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TESTING APPROPRIATE ON-FARM TRIAL DESIGNS AND STATISTICAL METHODS FOR COTTON PRECISION FARMING

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Abstract

Precision agriculture in cotton has lagged behind the use of spatial technologies in grain and oilseed crops because the commercialization of cotton yield monitors (YM) occurred several years after the introduction of grain yield monitors. In 2001, 37% of U.S. corn acreage was harvested with a YM, but less than two percent of U.S. cotton was harvested with a YM. Now that cotton yield monitors are available, cotton farmers' interest in on-farm comparisons is growing. Cotton YM data can be collected on-the-go, and planned on-farm comparisons implemented, harvested and analyzed without interfering with crop production. This is particularly important for some inputs specific to cotton such as midseason insecticides, growth regulators, and defoliants applied with aerial applicators. If farmers want to compare input products or rates, larger treatment blocks would be easiest to implement. The objective of this study was to determine if spatial analysis could lead to better farm management decisions from the limited replication data farmers currently collect with cotton YM.

To demonstrate how spatial analysis methods apply to on-farm cotton research, two regression methods were used on large block tillage comparisons. Four tillage treatments were applied to cotton at the University of Arizona's Maricopa Agricultural Center. Results indicate that ANOVA using a spatial regression model provides more accurate results compared to standard ANOVA. When standard ANOVA was used, significance levels indicated two treatment variables were different from the mean at the 10% level and one at the 5% level while with spatial ANOVA three treatment variables were different from the mean at the 5% level and one at the 1% level. These results indicate more information is gained about local variations over the production surface when spatial autocorrelation is taken into account. Using ordinary ANOVA, these effects would not be identified.

Introduction

Many cotton farmers conduct on-farm comparisons (OFC) of new varieties and other categorical practices in large non-replicated blocks. Although these OFC are not considered statistically valid from the perspective of traditional agronomic research methods, farmers nevertheless continue to conduct these comparisons to provide information for farm management decisions. With precision agriculture (PA) technologies and spatial regression methods, farmers have new opportunities for OFC. The general objective of this study was to determine if spatial analysis could help cotton farmers make better use of the limited replication data they currently collect with PA technologies, specifically cotton yield monitors (YM).

PA is information technology applied to agriculture, including global positioning systems (GPS) and geographical information systems (GIS). PA technologies have spread rapidly with 36% of corn and 29% of soybean acreage harvested in 2001 and 2002, respectively using YM. However, YM cotton acres harvested were below two percent of the total (Griffin et al., 2004a). Approximately half of all 2004 corn and soybean acres harvested are expected to be harvested with a combine equipped with a YM. It is expected that cotton YM adoption will follow similar patterns.

In grain YM data collection, spatial analysis is being used to improve the reliability of farm management decisions. Spatial analysis combines techniques from geography, geostatistics, and regional economics and applies them to YM data. For cotton, spatial analysis can help growers and those that advise them to cope with the large plots required by aerial application and spatial patterns created by irrigation or natural soil factors. The finer scale row data from cotton monitors allow greater spatial detail and flexibility in analysis. Suspect data points, outliers or even entire cotton rows may be removed from analysis leaving an adequate number of observations.

Several publications have described OFC in mechanized agriculture (Anderson and Honeyman, 1999; Bramley et al., 1999; Knighton, 2001; Nafziger, 2003; Whelan et al., 2003; Wittig and Wicks, 2001) and the economic ramifications when replications, treatments, or site years are reduced (Young et al., 2004). These methodologies for OFC were derived from small plot designs developed in the early 20th century for the technology available at that time. These publications recommend designs such as strip or split planter trials to accommodate variability across the field. Some studies have taken OFC a step further by integrating PA technologies to measure variability and record yield data (Adams and Cook, 2000; Anselin et al., 2004; Brouder and Nielsen, 2000; Doerge and Gardner, 2001; Griffin et al., 2004b; Knight and Pettitt, 2003; Lark and Wheeler, 2003; Lowenberg-DeBoer, 2002 a and b; Lowenberg-DeBoer et al., 2003; Lyle et al., 2003; Nafziger, 2001; Nielsen, 2000; Whelan et al., 2003). This study builds upon the work of Griffin et al. (2004b), Lowenberg-DeBoer et al. (2003), Hurley et al. (2001), Lambert et al., 2002, and Anselin et al. (2004) and applies it to cotton.

It has long been known that crop yields vary spatially, even over small areas. Fisher reported that one acre of wheat in 1910 at Rothamsted was harvested in 500 small plots, with yield varying by approximately 30% from the mean (Fisher, 1931). Field heterogeneity is not randomly but systematically distributed, with plots near one another more alike than plots farther apart (Fisher, 1931; Littell et al., 1996). This spatial autocorrelation has traditionally been counteracted by reducing experimental unit sizes, i.e. plot size, until it could be assumed that the experimental units were homogeneous. In addition, randomization and replication were used with entire replicates placed such that no spatial autocorrelation was assumed to exist in replicates (Fisher, 1926). Data on soils, topography or other field characteristics are used with spatial analysis to help explain patterns. Inference drawn from analysis of variance (ANOVA) results is compromised when spatial autocorrelation is present in the data (Griffin et al., 2004b). If the systematic component of variability can be appropriately analyzed, farmers can have more confidence in results from their experiments.

From the standpoint of classical statistics, one of the key problems with PA data, and particularly YM data, is that it is inherently spatially autocorrelated. Spatial regression methods are useful for modeling spatial autocorrelation (Anselin, 1988; Cressie, 1993). Lambert et al. (2002) identified several types of spatial statistics appropriate for analyzing spatially autocorrelated YM data. Anselin et al. (2004) and Hurley et al. (2001) used spatial statistics to analyze data from designs derived from small plot statistics. Lowenberg-DeBoer et al. (2003) suggested that large block limited replication designs may be appropriate if spatial statistics are used. Cressie (1993, p 7) wrote that “in areas such as geology, ecology, and environmental science, it is not often possible (nor always appropriate) to randomize, block, and replicate the data. There is a need for new statistical models and approaches that address new questions arising form old and new technologies.” This idea can be extended to the agricultural field sciences with PA as an example of a new set of technologies.

Many university extension systems provide regional recommendations for input use under general agricultural practices. Better farm management decisions can often be made by incorporating OFC results. Lowenberg-DeBoer and Urcola (2003) report most commercial Corn Belt farmers do some planned comparisons each season. Most of these comparisons are large block, split field or paired field designs. Farmers base their decisions on average yield per block or field, paying little attention to within field variability. OFC data seem to be most important for farmers who use YMs. Cotton farmers are expected to conduct similar experiments.

Traditional agronomic cotton OFC use small plot designs intended to reduce heterogeneity within experimental units. Small plot designs such as randomized complete blocks (RCB), latin squares and split plots require intensive planning, management, and labor efforts during planting and harvesting operations. During these times, farmer's value of time and labor is highest, discouraging implementation of these experimental designs. Familiar experimental designs are often costly and cumbersome, interfering with production logistics. Even though OFC designs derived from small plot research, such as strip or split planter trials, reduce time requirements compared to RCB designs, perceived benefits of research may still not overcome resource and time costs.

There are also logistical problems with strip trials. For split planter trials on a farm with a four-row cotton picker, filling every four rows of planter boxes with a different variety, seed treatment, furrow insecticide or fungicide potentially leads to human error. When a change of treatments is made, filling planter boxes with small quantities of seed and cleaning boxes for successive varieties hinders planting operations. With larger farms, the person planning may not be the person planting, potentially leading to communication and coordination problems. From the research analysis viewpoint, it is a complex and tedious task to keep treatments and cotton picker passes in line.

Timing and application of inputs for cotton production complicate implementation of OFC. In general, cotton farmers apply more inputs than grain farmers. In addition to variety, fertilizer, herbicide, and planting time insecticide treatments commonly used by grain farmers, cotton producers might wish to compare mid-season application of insecticide, growth regulator, or defoliant products. Aerial applications are quite common in cotton, so strip trials are hard to implement. Furrow irrigation is commonly used in cotton. Important differences in the amount of water plants receive from one end of a field to the other can occur.

Many of the problems associated with small plot, strip designs, or specific factors affecting cotton OFC could be eliminated if large experimental units were appropriate OFC designs. Many farmers already conduct planned comparison experiments on single non-replicated large blocks, particularly with new varieties to guide seed decisions in subsequent years. This effort to compare treatments indicates farmers are interested in conducting OFC and willing to implement large single block designs. They choose experimental designs for which the cost (mainly in terms of time) is acceptable relative to the perceived benefit. For instance, instead of cleaning planter boxes and taking the time to refill them with selected varieties or different types of treated seed, with large block designs planter boxes are filled with the same product and then treatments are changed during normal reloading times. Other than planning and analysis in the off-season, large block designs require minimal additional effort during planting or harvesting time compared to classical designs. Large blocks also offer the advantage of being less sensitive to human and mechanical error or treatment edge effects, especially from drift and mobility of pesticides and pests.

PA technologies such as GPS, YMs and others provide many geo-referenced observations per acre at relatively low cost. Aside from calibration, collecting YM data requires little extra time during harvest season. The cotton picker YM has a distinct benefit over the combine YM because it can collect data by row. Combine YMs aggregate data across combine heads which may be 30 feet (8 meters) wide or more. To generate usable data, grain growers need to be very careful that harvest passes match exactly the pattern of planter or input application equipment to avoid mixing yields from different treatments. Large blocks offer the benefit of manageable treatment edge effects. If edge effects are thought to exist, YM points near treatment borders can be excluded from analysis.

Methodology

The field study was conducted at the University of Arizona's Maricopa Agricultural Center 25 miles (40 km) south of Phoenix in 2002. Two soil series dominated the field; Mohall (fine-loamy, mixed hyperthermic Typic Haplargid) and Casa Grande (fine-loamy, mixed hyperthermic Typic Natrargids). These sodic-saline alluvial soils formed in the floodplain of the Santa Cruz River. The six-hectare precision-leveled field was planted to cotton (*Gossypium hirsutum L.*, cv Delta Pine 448B). Operations included a conventional and three reduced tillage treatments; Conventional (shred, disk, rip, disk, list), Rotovator (shred, rotovate), Sundance (shred, root pull, rip/list), and Pegasus (single combined operation) in five large block replications (Figure 1). The individual treatment strip size ranged from 540 feet (165 m) long in the north to 570 feet (174 m) in the south. Treatment blocks were approximately 130 feet (40 m) or 40 cotton rows wide for Conventional and 36 feet (11 m) or 12 cotton rows wide for the other three reduced tillage treatments.

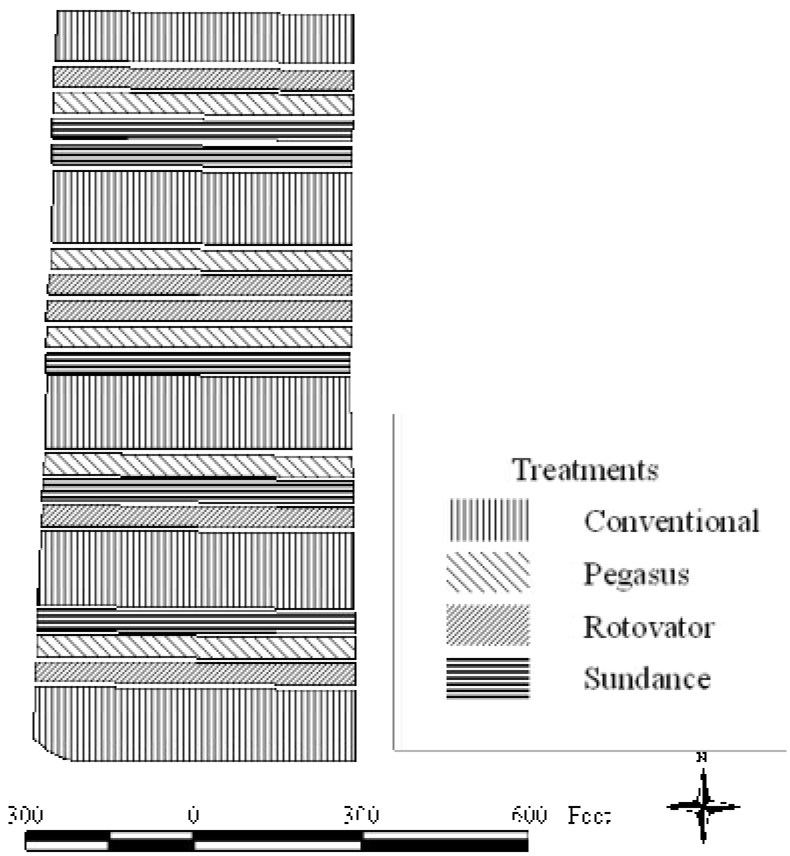

Figure 1: Experimental design of tillage treatments.

Soil clay content was derived from EM38 measurements and calibrated with additional samples analyzed in the laboratory. Yield data from a four-row picker was collected by optical flow sensors in an AGRIplan system and aggregated before logging. A weigh boll buggy was used to monitor the calibration of the cotton picker YM.

Analysis

Yield, soil clay content, and treatment location data were analyzed in ArcView (ESRI, Redlands, CA). YM data was appended to the less dense soils data by taking a simple average of all yield data points within 13 feet (4 m) for the purpose of assigning dependent data points (yield) to the location of explanatory variable data points (soil data) in the statistical analysis. A spatial weights matrix constructed on observations within a Euclidean distance of 23 feet (7 m), the minimal distance allowed by the software for the data, was created in GeoDa (Spatial Analysis Laboratory, University of Illinois, Urbana-Champaign, IL) (Anselin, 2003). The Euclidian distance was chosen because the data set was imported as points rather than polygons. Cotton lint yield was the dependent variable while explanatory variables included percent clay content, tillage treatment dummy, and an interaction term of tillage treatment and clay content.

The whole field yield average was 4249 lbs ac^{-1} (4762 kg ha^{-1}) with a standard deviation of 901 lbs (1011 kg). Cotton yields ranged from a minimum of 1263 lbs ac^{-1} (1416 kg ha^{-1}) to a maximum of 6344 lbs ac^{-1} (7112 kg ha^{-1}) (Figures 2 and 3). Soil clay content ranged from a minimum of 7.9% to a maximum of 31.6% with a mean of 23.2% (Figures 2 and 3).

First, an analysis of variance (ANOVA) was run. Spatial diagnostics indicated that the ANOVA error terms were highly autocorrelated. A Moran's I was calculated from the residuals as 0.77 (p-value = 0.0010) indicating spatial autocorrelation was present in the data (Anselin, 1988) (Table 1). Robust Lagrange Multiplier tests indicated that spatial autocorrelation was in the residuals (error) rather than in the dependent variables (lag); therefore a spatial analysis of variance (SANOVA) regression was conducted since SANOVA can account for spatial autocorrelation. ANOVA and SANOVA regression results from GeoDa are presented in Table 1.

Table 1: Results from ANOVA and SANOVA

Variable	ANOVA		SANOVA	
	Estimate lbs ac^{-1}	t-stat*	Estimate lbs ac^{-1}	t-stat*
Intercept	1418.7	13.13	3838.1	24.02
Clay content	137.0	29.25	57.8	9.62
Pegasus	-338.2	-1.66	-623.7	-2.20
Rotovator	425.1	2.02	-1780.5	-6.70
Sundance	-273.8	-1.41	-1653.9	-5.57
Clay by Pegasus	-18.3	-2.19	-54.5	-5.17
Clay by Rotovator	-38.7	-4.30	17.0.	1.64
Clay by Sundance	-18.1	-2.18	-10.9	-0.97
Lambda	NA		0.92	172.82
Measures of fit				
Mean Squared Error	656		280	
Adjusted R^2	0.46		0.90	
df	2361		2361	
Diagnostics tests			Value	
Moran's I (error)			0.77	
Lagrange Multiplier (lag)			2492	
Robust Lagrange Multiplier (lag)			17.8	
Lagrange Multiplier (error)			2634	
Robust Lagrange Multiplier (error)			160.5	

* critical t-statistic is 1.56 for 10%, 1.96 for 5%, and 2.58 for 1% levels

Results

Traditional analysis using ANOVA indicated that only the Rotovator treatment was different from the Conventional treatment (Table 1). The Clay variable and all three Clay interaction coefficients are highly significant in the ANOVA. In the SANOVA the spatial autoregressive term (lambda) is highly significant suggesting that the non-spatial ANOVA analysis is misspecified and may provide misleading results. The Clay coefficient estimate is much lower in the SANOVA than in the ANOVA results, and only one Clay interaction term is significant in the SANOVA. In the ANOVA the Clay variables, including interactions, were probably absorbing much of the spatial structure effects. When spatial structure is explicitly modeled in the SANOVA, the Clay variables lose their spatial structure function and should more closely reflect the actual effect of clay on yield. When SANOVA was used, all three treatments and Pegasus by clay content interaction term were significantly different from the Conventional treatment. Expected yields for a range of clay levels with ANOVA and SANOVA estimates are plotted in Figures 2 and 3, respectively.

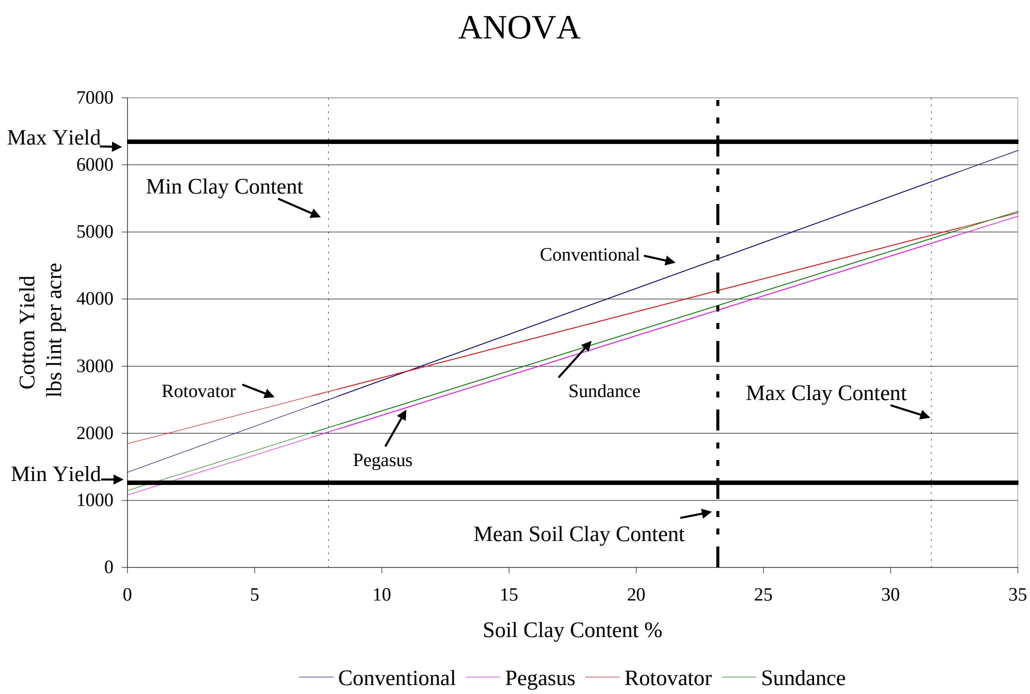

Figure 2: Predicted cotton yields using estimated ANOVA coefficients.

Both ANOVA and SANOVA figures show Conventional tillage yields above those of other tillage types over most of the range of clay levels found in the field. The SANOVA shows a clear separation with Conventional yielding more than the other tillage types over the whole range, while the ANOVA indicates that Rotovator yields are near those of conventional tillage for low clay levels. Among the reduced tillage treatments, both analyses show that at the mean Sundance and Pegasus are not statistically different from each other, and Rotovator is different from the other reduced tillage types. Among all treatments, only Sundance and Pegasus are not significantly different at the mean soil clay content at the 10% confidence level in either analysis method. At the mean soil clay content, Conventional was superior to Rotovator, which was superior to Pegasus and Sundance.

A key contribution of the SANOVA is that it clarifies the effect of soil clay on tillage choice. Probably because the clay variable was absorbing spatial structure, the yield response to clay content of all four tillage systems are similar under ANOVA estimation (Figure 2) while they are remarkably different when spatial structure of the YM and crop GIS layers is explicitly modeled (Figure 3).

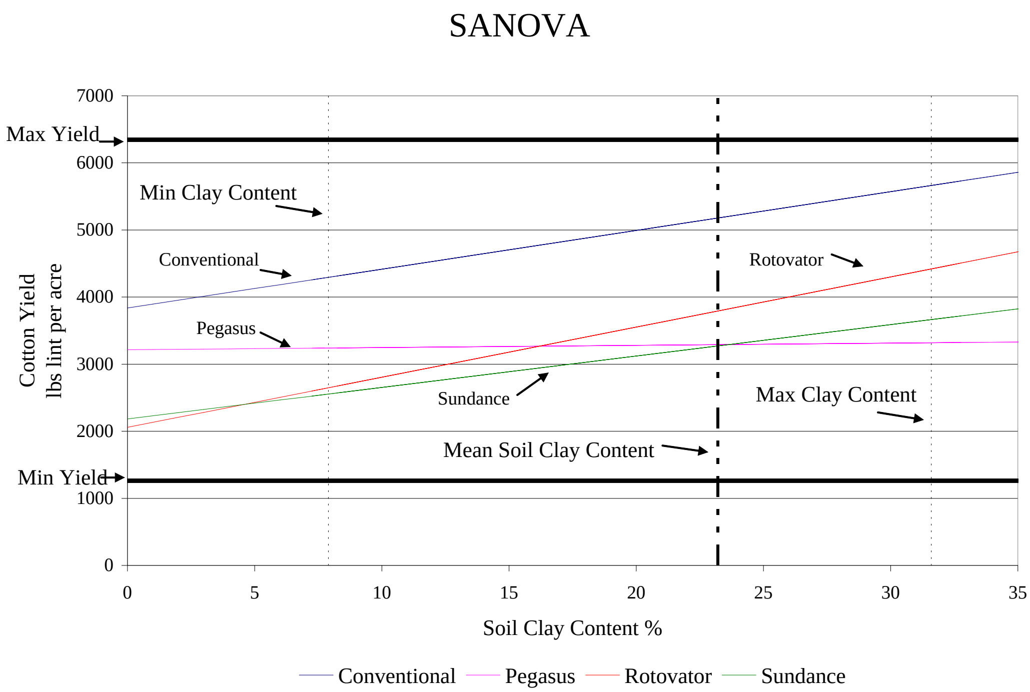

Figure 3: Predicted cotton yields using estimated spatial model coefficients (SANOVA).

If the grower were considering adoption of one of the reduced tillage systems, their decision would differ depending upon soil clay content and the analysis method used. Over the observed range of clay content percentages of the field and ANOVA results, the yield maximizing decision maker would choose Rotovator (Figure 2). However, when the SANOVA is used for decision-making Rotovator would be chosen for fields with over 16% clay content and Pegasus system considered for fields with less than 16% clay content (Figure 3).

If the relationships in the 2002 data were confirmed in subsequent seasons, a grower who wanted to use reduced tillage systems for soil conservation or other reasons might decide on a field-specific tillage plan. Varying tillage within fields is unlikely with current equipment because it would complicate logistics. But fields where soil clay content is low might be managed differently from those which have generally higher clay contents. Tillage effects may also be related to other soil and landscape properties such as slope, aspect, or organic matter.

Summary and Future Work

This study provides an example of the potential for spatial analysis of cotton yield monitor data. In this data set, the SANOVA more clearly demonstrated the yield superiority of Conventional tillage and it clarified the role of soil clay levels in choice of alternative tillage systems. The ANOVA analysis was misspecified because the assumption of independent errors was violated and the soil clay variable absorbed spatial structure effects. Spatial analysis techniques are being evaluated in four states on farmer-fields. If information that is more reliable can be gleaned from the limited replication data that growers are already collecting with YM data, they will be able to make better farm management decisions. These analyses have been conducted on corn and soybean in the Corn Belt, cotton from Arizona, and rice in the Mid-South. These methods have been shown to be beneficial especially for cotton because of unique input application practices and row-scale data. YM data analysis services have also been integrated into Purdue University's Top Farmer Crop Workshop (www.agecon.purdue.edu/topfarmer). Further testing and demonstrations of spatial analyses are being identified in other crops across differing regions.

Disclaimers

The purpose of this study was to compare traditional ANOVA analyses to spatial analysis methods in evaluation of treatments from farm-level field trials. Results are from a single year at a single location, therefore tillage system rankings are not intended to be used as generalizable knowledge across regions, growers, or tillage systems, but rather as a demonstration into alternative methods of on-farm experimentation and data analysis.

The opinions and conclusions expressed here are those of the authors and do not necessarily represent the views of the United States Department of Agriculture. Mention of specific suppliers of hardware and software in this manuscript is for informative purposes only and does not imply endorsement by the United States Department of Agriculture.

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