used for developing the "as–applied" spatial data model and illustrating its assessment capabilities. Fields B (9.2 ha) and C (34.2 ha) served for validating the "as–applied" spatial data model. The fields were subdivided into 0.4 ha square management zones. Fields A, B, and C contained 31, 25, and 89 management zones, respectively. Some individual management zones were larger or smaller than 0.4 ha due to irregular field shapes. The SSToolbox (SST, 1999) software package was used to generate the application prescription maps (figs. 1, 2, and 3). Table 1 provides summary statistics for all three fields and application prescription maps.

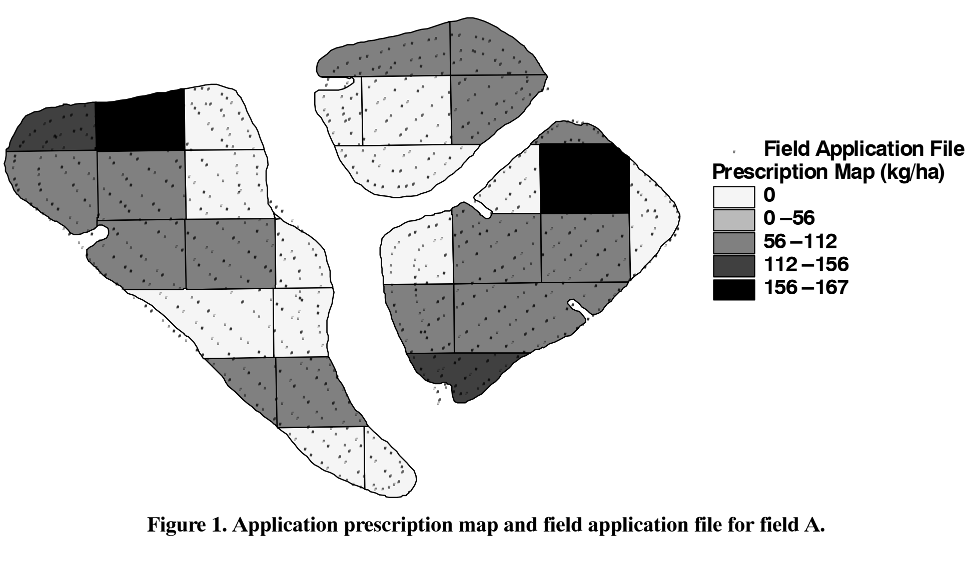

Figure 1. Application prescription map and field application file for field A.

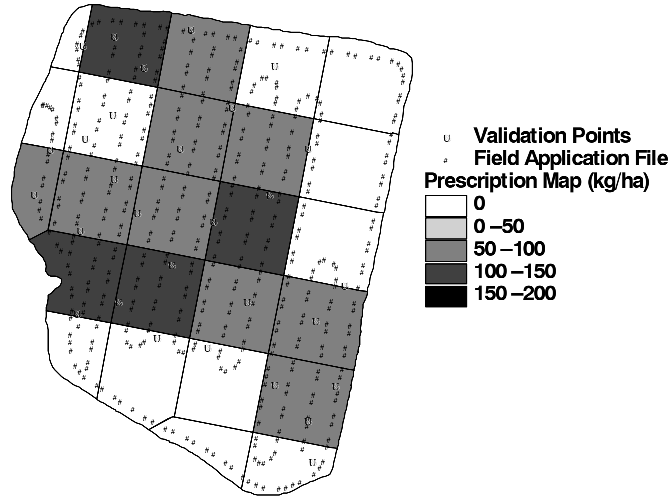

Figure 2. Application prescription map, field application file, and validation points for field B.

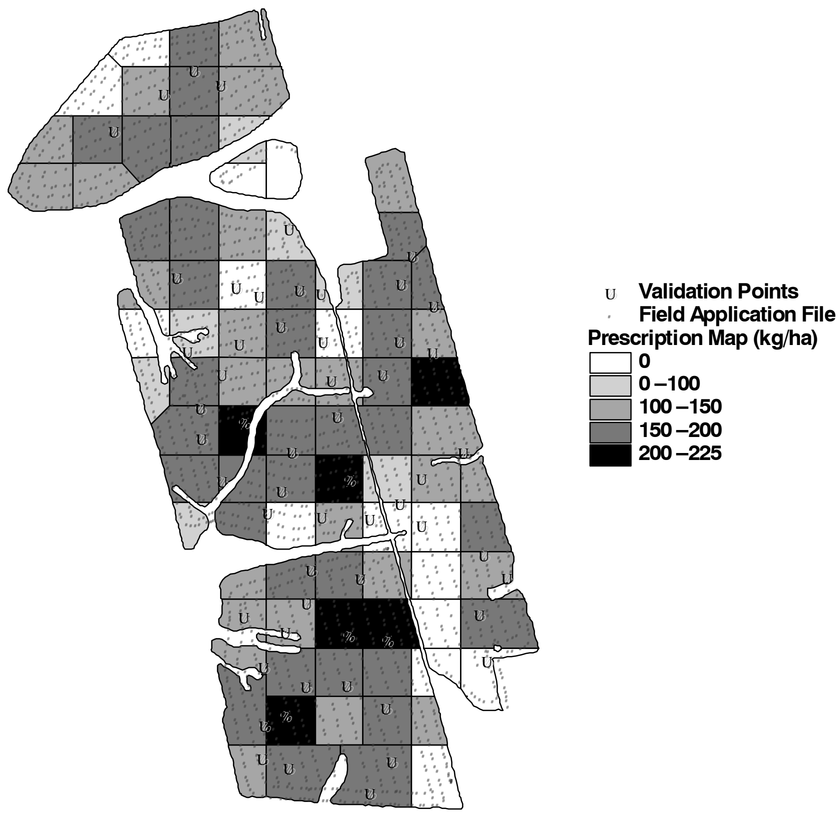

Figure 3. Application prescription map, field application file, and validation points for field C.

AgView software by GIS Solutions (GIS, 1999) was used to execute the VR control and generate the FAF. Based on the spinner spreader's location during application, AgView uses the prescription map to pass the desired application rates to a MidTech TASC 6200 controller. In turn, the MidTech controller regulates the amount of murate of potash being applied and simultaneously echoes the accumulated applied volume back to AgView. AgView records the position and volume of applied fertilizer at each location and saves this information as a spatial data layer in ESRI's "shape file" format (figs. 1, 2, and 3).

The first step in the analysis process was to reproject the FAFs from geographic coordinates (WGS 84) into the State Plane, Kentucky North coordinate system using ArcView's projection utility. Either State Plane or Universal Transverse Mercator (UTM) coordinates are required to create polygons with area properties for representing the distribution of murate of potash. Projecting data from WGS 84 (decimal degrees) into a Euclidean coordinate system simplifies dimensional analysis, such as measuring distances and generating defined shapes, within software code.

Previous work using the same VR spinner spreader truck for modeling of VR application of murate of potash permits the selection of transverse distribution patterns to describe VR application (Fulton et al., 2001). For simplicity and initial program development, three distribution patterns were

Table 1. Prescription map summary statistics.

Prescription Map	Field A	Field B	Field C
Field area (ha)	9.6	9.2	34.3
Number of zones	31	25	89
Application rate (kg/ha)			
Minimum	0.0	0.0	0.0
Maximum	166.2	145.3	211.0
Range (kg/ha)	Percent of Area (%)		
0.0	37.6	44.9	15.9
0.1 – 100.0	42.0	38.2	5.9
100.1 – 125.0	10.5	8.1	10.8
125.1 – 150.0	2.4	8.8	17.7
150.1 – 175.0	7.5	0.0	27.2
175.1 – 212.0	0.0	0.0	22.5

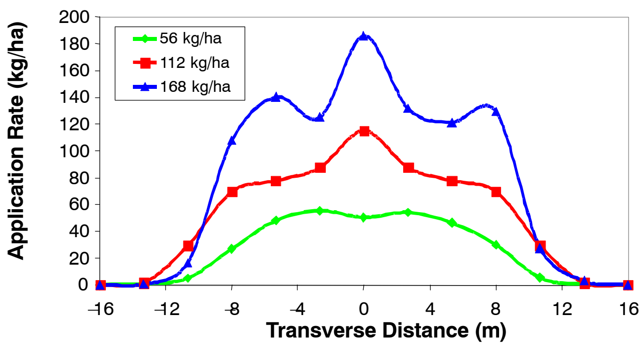

Figure 4. Low, medium, and high distribution patterns.

chosen to represent high, medium, and low application rates (fig. 4). The modeled uniform 168.1 and 56.0 kg/ha distribution patterns determined by Fulton et al. (2001) were used to represent the high and low rates, respectively. The medium rate was selected as 112.1 kg/ha, and the associated distribution pattern was extracted from the appropriate location of the rate change (56.0 to 168.1 kg/ha) application surface created by Fulton et al. (2001). Each distribution pattern was scaled using its summed deposition for that pattern. The application rate ranges for these three categories and the scaled distribution patterns are presented in table 2.

Next, the FAFs were used in combination with the appropriate distribution patterns to create an "as–applied" surface for this field. To merge this data and create the "as–applied" surface, an Avenue script was developed for ArcView (ESRI, 1999). A single script was written to read the reprojected shape file, determine the applied volume, and then assign application polygons at each point representing the appropriate distribution pattern.

The first function performed by the script was to compute the amount of murate of potash applied per point by taking the difference in the total amount between consecutive points. A new column was generated within the database file to represent the quantity of material applied per point. The next step was to create polygons at each of the logged GPS fixes. This rectangular polygon was further subdivided into 13 equal–width rectangular sub–polygons, which were each assigned an application rate based upon the amount of material applied at the corresponding point.

The user was prompted for an offset distance to help improve the positioning of the application polygons. This offset distance provides a means to account for separation distance between the GPS antenna and actual point of application on the spreader. The GPS antenna on most spreaders is mounted on the cab or near the front of the spreader, while the spinners or application point is at the rear. In most cases, the applied material lands behind the dispersion point of the spinner discs. The Avenue script performs this spatial shift by moving all the points in the reprojected FAF back in time based on each point's current position and heading.

Spread width was set at 34.7 m based on the single–pass test data collected by Fulton et al. (2001). The length of the polygon was calculated from the distance between the midpoint of the GPS fix of interest and the GPS fixes on either side (fig. 5a). Based on these dimensions, a rectangular

Table 2. Scaled distribution pattern data.

Range (kg/ha)	Pattern Location (m)												
	–16.00	–13.35	–10.68	–8.00	–5.34	–2.67	0.00	2.67	5.34	8.00	10.68	13.35	16.00
0 – 75.0	0.000	0.0016	0.0167	0.0927	0.1436	0.1674	0.1557	0.1715	0.1488	0.0837	0.0158	0.0025	0.000
75.1 – 150.0	0.000	0.0021	0.0452	0.1079	0.1201	0.1357	0.1779	0.1357	0.1201	0.1079	0.0452	0.0021	0.000
150.1 – 225.0	0.000	0.0031	0.0278	0.1309	0.1227	0.1330	0.1880	0.1264	0.1420	0.1089	0.0167	0.0006	0.000

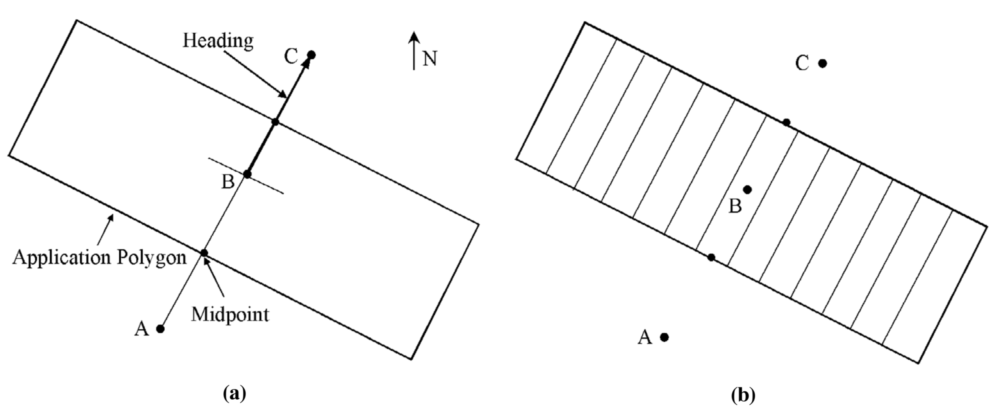

Figure 5. Polygon assignment to point B showing: (a) length and heading determination for proper orientation, and (b) division into 13 sub–polygons for distribution pattern allocation.

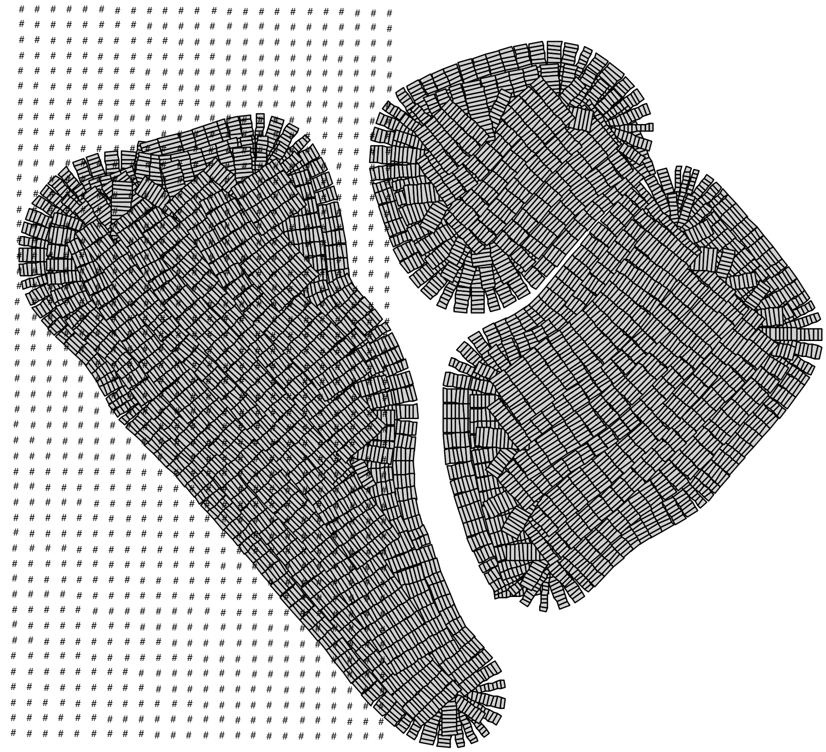

Figure 6. Grid generation (only left half shown) for specification of the “as–applied” surface for field A.

polygon was generated and assigned to each GPS fix. To orient the polygon, the heading of the spreader truck was determined by calculating the azimuth between the point of interest and the next point in time (fig. 5a). The polygon was then rotated perpendicular to the heading, as shown in figure 5.

Once oriented, the polygon was sub–divided (normal to the direction of travel) into 13 equal sub–polygons to facilitate the assignment of the distribution pattern (fig. 5b). The resulting distribution pattern polygon layer can be seen in figure 6. The start and end of pass points required a slightly altered method for applying a polygon since three consecutive points (one on either side of the point of interest) did not exist for determining a midpoint and heading. To resolve this situation, a ghost point was placed at a distance from the point of interest equal in magnitude to the distance between the point of interest and the adjacent point in the opposite direction. This provided a means to calculate a heading and assign a polygon for these unique cases.

The next step performed within the Avenue script was assigning the amount of applied material to each polygon. The normalized distribution patterns in table 2 were used to specify the distribution of material applied at each sub–polygon. The amount of murate of potash applied at the point of interest was multiplied by the scaled level of deposition for each sub–polygon. The applied quantity of material in each polygon was converted to an application rate by dividing this quantity by the polygon area.

A matrix of points was generated (fig. 6) for specification of the “as–applied” surface. Only half of the matrix is shown to better display the polygon layer. The user was prompted for the grid spacing. A 3.05 m spacing was chosen for field A. At each point, the application rates were summed for all intersecting polygons to estimate the total application rate,

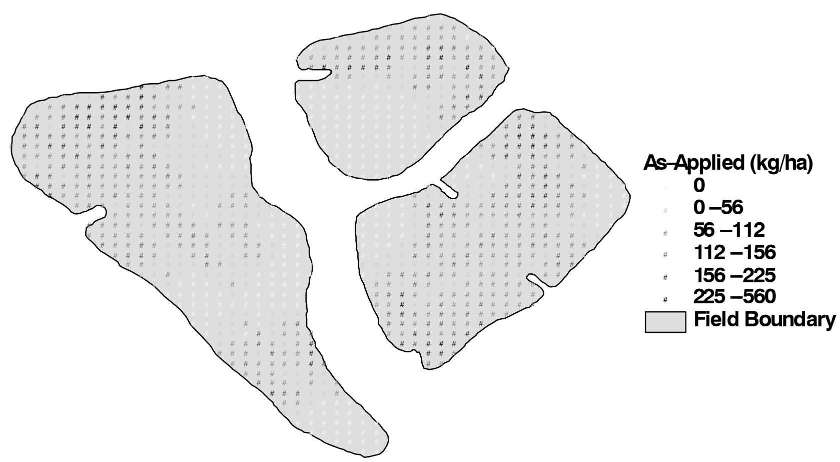

Figure 7. Generated “as–applied” surface for field A.

Table 3. Summary statistics for the "as–applied" surface for field A.

Total number of points	952		
Application rate (kg/ha)			
Minimum	0.0		
Maximum	557.3		

Range (kg/ha)	Percent of Points	Percent Correct (%) Within 5 kg/ha	Percent Correct (%) Within 10 kg/ha
0.0	40.0	72.0	80.0
78.3 – 80.0	11.8	8.0	18.8
80.1 – 90.0	21.6	16.5	27.7
90.1 – 100.0	7.1	13.2	23.5
100.1 – 110.0	3.9	10.8	27.0
110.1 – 120.0	6.4	14.8	29.5
120.1 – 166.2	9.6	6.6	12.1

thus creating the "as–applied" surface (fig. 7). Table 3 presents the summary statistics for the generated "as–applied" surface for field A.

The last step was to compare the "as–applied" surface to the prescription map to assess application accuracy for field A. Figure 8 shows the "as–applied" surface superimposed over the prescription map for field A with corresponding legends used for each map to provide a visual portrayal of application errors. Thus, visible points indicate deviations from the prescription map.

Validation of the "as–applied" spatial data model consisted of randomly placing collection pans within fields B and C. A total of 29 and 58 pans were placed in fields B and C, respectively, to collect applied murate of potash. Fulton et al. (2001) described collection pan size, which was in accordance with ASAE Standard S341.2 (*ASAE Standards*, 1997). The prescription maps were uploaded into the control system of the VRT applicator. The experienced machine operator was instructed to apply as normal, ignoring the pan placement during application. Figures 2 and 3 show the application traverse for each field representing the FAF created by AgView. A foam marker was used for guidance. For these fields, the operator did not drive over some management zones that required zero application in order to save time. Subsequent to application, test pan locations were recorded using a DGPS receiver (figs. 2 and 3). The murate of potash collected in each pan was bagged, identified, and weighed. The ratio of sample mass to pan collection area provided the actual application rate.

Each field's validation points were imported into ArcView 3.2 along with the "as–applied" files. The "as–applied" procedure was implemented as described above by reprojecting all shape files into Kentucky State Plane North and then executing the Avenue script. For fields B and C, the Avenue script was executed twice. The first run used the validation shape files in place of the matrix layer to predict the application rates for each validation point. These predicted results were then compared to the actual application rates to assess the "as–applied" spatial data model accuracy. The second run was used to generate an "as–applied" surface for each field (figs. 9 and 10). The generated "as–applied" surfaces are a 10 × 10 m grid of points. Table 4 contains summary statistics for the validation points (actual and predicted) and "as–applied" surfaces for these two fields.

Finally, the effect of different offsets on the validity of the spatial data model was investigated. The Avenue script was executed repeatedly using different offsets for each field. The actual and predicted data for each offset was compared to determine the best offset for each field.

Results and Discussion

The prescribed application rates for field A ranged from 0.0 to 166.2 kg/ha for the various management zones (table 1). Zones requiring no murate of potash made up 37.6% of the field area, which is depicted in figure 1. A total of 16 zones, or 62.4% of the field area, required some application of murate of potash.

The "as–applied" surface (fig. 7) shows a large range in the predicted application rates. A total of 952 points represented the "as–applied" surface with rates ranging from 0 to 557 kg/ha (table 3). Figure 8 presents an overlay of the "as–applied" surface and prescription map for field A. The legends for these layers are equivalent; therefore, visible points correspond to deviations from the desired application rates. Variability existed within all the management zones; those zones requiring the highest application rates had the most variability. Zones requiring no application typically exhibited less variability, which would be expected since no material was applied.

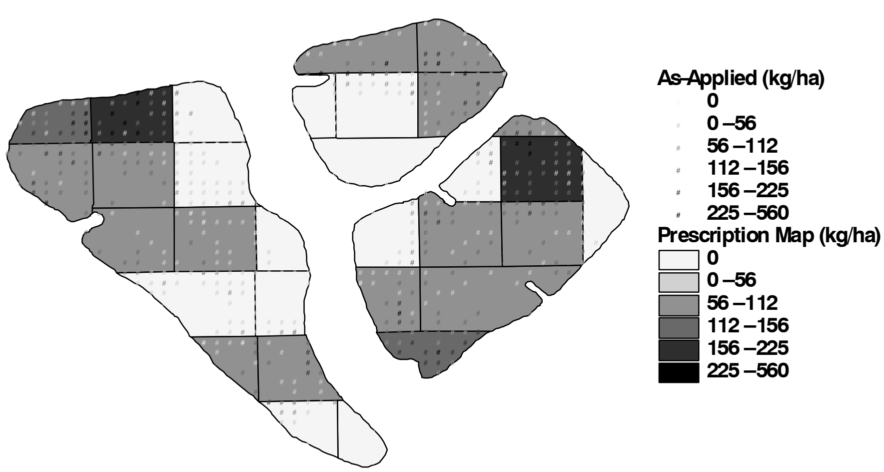

Figure 8. "As–applied" surface superimposed on the prescription map for field A.

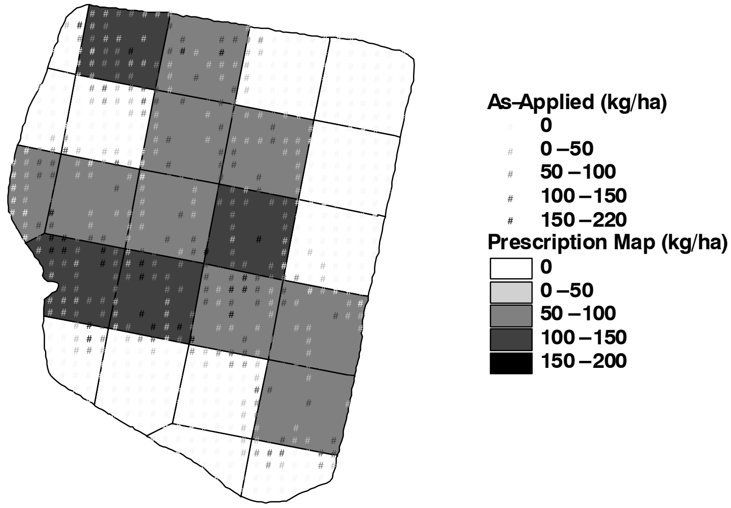

Figure 9. "As–applied" surface superimposed on the prescription map for field B.

Figure 10. "As–applied" surface superimposed on the prescription map for field C.

Table 4. Statistics for the various layers of fields B and C.

Validation Points	Field B	Field C
Number of points	29	58
Predicted application rate (kg/ha)		
Minimum	0.0	0.0
Maximum	141.1	233.4
Actual application rate (kg/ha)		
Minimum	0.0	0.0
Maximum	133.3	292.4
As–Applied Surface		
Number of points	909	3420
Application rate (kg/ha)		
Minimum	0.0	0.0
Maximum	218.7	803.5

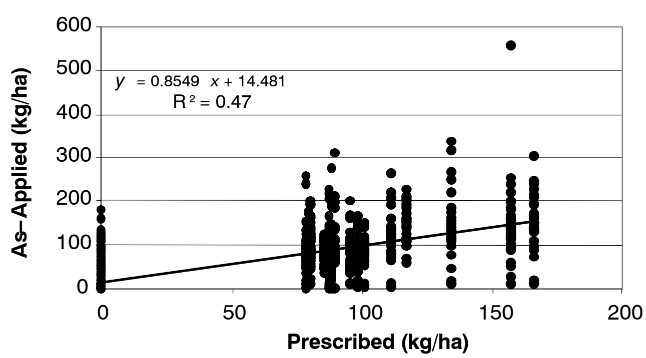

Figure 11. Prescribed versus the "as–applied" (predicted) application rates.

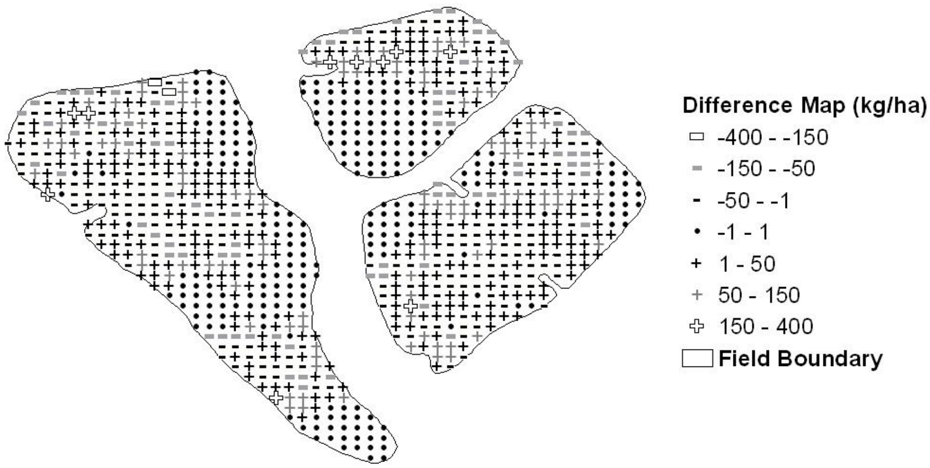

Figure 12. Difference between the "as–applied" surface and prescription map for field A.

Table 3 provides a statistical breakdown of the distribution of application rates for the "as–applied" surface. As expected, the best results were in zones requiring zero application. Forty percent of the points received 0.0 kg/ha, with 80% of those points within 10 kg/ha of the desired 0.0 kg/ha application rate. The results do not indicate that application errors were rate sensitive for the spreader. None of the rate categories appear to generate larger errors than others. However, the percent correct numbers seem to show that the spreader performed slightly better in the range from 80 to 120 kg/ha. The two outermost ranges, disregarding the 0 kg/ha category, showed the greatest errors for both the within 5 kg/ha and within 10 kg/ha columns.

Few points from the "as–applied" surface were close to the desired application rates of the prescription map. The number of correct points for the within 10 kg/ha column was between 12% and 29% for most application ranges. These small percentages represent deviations from the prescription map that are indicative of poor application by the spinner spreader.

Seven percent of the points were greater than the maximum application rate (166.2 kg/ha) called for by the prescription. These high values could be attributed to errors ranging from control issues, such as hydraulic flow variations during rate changes, to multiple overlaps at headlands. It appears that many of the high rates occurred near the headlands.

The prescribed applications rates were compared to the "as–applied" (predicted) rates using linear regression (fig. 11). The relatively low R^2 value of 0.47 indicated a weak relationship between the predicted and prescribed application rates. An R^2 of 0.70 or higher would seem to specify a more acceptable application job. It must also be recognized that shortcomings of the model may contribute to the low application accuracy.

A difference map was created to compare the "as–applied" surface to the prescription map (fig. 12) to show the areas receiving over– and under–application of murate of potash. The legend was selected so that the large and dark symbols indicate larger deviations. The plus signs indicate over–application, while the minus signs represent under–application. Circles represent only slight variability from the desired prescription applications. As discussed above, the most accurate applications occurred in the zones requiring no application, with a high percentage (95%) of the circles falling within the 13 zero application zones. A few black symbols can be seen, but most of the difference appears to fall between –50 and 50 kg/ha. Table 5 presents a breakdown for rate difference ranges found in the legend of figure 12. Nearly 79% of the points occurred between –50 and 50 kg/ha. Very few points (1.4%) were in the ranges of –150 to –400 kg/ha and 150 to 400 kg/ha. The summary statistics indicate more over–application than under–application, which could be indicative of the operator not maintaining a large enough pass–to–pass spacing. The benefit of a difference surface is that it provides a quick visual assessment of application errors.

Deviations from the desired application rate may be attributed to many factors. The control system was incapable of performing instantaneous rate changes at zone boundaries, thereby creating a situation in which the desired rate at zone boundaries was rarely achieved. This was most prevalent along zone boundaries that specify no application (fig. 8). The AgView software used in this study incorporated a "look–ahead" feature that initiates rate changes early to compensate for actuator lag. A 3 sec "look–ahead" time was used for this spreader system based on the results of Fulton et al. (2001). Similarly, the "as–applied" points around the field boundary seemed to receive reduced rates. This is apparent in management zones at the top of figure 8. These under–applied areas could result from the proximity to the periphery of the field, where parallel overlapping passes by the spreader were not performed.

The path chosen by the operator influenced material application accuracy for fields A and C. Many times, the operator was unable to navigate parallel to management zone

Table 5. Rate difference categorization between the "as–applied" surface and prescription map for field A.

Rate Difference Range (kg/ha)	Percent
–150 to –400	0.2
–50 to –150	8.6
–1 to –50	22.1
–1 to 1	28.0
1 to 50	28.6
50 to 150	11.3
150 to 400	1.2

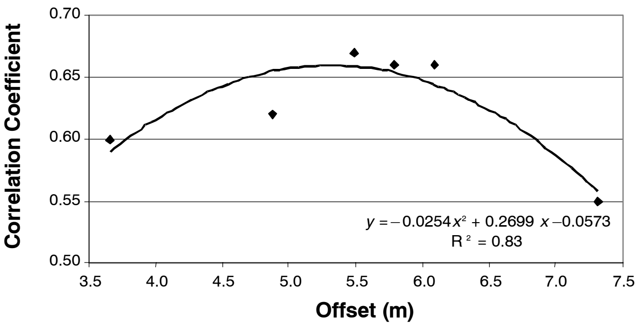

Figure 13. Plot of the correlation coefficient versus offset distance for field B.

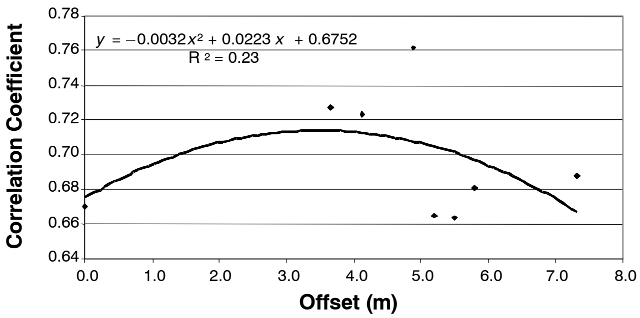

Figure 14. Plot of the correlation coefficient versus offset distance for field C.

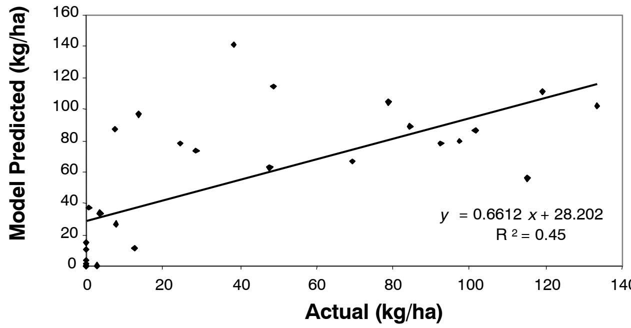

Figure 15. Plot of predicted versus actual application rates for field B.

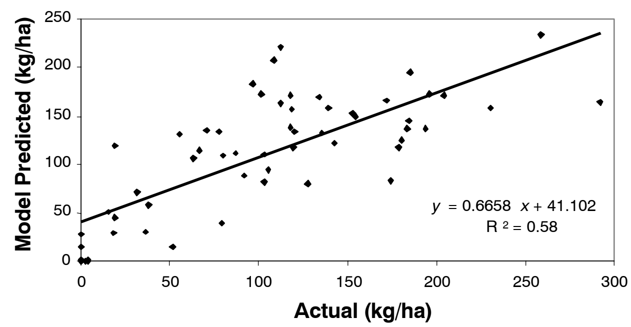

Figure 16. Plot of predicted versus actual application rates for field C.

boundaries (figs. 1 and 3). For these fields, the operator drove diagonally to the management zones since that provided the longest, straightest parallel passes for covering these irregular shaped fields. The traffic pattern in field B was parallel to the zones (fig. 2). There were noticeably more errors in fields A and C, especially in the zone corners where the spreader was in a particular zone for only a brief period of time. Orienting management zones parallel to traffic patterns could improve application accuracy. Misalignment of zones to traffic patterns is typical with irregular–shaped fields. Regardless of the chosen traffic pattern, the "as–applied" spatial data model should properly predict the application of granular materials.

Another factor affecting application accuracy was pass–to–pass spacing. The effective spread width of this applicator was 16.0 m. However, parallel passes and spacing varied in all three fields, as can be observed in figures 1, 2, and 3.

The validation of the "as–applied" spatial data model focused on its predictability and not on comparing the "as–applied" surfaces to the application prescriptions. Figures 9 and 10 demonstrate that significant differences exist between the prescription maps and "as–applied" surfaces for fields B and C. The legends for each layer are the same; therefore, the appearance of a point illustrates deviation from the desired application. Both "as–applied" surfaces show noticeable deviation from the prescription maps for VR application of murate of potash.

Various offset distances were used in the model to determine the effect on the "as–applied" surfaces. The user–selected offset distance serves to compensate for GPS latency and antenna position in relation to the application point. The predicted application rates for each offset were then compared to the actual application data. An offset of 5.5 m produced the highest correlation (R = 0.67) for field B, with 5.8 m and 6.1 m offsets resulting in correlations of 0.66 (fig. 13). The highest correlation (0.76) for field C was found at an offset of 4.9 m (fig. 14). A polynomial regression line was fit to the offset data. The polynomial fit for field B (fig. 13) indicates that the appropriate offset is somewhere around 5.5 m. However, a poor polynomial fit was found for field C (fig. 14). From this fit, an offset of 3.5 m provided the best results. Therefore, offsets of 5.5 m for field B and 4.9 m for field C were selected for analyzing the validity of the model. These were the highest correlation coefficients computed for each field. Thus, these offsets were entered into the model for predicting the application rate at each validation point.

The reason for the different offsets for each field is not understood. It would be expected that the same offset distance would generate the highest correlation coefficient for predicting the application rates on each field. However, only a 0.6 m variation existed, which is relatively small compared to the size of the machine. The same spreader setup was used on each field, but the difference could be that application occurred on different days at varying ground speeds. Variations in murate of potash sources (particle density and origin) may have contributed to the differences.

The actual versus predicted application rates for the validation points were plotted to determine the performance of the "as–applied" spatial data model (figs. 15 and 16). As can be observed, the model's performance was not extremely strong in predicting the actual application rates. A linear regression was fitted to the data (figs. 15 and 16), confirming this observation. Coefficients of determination (R^2) equal to 0.45 (field B) and 0.58 (field C) along with slopes around 0.66 were computed, indicating a weak linear relationship. As can be seen, the model worked better on Field C. Although the model showed weak correlation with the actual application rates, it performed better than expected considering the

Table 6. Comparison of various layers.

Comparison	R^2 Field B	R^2 Field C
Actual versus predicted	0.45	0.58
Actual versus prescription map	0.16	0.21

current shortcomings of representing the application area with rectangular polygons.

Very poor correlations were found between the actual application rates and prescription maps for fields B and C (R^2 values of 0.16 and 0.21, respectively; table 6). These values are much lower than those determined when comparing the actual and predicted application rates. This is indicative of poor performance by the VR spinner spreader. The VRT spinner spreader was unable to apply what the prescription required. Possible explanations for the high deviations may include VRT hardware and software latency, operator error, and spreader setup and calibration.

The low correlation observed also shows that the "as–applied" spatial data model better estimates actual application rates than prescription maps. Application errors exist for both fixed and VR application. The assumption that VRT application is consistent with prescription maps is misleading. Further, these low correlations demonstrate that using prescription maps for analysis purposes is not appropriate. While the "as–applied" surfaces do not accurately predict actual application rates, they appear to be a better representation of actual application than the prescription maps. However, modifications to the current model are needed to improve "as–applied" map generation accuracy.

Summary and Conclusions

"As–applied" surfaces were generated in ArcView using distribution patterns characterized by Fulton et al. (2001) and an FAF. Avenue scripts were written to generate the "as–applied" surfaces by merging the distribution pattern information and the FAF within ArcView. "As–applied" surfaces were compared to prescription maps to assess application errors and demonstrate the utility of "as–applied" surfaces. An R^2 of 0.47 was calculated for field A, indicating poor performance by the VR spinner spreader. The resulting "as–applied" surface showed errors existed especially at the intersection of management zones where rate changes occurred. Variability also existed within zones requiring higher application rates. Zones requiring zero application received only a small amount of material proximal to the borders of zones requiring murate of potash. This illustrated the need to properly set the "look–ahead" time in software application packages to improve application during rate changes when moving between zones. A difference surface was also generated to provide a visual representation for the spread quality by showing areas receiving over– and under–application of murate of potash.

Validation studies showed that the current "as–applied" spatial data model did a reasonable job of estimating field application of murate of potash. Even though relatively weak relationships (R^2 values of 0.45 and 0.58) were found between the predicted and actual application rates for fields B and C, respectively, the "as–applied" surface provided a better estimate of actual application rates than the prescription map. Very poor correlations (R^2 values of 0.16 and 0.21) were determined between the actual application rates and prescription maps for field B and C. These results reveal the undesirable performance of the VRT applicator, as well as the inability of prescription maps to depict actual application of products. Ultimately, this lack of correlation could be indicative of escalated application errors when moving from fixed– to variable–rate application.

Offsets of 5.5 m (field B) and 4.9 m (field C) were determined to produce the best results for generating the "as–applied" surfaces. The reason for this difference in offsets is unknown. The effect of offset on the "as–applied" results needs further investigation to determine if different offsets are needed on a field–by–field basis. However, the difference (0.6 m) for these results is small when considering the application area of granular products.

In conclusion, the significance of this "as–applied" spatial data model is that it represents how granular materials are distributed during field application using spinner spreaders. The "as–applied" spatial data model developed provides important insight into understanding VRT application errors. Making the assumption that the prescription map represents field application and using it for analysis purposes is misleading. Without properly knowing how materials are distributed across fields, true evaluations cannot be made about VRT.

Future Work

The low correlations found between the model and actual application rates indicated that improvements are needed to the current "as–applied" model. Perhaps the most significant improvement warranted is to model curvilinear travel with annular or trapezoidal polygons. Currently, the rectangular representation (fig. 6) creates open spaces and overlap between polygons when moving in a curvilinear fashion. In addition, the incorporation of a simulation technique to account for distribution pattern variability is needed to better represent field application by a spinner spreader. Finally, the last modification consists of investigating the possibility of modeling the distribution pattern in two dimensions instead of one dimension. Additional validation will be required to ensure the efficacy of the approach for use with multiple granular products and different classes of application equipment.

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