**In-Season Precision Applications of Fluid Fertilizer to Optimize Cotton Productivity and Nitrogen Use Efficiency**

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**Abstract**

Current nitrogen (N) fertility recommendations should possibly be modified because of the significant yield increases resultant from new cotton cultivars and improved management practices. On the other hand, it is essential to develop innovative approaches that can manage N fertilizer more efficiently to increase grower profitability due to substantially increased N prices. The objectives of this study for 2011 were to estimate the spatial variations in lint yield, normalized difference vegetation index (NDVI), leaf N concentration, and soil nitrate within a field, and to evaluate the relationships among cotton lint yield, canopy NDVI, and leaf N under Tennessee production environments. A field experiment was conducted on a private farm in Gibson County, west Tennessee in 2011. Five N application rate treatments of 0, 40, 80, 120, and 160 lb N/acre were evaluated as side dress N in large strip plots (38-ft wide running the length of the field) in a randomized complete block design with three replicates. Each strip plot was divided into eight 100-ft long sub plots. Soil nitrate and ammonium prior to cotton planting and after harvest, canopy NDVI readings and leaf N concentrations at the early square and early, mid, and late bloom growth stages, and lint yields at harvest were measured on a sub plot basis. The 2011 results showed statistically significant but weak correlations of lint yield with canopy NDVI readings no matter when NDVI values were collected. Canopy NDVI was not a strong indicator of plant N nutrition during early square to late bloom. There was significant global spatial autocorrelation of residual lint yields (N treatment effects on yields excluded) within the test field based on Moran's I statistic. The LISA cluster map showed that there were some significant local clusters of residual lint yields within this test field. Overall, there was significant global and some significant local spatial dependence of lint yields relating to the characteristics of this test field.

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### Introduction

Presently, nitrogen (N) fertilizers are recommended to be applied at 30-60 lb N/acre on bottom soils and 60-80 lb N/acre on upland soils before or at cotton planting in Tennessee. These recommendations have been used for decades without any major modifications. Because of the significant yield increases resultant from new cotton cultivars and improvements in management practices, there is a need to re-evaluate the current N recommendations to see whether N application rates are adequate for new cultivars to reach their optimal yield potentials.

On the other hand, there is an urgent need to develop innovative approaches that can manage N fertilizer more efficiently to increase grower profitability due to substantially increased N prices during the last several years. Overall, there are two major factors limiting N use efficiency in the current cotton N management systems. Firstly, the current N management systems were developed based on a state or regional scale, and they have no capability to cope with spatial variability within individual fields. Under the current systems, cotton producers use a uniform N fertilizer rate for the entire field or even the entire farm, which often results in under- and over-applications of N. Secondly, large doses of N are usually applied early in the season (pre-planting or at planting) before cotton plants can effectively uptake and utilize it; this puts the applied N at high risk to environmental losses. In order to solve these two problems, there is a need to develop new N management systems that can generate variable-rate N recommendations for different areas within a field and emphasize the application of N in the mid-season.

Measuring crop N nutrition status during the season by optically sensing crop canopy seems to be a viable precision N management tool for variable-rate N applications within the field, emphasizing N application in the mid-season, and minimizing the cost of N application. Researchers have utilized on-vehicle, real-time optical sensing of crop canopy to generate Normalized Differential Vegetation Index (NDVI) to assess crop N nutrition status. This approach enables on-the-go diagnoses of crop N deficiency, real-time applying N fertilizer at variable rates, and precisely treating each area sensed without processing data or determining location within a field beforehand. Research on wheat and corn has shown an about 15% increase in N use efficiency and some significant yield increases with this approach. So far, precision N research has been focused on wheat and corn. Little investigation has been documented on cotton.

The objectives of this study were to: 1) determine the optimal N fertilizer application rates for high-yielding cotton production systems in Tennessee; 2) estimate the spatial variations in lint yield, NDVI, leaf N concentration, and soil nitrate within a field; 3) investigate the relationships between lint yield and NDVI, and between NDVI and crop N nutrition status; and 4) if there is a significant relationship between cotton yield and canopy NDVI, then algorithms will be developed for variable-rate N applications within a field, based on the relationship between lint yield and NDVI. The algorithms for variable-rate N applications will be compared with the uniform-rate N application system in terms of N fertilizer consumption and lint yield. In 2011, our work focused on the Objectives 2 & 3.

Overall, if this project has been carried out successfully, it will provide accurate N fertilizer recommendations for high-yielding cotton production systems. It will also generate appropriate algorithms for in-season variable-rate N applications within a field on cotton. All these can significantly reduce N fertilizer consumption and improve cotton productivity, and thus increase grower profitability.

## Materials and Methods

A field experiment was conducted on a private farm in western Tennessee in 2011. The cooperative farmer was Jeff Dodd in Gibson County. The experiment in 2011 was conducted on the same field with the same plot layout as in 2009 and 2010. This producer applied 40 lb/a N across the test field as pre-plant N in the form of calcium nitrate (27% N) before cotton planting in 2011.

Five N application rate treatments of 0, 40, 80, 120, and 160 lb N/acre were evaluated as side dress N in large strip plots (38-ft wide strips running the length of the field) in a randomized complete block design with three replicates. The dates of cotton planting and N treatment implementation are presented in Table 1. Cotton was planted in 38” rows. This test was managed using the recommended best management practices except the N treatments (Table 1).

Each strip plot in this test was divided into eight 100-ft long sub plots. A composite soil sample was taken at a depth of 2-ft. for nitrate and ammonium in the soil profile on a sub plot basis prior to treatment initiation. Canopy NDVI data were collected from each sub plot at the early square and early, mid, and late bloom growth stages using the GreenSeeker® (NTech Industries, Inc., CA) RT 200 Data Collection and Mapping System (Table 1). A composite leaf sample (10 blades + petioles) was collected on a sub plot basis for four times at about the same dates when NDVI data were taken (Table 1). All leaf samples were analyzed for N concentrations using our own LECO Tru-Spec Analyzer. Cotton harvest was completed on a sub plot basis in early October by harvesting the central six rows of cotton. A post-harvest soil sample was collected for soil nitrate and ammonium at a 2-ft depth from each sub plot.

Correlations of lint yield with canopy NDVI and leaf N concentrations and the coefficient of variation (CV) for each strip plot were estimated using SAS Statistical Software v.9.1. Spatial variations in lint yield, canopy NDVI, leaf N, and post-harvest soil N within the experiment were visualized in GIS maps using ArcView v.9.3. A quadratic regression of lint yield was conducted using the classic and spatial error models in GeoDa 0.9.5-i (Beta) with a weight matrix created using a 2nd order queen's contiguity model that includes all lower contiguity orders. In order to evaluate the spatial dependence of lint yield relating to the characteristics of the test field (not to N treatments), we removed the effects of side dress N treatments on lint yields from the lint yields data using the spatial error model, and we used the residual lint yields (which were obtained in the spatial error model in GeoDa and in which N treatment effects on lint yields had been excluded) to make Moran's I statistic and scatter plot and the Localized Indicators of Spatial Autocorrelation (LISA) cluster map. Moran's I statistics and scatter plot and the LISA cluster map of residual lint yields were created in GeoDa using the 2nd order queen's contiguity model that includes all lower contiguity orders.

## Results and Discussion

### Correlations of Lint Yields with Canopy NDVI and Leaf N

The correlations of lint yield with canopy NDVI were statistically significant at early square and early, mid, and late bloom stages (Table 2). The correlations of lint yield with leaf N were significant at mid and late bloom stages (Table 2). There was significant correlation of leaf N with canopy NDVI at mid and late bloom stages (Table 2). Overall, the determination coefficient ($R^2$) values for the above correlations in 2011 were similar to those in 2010, but lower than those in 2009; which suggests that the correlations of lint yields with canopy NDVI and leaf N vary with years.

### Spatial Analyses

ArcView GIS maps of canopy NDVI, leaf N, lint yields, and post-harvest soil N at Gibson are presented in Fig. 1 to 10, respectively. The lint yield map shows that spatial variations in lint yield did exist within most strip plots. Visually, it seemed lint yield had a better correlation with canopy NDVI at late bloom (August 17) than the other growth stages. The post harvest soil N map indicates that the side dress N treatments implemented early in the season did not show evident impacts on soil nitrate and ammonium after cotton harvest, which suggests that residual nitrate and ammonium from the N treatments was ignorable in the soil after harvest.

In order to examine the spatial dependence of lint yields within the test field, we conducted a quadratic regression of lint yields with side dress N application rates using the classic model in the GeoDa software, and we observed significant spatial dependence of lint yields within the test field (data not presented). Then, the spatial error model in GeoDa was used to conduct the quadratic regression of lint yields with side dress N rates; the output was presented in Table 3.

In order to visualize the spatial dependence of lint yield relating to the characteristics of the test field (not to N treatments), we used the residual lint yields (which were obtained in the spatial error model in GoeDa and in which N treatment effects on lint yields had been excluded) to make Moran's I statistic and scatter plot and LISA cluster map. Moran's I statistic and scatter plot and LISA cluster map are presented in Fig. 11, and 12, respectively.

Moran's I and scatter plot evaluates global spatial autocorrelation. Moran scatter plot provides a visual exploration of global spatial autocorrelation. The four quadrants in the Moran scatter plot provide a classification of four types of spatial autocorrelation: high-high and low-low for positive autocorrelation; low-high and high-low for negative spatial autocorrelation. The value listed at the top of the graph is the Moran's I statistic. Fig. 11 shows that there was significant ($p = 0.001$)

spatial autocorrelation of residual lint yields (N treatment effects on yields excluded) within the tested field.

The LISA cluster map estimates local spatial autocorrelation. It contains information on only those locations that have significant spatial autocorrelation. Four types of spatial autocorrelations are colored in four different colors: dark red for high-high, dark blue for low-low, pink for high-low, and light blue for low-high. The LISA cluster map in Fig. 12 shows that there were some significant local clusters of residual lint yields (N treatment effects on yields excluded) within this tested field. Specifically, there were eighteen sub plots with high residual yields surrounded by high residual yield neighbors, sixteen low residual yield sub plots were surrounded by low residual yield neighbors, four sub plots with low residual yields were surrounded by high residual yield neighbors, and two high residual yield sub plots were surrounded by low residual yield neighbors.

**Spatial Variations within Each Strip Plot**

Coefficients of variation (CV) were generally low for canopy NDVI and leaf N within each strip plot at the early square and early, mid, and late bloom stages (Table 4). The CV values were greater with lint yields and postharvest soil nitrate and ammonium (Table 4). Since all the sub plots within a strip plot received the identical N treatment, the CV value for each strip plot in Table 4 reflects the spatial variations within that strip plot. The CV results of 2011 showed the same trends as those of 2009 and 2010.

## Acknowledgments

This project was supported in part by Fluid Fertilizer Foundation. We appreciate the cooperative farmer Jeff Dodd (Gibson County) for allowing us to conduct this test on his farm. We also appreciate the technical cooperation of the Textile Service Laboratory of Cotton Inc. Technical assistance was provided by Bob Sharp, Well Goforth, Tracy Bush, Matt Ross, Dereck Eison, and others.

**Table 1. Major operations performed at Gibson in 2011.**

| List of operations performed | Date performed |
|---|---|
| Cotton planting | 5/21/11 |
| Side dress liquid nitrogen treatments | 6/15/11 |
| Collected early square leaf samples | 7/5/11 |
| Collected early bloom leaf samples | 7/27/11 |
| Collected mid-bloom leaf samples | 8/4/11 |
| Collected late bloom leaf samples | 8/17/11 |
| Recorded canopy NDVI at early square | 7/5/11 |
| Recorded canopy NDVI at early bloom | 7/27/11 |
| Recorded canopy NDVI at mid-bloom | 8/4/11 |
| Recorded canopy NDVI at late bloom | 8/17/11 |
| Dried and ground all leaf samples & shipped them for analyses | 10/14/11 |
| Harvested center 6 rows of each 12-row plot | 10/1/11 |
| Collected seed cotton samples for lint quality | 10/1/11 |
| Collected 2 ft. post-harvest soil samples | 11/10/11 |
| Dried and ground all soil samples & shipped them for analysis | 12/6/11 |

**Table 2. Correlations among lint yield, canopy NDVI, and leaf N concentration at Gibson in 2011.**

| Dependent variable (Y) | Independent variable (X) | $R^2$ | R | P |
|---|---|---|---|---|
| Lint yield | NDVI_7-5-11 | 0.13 | 0.36 | <0.0001 |
| Lint yield | NDVI_7-27-11 | 0.18 | 0.42 | <0.0001 |
| Lint yield | NDVI_8-4-11 | 0.29 | 0.54 | <0.0001 |
| Lint yield | NDVI_8-17-11 | 0.26 | 0.51 | <0.0001 |
| Lint yield | Leaf N_7-5-11 | 0.02 | 0.14 | 0.1143 |
| Lint yield | Leaf N_7-27-11 | 0.01 | 0.10 | 0.1934 |
| Lint yield | Leaf N_8-4-11 | 0.05 | 0.22 | 0.0243 |
| Lint yield | Leaf N_8-17-11 | 0.04 | 0.20 | 0.0213 |
| Leaf N_7-5-11 | NDVI_7-5-11 | 0.01 | 0.10 | 0.1954 |
| Leaf N_7-27-11 | NDVI_7-27-11 | 0.00 | 0.00 | 0.9943 |
| Leaf N_8-4-11 | NDVI_8-4-11 | 0.05 | 0.22 | 0.0183 |
| Leaf N_8-17-11 | NDVI_8-17-11 | 0.08 | 0.28 | 0.0024 |

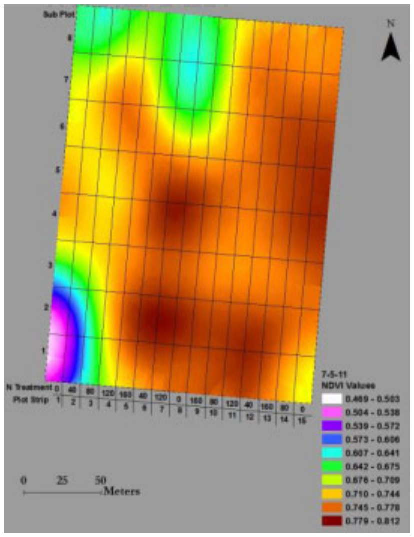
**Table 3. Regression summary of output using spatial error model at Gibson in 2011.**

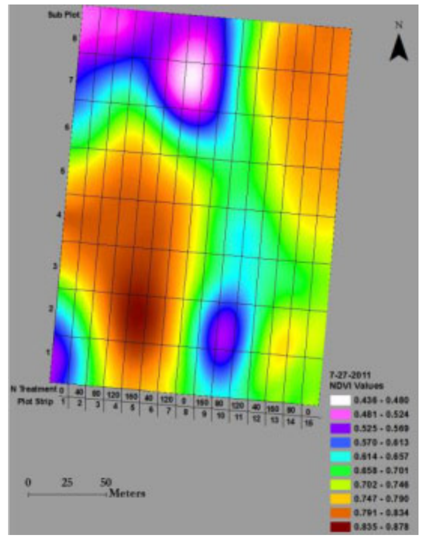
| Variable | Coefficient | Std. Error | z-value | Probability |
|---|---|---|---|---|
| CONSTANT | 66.80268 | 6.4063 | 10.42765 | 0.0000000 |
| N | 0.2812453 | 0.1199682 | 2.344331 | 0.0190612 |
| N*N | -0.0008253423 | 0.0006874219 | -1.200634 | 0.2298932 |
| LAMBDA | 0.6661434 | 0.09001163 | 7.400636 | 0.0000000 |

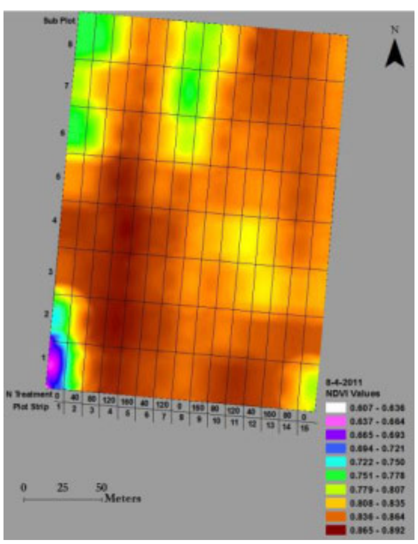
**Table 4. Coefficient of variation (%) in canopy NDVI, leaf N, lint yield, and post-harvest soil N within each strip plot at Gibson in 2011.**

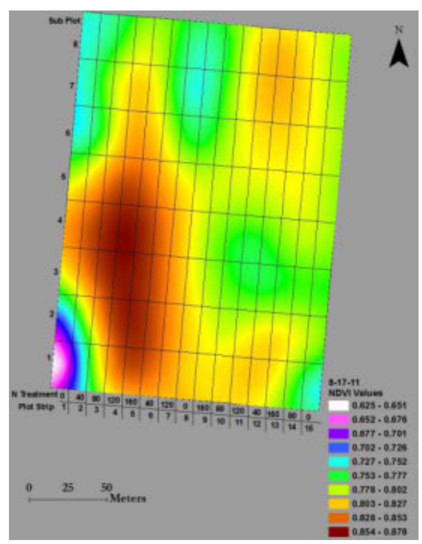
| Strip plot | N rate | NDVI 7-5-11 | NDVI 7-27-11 | NDVI 8-4-11 | NDVI 8-17-11 | Leaf N 7-5-11 | Leaf N 7-27-11 | Leaf N 8-4-11 | Leaf N 8-17-11 | Yield | Post-harvest soil N |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 19.2 | 10.1 | 11.3 | 9.3 | 8.3 | 13.1 | 14.8 | 18.1 | 5.6 | 79.7 |
| 2 | 40 | 10.3 | 7.5 | 5.6 | 3.6 | 5.4 | 8.2 | 16.3 | 11.3 | 23.2 | 37.5 |
| 3 | 80 | 4.3 | 4.2 | 3.2 | 2.7 | 5.3 | 7.0 | 7.5 | 5.1 | 17.5 | 34.9 |
| 4 | 120 | 6.1 | 7.0 | 1.5 | 1.0 | 7.5 | 4.7 | 6.7 | 6.4 | 13.7 | 58.7 |
| 5 | 160 | 2.8 | 2.2 | 1.7 | 1.4 | 2.4 | 5.8 | 4.3 | 3.3 | 9.6 | 60.3 |
| 6 | 40 | 5.8 | 8.6 | 2.9 | 2.1 | 4.3 | 3.8 | 3.7 | 6.6 | 29.3 | 51.1 |
| 7 | 120 | 18.0 | 13.8 | 6.8 | 5.3 | 6.3 | 3.1 | 3.1 | 5.7 | 27.0 | 49.9 |
| 8 | 0 | 6.1 | 5.1 | 2.4 | 1.2 | 5.6 | 6.1 | 7.7 | 8.7 | 19.5 | 59.8 |
| 9 | 160 | 5.1 | 4.0 | 3.0 | 1.9 | 3.9 | 5.5 | 3.0 | 4.5 | 20.1 | 103.2 |
| 10 | 80 | 4.4 | 19.7 | 2.2 | 1.9 | 3.2 | 9.2 | 2.2 | 4.7 | 20.3 | 53.9 |
| 11 | 120 | 1.6 | 3.4 | 3.0 | 1.9 | 3.2 | 8.6 | 3.9 | 3.9 | 13.4 | 79.3 |
| 12 | 40 | 3.8 | 3.9 | 2.8 | 2.3 | 4.4 | 10.5 | 2.6 | 8.3 | 36.3 | 59.2 |
| 13 | 160 | 2.1 | 1.8 | 1.5 | 1.3 | 4.5 | 4.8 | 3.6 | 4.9 | 24.0 | 40.8 |
| 14 | 80 | 3.4 | 4.9 | 1.0 | 1.0 | 2.9 | 3.5 | 4.2 | 5.0 | 19.0 | 72.8 |
| 15 | 0 | 7.6 | 5.4 | 2.9 | 3.0 | 4.0 | 7.0 | 3.9 | 9.4 | 9.1 | 22.0 |

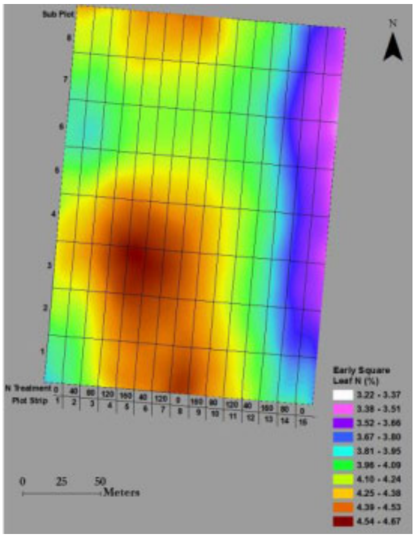
**Fig. 1 to 10. ArcView GIS Maps of canopy NDVI, leaf N, lint yield, and post-harvest soil N at Gibson in 2011.**

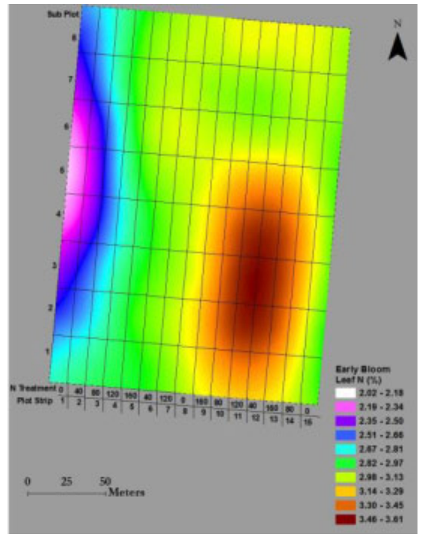


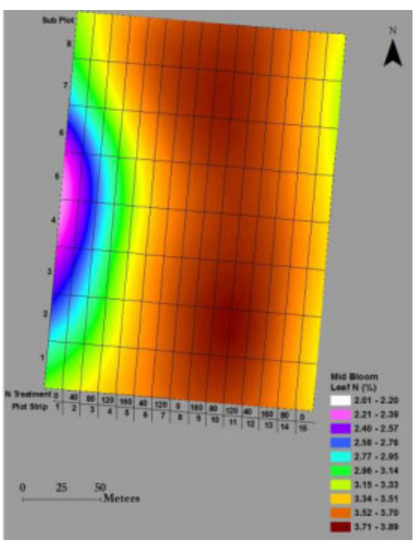



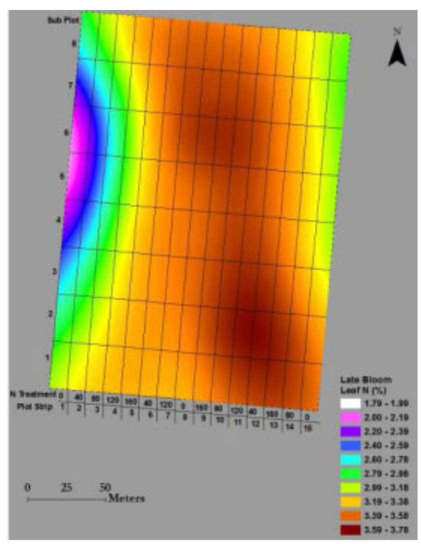



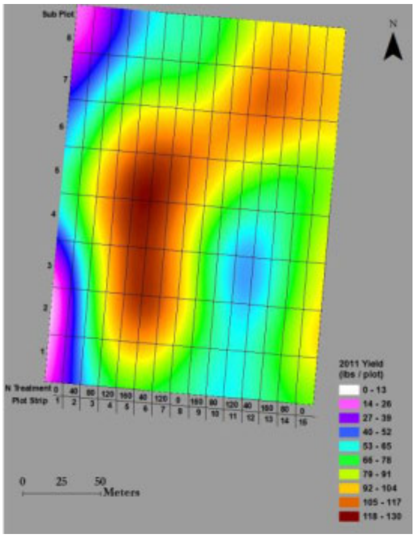




Sub Plot
N Treatment
Plot Strip
N
0 25 50
Meters
Early Square
Leaf N (%)
3.22 - 3.37
3.38 - 3.51
3.52 - 3.66
3.67 - 3.80
3.81 - 3.95
3.96 - 4.09
4.10 - 4.24
4.25 - 4.38
4.39 - 4.53
4.54 - 4.67


Sub Plot
N Treatment
Plot Strip
N
0 25 50
Meters
Early Bloom
Leaf N (%)
2.02 - 2.18
2.19 - 2.34
2.35 - 2.50
2.51 - 2.66
2.67 - 2.81
2.82 - 2.97
2.98 - 3.13
3.14 - 3.29
3.30 - 3.45
3.46 - 3.61


Sub Plot
N Treatment
Plot Strip
N
0 25 50
Meters
Mid Bloom
Leaf N (%)
2.01 - 2.20
2.21 - 2.39
2.40 - 2.57
2.58 - 2.76
2.77 - 2.95
2.96 - 3.14
3.15 - 3.33
3.34 - 3.51
3.52 - 3.70
3.71 - 3.89


Sub Plot
N Treatment
Plot Strip
N
0 25 50
Meters
Late Bloom
Leaf N (%)
1.79 - 1.99
2.00 - 2.19
2.20 - 2.39
2.40 - 2.59
2.60 - 2.78
2.79 - 2.98
2.99 - 3.18
3.19 - 3.38
3.39 - 3.58
3.59 - 3.78


Sub Plot
N
N Treatment
Plot Strip
0 25 50
Meters
2011 Yield (lbs / plot)
0 - 13
14 - 26
27 - 39
40 - 52
53 - 65
66 - 78
79 - 91
92 - 104
105 - 117
118 - 130

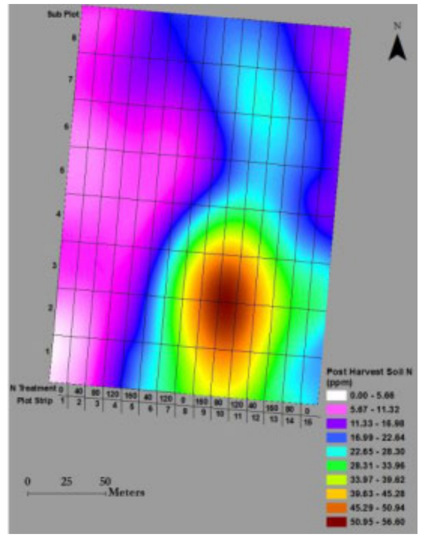

Sub Plot
N
N Treatment
Plot Strip
0 25 50
Meters
Post Harvest Soil N (ppm)
0.00 - 5.66
5.67 - 11.32
11.33 - 16.98
16.99 - 22.64
22.65 - 28.30
28.31 - 33.96
33.97 - 39.62
39.63 - 45.28
45.29 - 50.94
50.95 - 56.60

**Fig. 11. Moran's I and scatter plot of residual lint yield (N treatment effects on yields excluded) at Gibson in 2011.**

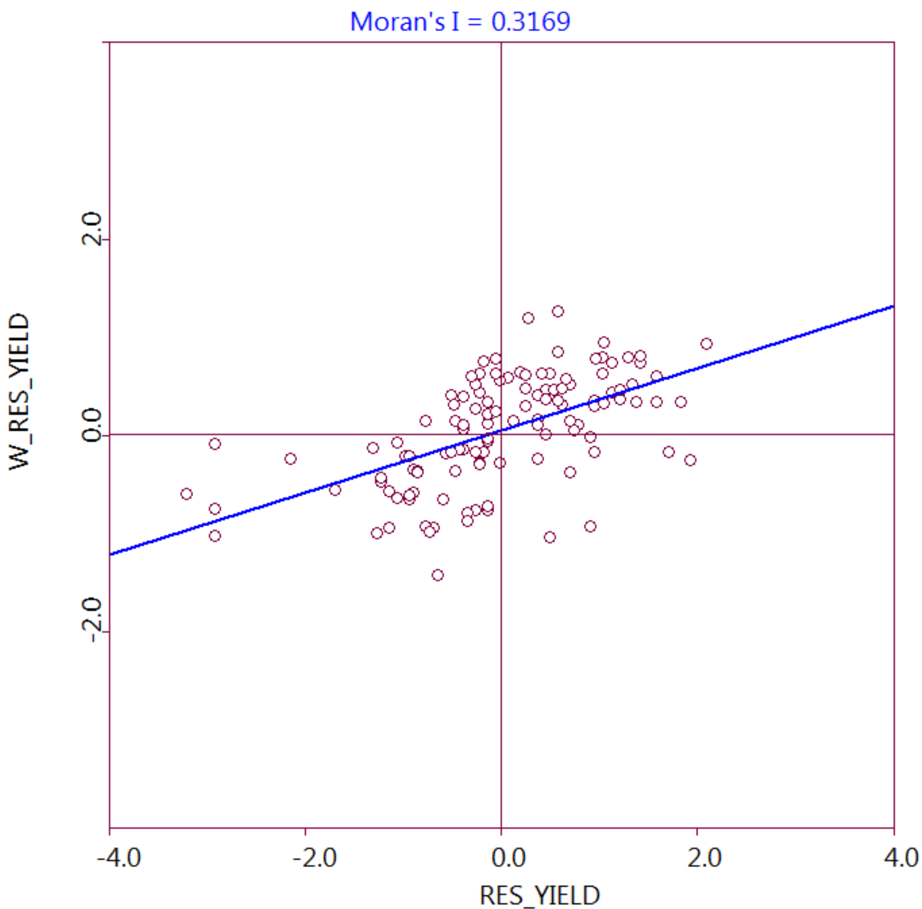


**Fig. 12. LISA cluster map of lint yield (N treatment effects on yields excluded) at Gibson in 2011.**