2003 BELTWIDE COTTON CONFERENCES, NASHVILLE, TN – JANUARY 6-10

AN ECONOMIC ANALYSIS OF WHOLE-FIELD FARMING VERSUS PRECISION FARMING: THE CASE OF COTTON

Susan E. Watson
The University of Louisiana – Monroe
Monroe, LA
Eduardo Segarra
Texas Tech University
Lubbock, TX
Robert Lascano, Hong Li, Kevin Bronson, and Jill Booker
Texas A&M Research and Extension Center
Lubbock, TX

Abstract

The viability of agriculture is critical to the Texas economy. This creates a need to produce commodities with efficient input levels, not only satisfy environmental standards, but to ensure maximum profitability for Texas producers as well. One method of satisfying these requirements is the implementation of precision farming. Precision farming management practices were compared with traditional whole-field farming management practices with respect to yield, nitrogen fertilizer input levels, and net present value of returns above nitrogen and water costs. On the average, precision farming increased yield and net present value of returns above nitrogen and water costs (NPVR) by 0.1649% and 0.1984%, respectively, as compared to whole-field farming. However, precision farming also used 0.1564% more nitrogen application on the average. Additionally, precision farming proved to have a smaller yield and NPVR variance.

Introduction

In Texas, agriculture is the second-largest industry, contributing $80 billion dollars to the state's economy annually, as well as producing 16% of the gross state product. Almost 80% of the land in Texas is used in some form of agricultural production activity. The agricultural industry also employs 20% of the state's residents (TDA press release, 2001). Therefore, agriculture in Texas has a large economic impact that cannot be ignored.

There are several commodities, including cotton, that lead the state's agricultural industry in importance in terms of production and generation of revenue. Therefore, cotton is addressed in this study due to its importance in Texas. The Southern High Plains of Texas (SHPT) is the region in this study; largely due to the emphasis and importance it commands in agricultural production. The SHPT is a semi-arid region, which encompasses 22 million acres, located in the northwestern portion of the state.

Cotton is the most important crop in this area in terms of value and acreage. Of the approximately 6 million acres of cotton planted annually in Texas, 2.6 to 3.3 million acres are planted in the SHPT region, with approximately half of these acres irrigated (Segarra et al., 1989). Cotton earns more dollars per gallon of irrigation water applied than any other crop grown in the region. Cotton lint yields in Texas have averaged approximately 450 pounds per acre since 1992. Cotton is also unique in that it adapts to poor soils and uses fertilizers efficiently (National Cotton Council).

Currently, production agriculture is facing challenges such as increasing cost of production, shortage of irrigation water, and increased public concern for the impacts of agricultural production on the environment. To survive in the world market, producers must produce high quality products at low prices while employing environmentally friendly practices. Increased uses of fertilizers, pesticides, and other chemicals have contributed toward the enhancement of agriculture's productivity in recent decades. Today, technology adoption is seen as the key to increasing agriculture's productivity as available resources decline. Precision agriculture technology is one technological advance that may have the potential to increase productivity. Therefore, precision agriculture is the focus of this study in analyzing the economics of cotton production in the Texas High Plains.

Traditional whole-field farming practices assume spatial and temporal field homogeneity, with optimal levels of input use not accounting for inherent differences within fields (Weiss, 1996). However, fields are not homogeneous, indicating that many field characteristics, such as nitrogen, sand, clay, and silt levels vary within the field. In general, optimal input use under traditional whole-field farming optimizes for average characteristics, for example, average residual nitrogen levels, within the field. In other words, traditional whole-field farming optimizes input use on what is best for the field as a whole, or "on average". Optimal input application rates are uniform across the field regardless of the specific characteristics and requirements of any particular location within the field. This may not be efficient if there is significant spatial variability of characteristics. All locations do not have the same yield potential, thus it appears that a uniform application may not necessarily result in optimal yields or profitability (Onken and Sunderman, 1972).

The differences within fields are addressed with precision farming. Precision farming involves the sampling, mapping, analysis, and management of specific areas within fields in recognition of spatial and temporal variability with respect to soil fertility, pest populations, and crop characteristics (Weiss, 1996). Precision farming optimizes input use under these conditions. With precision farming practices, potentially there are as many optimal applications as there are Global Positioning System (GPS) points in the field. Every location in the field is evaluated according to its specific characteristics and assigned an optimal input application rate unique to that location. Thus, there are many different application rates across the field.

Specific Problem

Potential advantages of precision farming may include higher average yield, lower farm input costs, and environmental benefits from applying fewer inputs (English et al., 2000). Thus, there is potential for increased profits if inputs can be allocated with greater economic efficiency across the field. This idea of "farming by the inch" provides a better understanding of the many factors that affect yields and profitability. Precision farming minimizes the likelihood of over-application or under-application of inputs because optimal input levels are not based on average conditions within a field. Inefficient use of inputs can cause producers to lose money and the environment to suffer.

The acceptance of precision farming practices in cotton production will ultimately depend on its economic performance as compared to conventional whole-field farming. Research efforts have been directed toward the new technologies involved with precision farming. There has been an expressed need for more information on the economic performance of precision farming.

Objectives

The overall objective of this study is to evaluate the profitability of precision farming and evaluate optimal decision rules for production of cotton in the Southern High Plains of Texas. The following are the specific objectives of this study:

1. To assess the spatial relationship between input utilization and cotton yields;
2. To derive optimal levels of spatial input use and develop decision rules for input application;
3. To assess the short-run and long-run economic implications of precision farming management practices.

Methods and Procedures

This section is composed of the following sub-sections: (1) the optimization model, (2) data considerations for cotton, (3) estimation of production function and input carry-over functions, (4) economic evaluation of whole-field farming versus precision farming, and (5) sensitivity analysis.

Optimization Model

Optimal decision rules for specific inputs are desired to maximize the net present value of returns to risk, management, overhead, and all other inputs in the production of cotton. The deterministic specification of the empirical dynamic optimization model formulated in this study, which will be used to derive optimal decision rules of input use for the cotton experiments is shown in equations (1) through (4):

$$\text{Max NPV} = \sum_{t=0}^{n}(PC_t{*}Y_t(XT_t) - PX_t{*}XA_t){*}(1+r)^{-t}) \quad (1)$$

subject to:

$$XT_t = XA_t + XR_t, \quad (2)$$
$$XR_{t+1} = f_t(XA_t, XR_t) \quad (3)$$
$$XR_0 = XR(0), \quad (4)$$
and $XA_t, XR_t, XT_t \geq 0$ for all t

Where, NPV is the net present value of returns to land, irrigation water, overhead, risk, and management from production; the length of the decision-maker's planning horizon is n years; PC_t is the price of cotton in year t; Y_t is the cotton yield function in year t; PX_t is the price of the input in year t; XA_t is the amount of input applied in year t; r is the discount rate; XT_t is the total amount of input available for crop growth in year t; XR_t is the residual amount of input already available in the soil in year t; and XR_0 is the initial residual amount of input available in the soil at the beginning of the planning horizon.

Equation (1) is the objective function, or performance measure of the optimization model. Equation (2) is the equality constraint that sums the amount of input applied and residual input to obtain the total amount of input available for cotton growth in any given year. This equation is used in the objective function to calculate cotton yield. Equation (3) is the equation that updates residual input annually, which is necessary for equation (2). This equation is also called the equation of motion because it updates the input residual at time t+1 depending on residual input at time t and input application at time t. Equation (4) is the initial input residual condition, which represents the residual level at the beginning of the planning horizon. Non-negativity constraints are also specified for input application, residual, and total amount of input.

Data Considerations for Cotton

The experiment was performed in the years 1999, 2000, and 2001. In the experiment, 100 locations were chosen from which to gather data. A Global Positioning System (GPS) was used to identify the latitude and longitude of the location in the field. Cotton lint yield was then measured in lbs./acre at each of these GPS locations. Residual nitrate-nitrogen was measured from 0 to 48 inches of the soil depth in 12-inch increments. Altitude measurements were also taken for each location. Silt, sand, and clay percentages of the soil were then measured as well as the amount of water applied in acre-inches for each specific location. Nitrogen was applied at a constant rate of 70 lbs./acre in 1999 across the field and at a rate of 90 lbs./acre in 2000 and 2001. The cotton was hand harvested in this experiment.

Estimation of Production and Input Carry-Over Functions

The data described in the previous section was used to estimate the production function, $Y = f\ (X)$, and the input carry-over function, $NR_{t+1} = f\ (NA, NR_t)$. Using GLM (General Linear Model) procedures in SAS, alternative functional forms were be evaluated to find the best statistical fit between yield (dependent variable) and crop characteristics, input levels, location characteristics, and other variables in the experiment (independent variables) (SAS, 1982). The carry-over function was estimated in SAS to represent the relationship between time t+1 input residual and the independent variables input residual in time t and input application in time t.

Economic Evaluation of Whole-Field Farming Versus Precision Farming

The economic feasibility of the two management practices was analyzed and compared with respect to input use, net present value of revenue above nitrogen and water costs, and yield. Based on the cotton experiment, optimal decision rules for a dynamic ten-year planning horizon were derived.

The optimization model in equations (1) through (4) are used in the cotton analysis. Combinations of two water, nitrogen, and commodity prices are solved for both precision farming and whole-field farming practices. A 5.0% discount rate are used for a 10-year planning horizon. Under the precision farming scenario, the initial residual nitrogen conditions vary across locations in the field. Under the whole-field farming scenario, the initial residual nitrogen conditions are held at the average initial condition across the whole field for all locations.

The optimal decision rules derived in this study for nitrogen use vary across time periods in the planning horizon for a given input and output price combination. However, given that a stable decision rule is desirable to simplify management implementation, an additional constraint of equating nitrogen input applications across time periods within the planning horizon is introduced. Cotton yield, net per-acre present value of returns above nitrogen and water costs, and ending residual nitrogen levels for the 10-year planning horizon are obtained. GAMS (General Algebraic Modeling System), a mathematical optimization software system developed by the World Bank, is used to solve the optimization models for both commodities and farm management practices.

Due to the changing prices of technology and region specific application costs, no costs for implementing precision farming above whole-field farming are included in the analysis. Thus, the cost of collecting the site-specific information, analysis of the data, and variable rate application costs have not been accounted for in this study. The decision to exclude these costs will allow the change in profitability per acre when employing precision farming technology to be compared to the current cost of implementation in the SHPT to determine the feasibility of implementing the new technology into farm management practices.

Sensitivity Analysis

The cotton models will be solved under a high irrigation water scenario with all possible combinations of two cotton prices, \$0.40 and \$0.60 per pound, two nitrogen prices, \$0.25 and \$0.30 per pound, and two water prices, \$2.68 and \$3.50 per acre-inch. Overall percentages changes in net revenues above nitrogen and water costs, cotton yields, and nitrogen application levels are analyzed to obtain an overall picture of the impacts of one management practice over the other.

Results

The purpose of this section is to present the results and findings of this research. First, the functions estimated and results of the optimization models are discussed. Comparisons between precision farming and conventional whole-field farming results are then drawn in terms of net revenues above nitrogen and water costs, yield, and nitrogen application levels. Finally, spatial probability density functions and cumulative density functions are analyzed to evaluate the spatial variability associated with each management practice.

Cotton yield was found to be a quadratic function of total nitrogen, which was defined as the addition of residual nitrogen from 0 to 12 inches of soil depth and nitrogen applied during the season, altitude, irrigation water, and year. The residual nitrate-nitrogen function, which estimated the residual nitrate-nitrogen from 0 to 12 inches of the soil depth at the end of the season, was found to be a linear function of residual nitrogen in the soil at the beginning of the season from 0 to 12 inches of soil depth, nitrogen application during the season, and an interaction between sand and water.

Yield was measured in lbs./acre and is represented as Y. Total nitrogen was measured in lbs./acre, and is represented as NT. Altitude was measured in feet above a base point and was defined as ALT. Water was measured in acre-inches and was defined as W. A dummy variable distinguishing between 1999 and other years when this experiment was conducted was defined as YEAR99, where a 1 was used in 1999 and a 0 was used in 2000 and 2001. Residual nitrate-nitrogen at the end of the season from 0 to 12 inches of soil depth was measured in lbs./acre and is defined as NR_{t+1}. Residual nitrate from 0 to 12 inches of soil depth was measured in lbs./acre at the beginning of the season is defined as NR_t. Nitrogen applied was measured in lbs./acre and is defined as NA. Sand is measured as a percentage of sand in the soil and is defined as SAND. The functions for yield, equation (5), and residual nitrate-nitrogen at the end of the season, equation (6), with their parameter estimates and corresponding t-values are shown in the following equations.

$$Y = 26891.40803 - 0.00288{*}\,NT{*}NT - 36.46115{*}ALT + 502.79486{*}W - 449.37288{*}YEAR99; \qquad (5)$$
$$(5.45) \qquad (-1.21) \qquad (-6.56) \qquad (26.89) \qquad (-24.01) \qquad R^2=.795$$

$$NR_{t+1} = 73.95487 + 0.28158{*}NR_t + 0.6336{*}NA - 0.11581{*}W{*}SAND; \qquad (6)$$
$$(2.11) \quad (3.09) \qquad (3.23) \quad (-4.50) \qquad R^2=.154$$

The R-squared was .795 for the yield model and .154 for the residual nitrate-nitrogen model. This indicates that 79.5% of the variation in irrigated cotton yield was explained by the total nitrogen available for plant uptake, altitude, irrigation water, and the year planted. It was also found that residual nitrate-nitrogen at the beginning of the season from 0 to 12 inches of soil depth, nitrogen application rates, and the interaction between sand and water accounted for 15.4% of the variation in ending residual nitrate-nitrogen levels from 0 to 12 inches of the soil depth. These models were estimated using the Generalized Linear Modeling (GLM) procedures in SAS (SAS, 1982). These results were then used to formulate non-linear dynamic mathematical optimization models using General Algebraic Modeling System (GAMS) to determine optimal input application decision rules (equations (1) through (4)). An additional constraint equating nitrogen application across time periods was added to obtain a simpler decision rule for producers to follow in their decision-making.

Overall, there were three scenarios analyzed: 1) precision farming, 2) naïve whole-field farming, and 3) actual whole-field farming. Under the precision farming scenario each individual location's characteristics within the field were used in the optimization modeling to determine the optimal nitrogen application level for each location. Under the naïve scenario, the initial nitrogen condition and location characteristics were set at the mean level of the field to determine a single optimal nitrogen application level for the entire field. The actual whole-field farming scenario used the optimal nitrogen application level determined under the naïve scenario and each individual location's characteristics. This scenario was evaluated because it provides the most realistic comparison of whole-field farming to precision farming.

Solutions to the 201-optimization models (100 for precision farming practices, 100 for actual whole-field farming, and 1 for the naïve whole-field farming approach) were obtained using GAMS and are presented in Table 1. This table depicts the results associated with a water price = \$2.68 acre-inch, a cotton price = \$0.40 /lb. and a nitrogen price = \$0.25/ lb. under a high level of irrigation water. For simplicity, only this solution will be discussed here. Table 1 lists the location, initial residual nitrogen in the soil, net present value of revenue above nitrogen and water costs on a per acre basis over the ten-year planning horizon for precision farming, yield per acre on an annual basis for precision farming, optimal nitrogen application levels for precision farming on a per acre basis, net present value of revenue above nitrogen and water costs on a per acre basis over the ten-year planning horizon for whole-field farming, yield per acre on an annual basis for whole-field farming, optimal nitrogen application for whole-field farming on a per acre basis, and the percentage changes between precision farming and whole-field farming with respect to net present value of revenues above nitrogen and water costs (NPVR), yield, and nitrogen application levels on a per acre basis. The naïve whole-field farming approach is shown at the end of the table in bold font, as well as average values and variances for precision and actual whole-field farming scenarios. The relative changes are emphasized when comparing the management practices. However, the table contains the actual calculations for each location under each management practice.

The locations shown in the table correspond to those in Figures 1 through 6 generated with MapInfo (Vertical Mapper). Table 1 shows the initial residual nitrogen levels in lbs./acre, which correspond to those in Figure 1. In Figure 1, the red areas indicate locations in the cotton field where residual nitrogen is highest, whereas the blue areas indicate locations in the field with the least residual nitrogen. As shown in Figure 1, the field had a higher concentration of residual nitrogen in the inner portion of the circle. For example, Table 1 shows that location 46a had 30.39 lbs./acre of residual nitrogen. This location can be found in Figure 1 in the inner circle at the north end of the field. Also, location 48a is shown to have 1.12 lbs./acre of residual nitrogen in Table 1 and can be seen in Figure 1 in the outer circle portion at the south end of the field.

The optimal levels of spatial nitrogen to apply are shown in Figure 2. For example, at location 51a, NPVR will be maximized if 58.83 lbs./acre of nitrogen are applied at that location. As shown in Table 1, under whole-field farming management, a uniform nitrogen application of 55.86 lbs./acre is shown to be optimal. Thus, at location 51a, 5.31% more nitrogen under precision farming management practices would be applied to maximize NPVR. Overall, for the whole field, precision farming is shown to use 0.1564% more nitrogen on average than whole-field farming.

Figure 3 shows the spatial cotton yield map for precision farming. The highest yielding portions of the field are located on the outer circle. For example, location 48a shows a yield of 973.25 lbs./acre under precision farming management practices. Figure 4 shows the spatial cotton yield map under the actual whole-field farming scenario. The same location, 48a, has an associated yield level of 966.87 lbs./acre, which represents a 0.66% increase in yield when employing precision farming practices. Overall, there are some locations in which yield is shown to decrease under precision farming practices. For example, at location 50a, yield decreases by 5.50% when implementing precision farming management practices. However, precision farming yields 939.12 lbs./acre on average, whereas the naïve whole-field farming approach yields 938.88. Notice that the later is higher than the actual whole-field farming yield of 937.96 lbs./acre. Therefore, yield is shown to increase by 0.1649% on average when using precision farming management practices.

Figure 5 illustrates the optimal levels of NPVR for a ten-year optimization model for precision farming practices. Notice that this figure is quite similar to the spatial yield map in Figure 3. Location 48a has a ten-year NPVR of $2,741.55 under precision farming management practices. Under whole-field farming management practices, the corresponding level is $2,739.79, which represents a 0.06% increase in NPVR from employing precision farming management practices.

Figure 6 shows the spatial NPVR for whole-field farming practices, which closely resembles the precision farming spatial NPVR map, however, notice that the scale is clearly lower. Also note that, the naïve approach is slightly more optimistic in forecasting NPVR than the actual whole-field farming scenario, but it is not as optimistic as the precision farming scenario. Overall, precision farming is shown to increase NPVR by 0.1984% on average for the whole field. However, it is clear from Figures 1 to 6 that it is important to look at individual locations to attempt to identify management zones, or areas where precision farming is likely to be more profitable.

Figures 7 and 8 show the spatial probability density functions (pdf) for cotton NPVR, and cotton yield, respectively. The dashed line pdf's represent the precision farming scenario, while the solid line pdf's represent the whole-field farming scenario. Spatial variability in NPVR is slightly lower under precision farming with a higher average NPVR. The spatial variability of yield is also shown to be is slightly lower under precision farming with a higher average yield.

Overall, these results indicate that precision farming is shown to be slightly more profitable on the average and is slightly less variable with respect to yield and NPVR. Figure 9 shows the cumulative density function (cdf) for both precision and whole-field farming NPVR. The precision farming scenario (dashed line), which is overall slightly to the right of the whole-field farming scenario (solid line), dominates. This is because as a whole, more NPVR would be expected from precision farming practices than from whole field farming practices.

The differences in yield, NPVR, and nitrogen application are small on average in this specific study. The differences in yield and NPVR variability between the management practices are shown to be minimal as well. Therefore, on average, precision farming is shown to be marginally better than whole-field farming in this experiment.

Summary and Conclusions

The purpose of this section is to summarize the results of this study. Then, conclusions are drawn and commonalities are discussed with respect to the profitability of precision farming in cotton production in the Southern High Plains of Texas.

On the average precision farming increased yield and NPVR by 0.1649% and 0.1984%, respectively, as compared to whole-field farming. However, precision farming also used 0.1564% more nitrogen application on the average. The naïve whole-field farming scenario overestimated both yields and NPVR as compared to the actual whole-field farming scenario. Precision farming also proved to have a smaller yield and NPVR variance.

Optimal nitrogen application was not significantly different in cotton when using precision farming technology as compared to whole-field farming. The spatial NPVR cdf for precision farming clearly dominated the whole-field farming cdf. Therefore, precision farming is shown to be more profitable than whole-field farming based on net revenues above nitrogen and water costs. As mentioned earlier, the purpose of determining the difference in NPVR when using precision farming practices was to determine the maximum amount a producer could spend to implement precision farming practices. Knowing that precision farming will cost more than whole-field farming to implement, this study determines the magnitude by a producer could afford to pay for the implementation of this new technology.

Several agricultural consulting groups in the Southern High Plains of Texas were contacted to determine the additional costs of implementing precision farming practices above whole-field farming. A wide range of responses left no real confidence in the values obtained. Therefore, the cost determined in Tennessee of $1.50 to $5.50 per acre, with an average increase of $3.08 per acre could be used as the baseline. However, the general consensus is that the cost of adoption would be higher in the Southern High Plains of Texas. In the experiment, precision farming would likely not be more profitable. The cotton study increased NPVR on an annual per acre basis by $0.365.

With the current cost of implementation of this technology, precision farming is expected to be more profitable today than whole-field farming is in the SHPT. This is very optimistic for precision farming as only one input was optimized. The results could reasonably be expected to improve even more if other inputs, such as phosphorus or water were to be considered. Future studies should address the specific costs of implementing this technology, as well as including more variable inputs. Also, a thorough risk analysis would be beneficial in future explorations.

References

English, B. C., R. K. Roberts, and D. E. Sleigh. February 2000. "Spatial Distribution of Precision Farming Technologies in Tennessee." Research Report, 00-05, Department of Agricultural Economics and Rural Sociology, University of Tennessee.

National Cotton Council of America. Online. Available:<<http://www.cotton.org/ncc/education/from_field_to_fabric.htm>>, 04-20-01.

Onken, A. B., and H. D. Sunderman. 1972. "Applied and Residual Nitrate-Nitrogen Effects on Irrigated Grain Sorghum Yield." Soil Science Society of America Proceedings, 36: 94-97.

SAS User's Guide: Statistics. SAS Institute Inc. 1982.

Segarra, E., D. E. Ethridge, C. R. Deussen, and A. B. Onken. 1989. "Nitrogen Carry-over Impacts in Irrigated Cotton Production, Southern High Plains of Texas." *Western Journal of Agricultural Economics,* 14(2): 300-309.

Texas Department of Agriculture. Online. Available: <<http://www.agr.state.tx.us/about/link4.htm>>04-24-01.

Vertical Mapper Manual. *Vertical Mapper for MapInfo, Version 1.50.*

Weiss, M. D. 1996. "Precision Farming and Spatial Economic Analysis: Research Challenges and Opportunities." *American Journal of Agricultural Economics,* 78: 1275-1280.

Table 1. Comparison of Precision Farming and Whole-Field Farming Scenarios with Water Price = $2.68/acre-inch, Cotton Price = $0.40/lb., and Nitrogen Price+$0.25/lb.

Location	NRES lbs./ac.	NREVpf $/acre	YIELDpf lbs./ac./yr.	NApf lbs./acre	NREVwf $/acre	YIELDwf lbs./ac./yr.	NAwf lbs./acre	NREV CH	YIELD CH	NA CH
1a	7.22	2493.26	878.52	36.16	2429.05	871.06	55.86	2.64%	0.86%	-35.27%
2a	6.67	2429.59	872.67	58.16	2430.41	871.48	55.86	-0.03%	0.14%	4.12%
3a	5.71	2547.68	905.56	52.55	2532.14	902.85	55.86	0.61%	0.30%	-5.92%
4a	8.02	2577.88	909.48	43.90	2534.52	903.58	55.86	1.71%	0.65%	-21.40%
5a	17.25	2558.78	909.76	53.60	2534.18	903.48	55.86	0.97%	0.70%	-4.05%
6a	7.70	2525.40	895.97	48.18	2494.82	891.34	55.86	1.23%	0.52%	-13.75%
7a	14.03	2463.94	893.89	74.98	2512.95	896.93	55.86	-1.95%	-0.34%	34.24%
8a	3.10	2627.17	925.70	45.62	2593.62	921.80	55.86	1.29%	0.42%	-18.34%
9a	5.47	2617.97	928.42	54.45	2608.46	926.38	55.86	0.36%	0.22%	-2.52%
10a	14.18	2599.99	918.52	47.36	2560.05	911.45	55.86	1.56%	0.78%	-15.22%
12a	4.63	2604.05	922.21	51.41	2504.18	894.22	55.86	3.99%	3.13%	-7.96%
13a	8.57	2571.89	916.26	57.69	2581.52	918.07	55.86	-0.37%	-0.20%	3.27%
14a	13.15	2545.55	910.10	60.73	2563.63	912.56	55.86	-0.71%	-0.27%	8.71%
15a	23.91	2512.56	898.57	58.35	2532.95	903.10	55.86	-0.81%	-0.50%	4.46%
16a	12.60	2577.97	919.02	59.02	2510.54	896.18	55.86	2.69%	2.55%	5.65%
17a	8.19	2607.86	926.82	56.83	2580.91	917.88	55.86	1.04%	0.97%	1.74%
18a	7.77	2573.59	915.71	55.98	2603.52	924.86	55.86	-1.15%	-0.99%	0.21%
19a	8.10	2597.87	921.18	52.74	2566.12	913.32	55.86	1.24%	0.86%	-5.58%
20a	6.51	2613.64	921.48	45.49	2582.42	918.35	55.86	1.21%	0.34%	-18.57%
21a	6.17	2654.56	937.15	50.37	2576.79	916.61	55.86	3.02%	2.24%	-9.83%
22a	7.26	2650.20	940.28	57.50	2630.74	933.25	55.86	0.74%	0.75%	2.93%
23a	2.49	2734.34	957.25	43.24	2653.77	940.35	55.86	3.04%	1.80%	-22.59%
24a	5.81	2667.23	949.02	63.10	2690.84	951.78	55.86	-0.88%	-0.29%	12.97%
25a	4.51	2567.98	925.84	74.98	2686.05	950.30	55.86	-4.40%	-2.57%	34.24%
26a	2.83	2640.52	943.19	67.00	2627.97	932.39	55.86	0.48%	1.16%	19.94%
27a	2.83	2693.87	957.21	63.10	2673.26	946.36	55.86	0.77%	1.15%	12.97%
28a	5.94	2689.70	955.00	61.58	2710.43	957.82	55.86	-0.76%	-0.29%	10.24%
29a	3.86	2610.55	930.04	60.73	2704.40	955.96	55.86	-3.47%	-2.71%	8.71%
30a	3.56	2593.41	920.11	53.31	2622.44	930.69	55.86	-1.11%	-1.14%	-4.56%
31a	3.73	2500.97	896.13	60.54	2582.04	918.23	55.86	-3.14%	-2.41%	8.37%
32a	3.79	2469.01	889.25	65.29	2511.98	896.63	55.86	-1.71%	-0.82%	16.88%
33a	5.92	2516.74	903.46	64.43	2492.88	890.74	55.86	0.96%	1.43%	15.35%
34a	3.01	2487.23	890.94	59.02	2541.58	905.76	55.86	-2.14%	-1.64%	5.65%
35a	7.81	2486.95	885.49	50.37	2488.66	889.44	55.86	-0.07%	-0.44%	-9.83%
36a	3.16	2448.84	878.57	58.16	2468.09	883.10	55.86	-0.78%	-0.51%	4.12%
37a	5.85	2426.34	868.68	53.41	2449.93	877.50	55.86	-0.96%	-1.00%	-4.39%
38a	3.52	2326.36	847.28	68.52	2415.90	867.00	55.86	-3.71%	-2.27%	22.67%
39a	8.78	2353.16	848.17	56.64	2357.42	848.97	55.86	-0.18%	-0.09%	1.40%
40a	3.83	2364.26	849.57	53.49	2352.89	847.57	55.86	0.48%	0.24%	-4.25%
41a	14.28	2344.20	841.11	49.70	2340.69	843.81	55.86	0.15%	-0.32%	-11.02%
42a	8.16	2284.19	822.85	50.18	2318.80	837.06	55.86	-1.49%	-1.70%	-10.17%
43a	13.25	2568.14	910.99	51.03	2252.75	816.70	55.86	14.00%	11.55%	-8.64%
44a	7.91	2486.37	890.72	59.02	2546.84	907.38	55.86	-2.37%	-1.84%	5.65%
45a	14.62	2481.70	874.99	36.11	2480.24	886.84	55.86	0.06%	-1.34%	-35.35%
46a	30.39	2391.50	853.19	45.43	2386.09	857.81	55.86	0.23%	-0.54%	-18.68%
47a	5.18	2740.46	967.02	55.79	2360.11	849.80	55.86	16.12%	13.79%	-0.13%
48a	1.12	2741.55	973.25	65.29	2739.79	966.87	55.86	0.06%	0.66%	16.88%
49a	0.84	2846.81	996.80	51.03	2770.48	976.34	55.86	2.76%	2.10%	-8.64%
50a	1.17	2643.94	940.28	60.70	2830.90	994.97	55.86	-6.60%	-5.50%	8.66%
51a	0.33	2671.14	947.50	58.83	2658.68	941.86	55.86	0.47%	0.60%	5.31%

Table 1 continued.

Location	NRES lbs./ac.	NREVpf $/acre	YIELDpf lbs./ac./yr.	NApf lbs./acre	NREVwf $/acre	YIELDwf lbs./ac./yr.	NAwf lbs./acre	NREV CH	YIELD CH	NA CH
52a	0.42	2627.01	931.57	55.12	2679.75	948.36	55.86	-1.97%	-1.77%	-1.32%
53a	0.45	2816.45	991.47	57.50	2624.14	931.21	55.86	7.33%	6.47%	2.93%
54a	0.46	2900.29	1017.28	57.50	2820.90	991.88	55.86	2.81%	2.56%	2.93%
55a	0.82	2724.83	962.27	55.98	2904.36	1017.62	55.86	-6.18%	-5.44%	0.21%
56a	2.87	2673.57	946.90	56.64	2722.05	961.40	55.86	-1.78%	-1.51%	1.40%
57a	1.14	2725.46	966.69	62.72	2675.09	946.92	55.86	1.88%	2.09%	12.29%
58a	0.78	2796.67	986.86	59.87	2746.18	968.84	55.86	1.84%	1.86%	7.18%
59a	6.65	2843.10	998.26	55.12	2801.73	985.97	55.86	1.48%	1.25%	-1.33%
60a	1.12	2820.49	988.96	51.48	2840.66	997.98	55.86	-0.71%	-0.90%	-7.85%
61a	1.67	2760.59	979.13	65.29	2805.42	987.11	55.86	-1.60%	-0.81%	16.88%
62a	5.35	2888.37	1013.66	57.50	2784.66	980.71	55.86	3.72%	3.36%	2.93%
63a	0.41	2944.16	1031.77	59.02	2893.79	1014.36	55.86	1.74%	1.72%	5.65%
64a	0.61	2873.73	998.74	40.86	2953.18	1032.67	55.86	-2.69%	-3.29%	-26.85%
65a	2.47	2829.65	999.60	63.96	2827.02	993.77	55.86	0.09%	0.59%	14.50%
66a	0.65	2965.41	1037.37	57.50	2854.76	1002.32	55.86	3.88%	3.50%	2.93%
67a	0.66	2920.47	1023.38	57.31	2969.68	1037.76	55.86	-1.66%	-1.39%	2.59%
68a	0.91	2688.13	955.29	62.91	2923.89	1023.64	55.86	-8.06%	-6.68%	12.63%
69a	1.29	2548.64	912.29	62.91	2708.86	957.34	55.86	-5.91%	-4.71%	12.63%
70a	1.28	2575.43	918.82	60.14	2569.46	914.35	55.86	0.23%	0.49%	7.66%
71a	1.11	2540.04	908.15	60.54	2587.61	919.95	55.86	-1.84%	-1.28%	8.37%
72a	0.48	2606.74	929.25	61.39	2554.11	909.62	55.86	2.06%	2.16%	9.90%
73a	2.15	2682.64	948.74	55.12	2621.62	930.44	55.86	2.33%	1.97%	-1.32%
74a	2.09	2670.40	946.04	56.83	2678.32	947.92	55.86	-0.30%	-0.20%	1.74%
75a	1.48	2695.62	953.27	55.98	2672.00	945.97	55.86	0.88%	0.77%	0.21%
76a	1.40	2737.87	963.86	52.08	2694.55	952.92	55.86	1.61%	1.15%	-6.77%
77a	1.28	2837.91	994.59	51.89	2725.07	962.34	55.86	4.14%	3.35%	-7.11%
78a	0.70	2834.27	989.84	46.09	2825.14	993.19	55.86	0.32%	-0.34%	-17.49%
79a	1.28	2707.19	961.30	63.10	2803.71	986.58	55.86	-3.44%	-2.56%	12.97%
80a	1.02	2841.69	993.77	48.72	2728.90	963.52	55.86	4.13%	3.14%	-12.78%
81a	0.86	2781.98	986.91	67.19	2819.29	991.39	55.86	-1.32%	-0.45%	20.28%
82a	0.90	2774.40	976.07	53.60	2817.00	990.68	55.86	-1.51%	-1.47%	-4.05%
83a	0.98	2836.99	989.85	44.76	2766.43	975.09	55.86	2.55%	1.51%	-19.87%
84a	0.56	2746.18	988.82	87.91	2803.40	986.49	55.86	-2.04%	0.24%	57.38%
85a	0.93	2823.88	996.20	61.39	2853.15	1001.83	55.86	-1.03%	-0.56%	9.90%
86a	0.49	2821.08	990.58	53.79	2840.62	997.96	55.86	-0.69%	-0.74%	-3.71%
87a	0.70	2895.80	1007.96	44.76	2813.90	989.73	55.86	2.91%	1.84%	-19.87%
88a	2.55	2899.92	1014.60	53.41	2860.05	1003.95	55.86	1.39%	1.06%	-4.39%
89a	2.19	2813.90	986.12	50.18	2890.36	1013.30	55.86	-2.65%	-2.68%	-10.17%
90a	1.58	2734.76	960.11	47.61	2795.23	983.97	55.86	-2.16%	-2.42%	-14.77%
91a	1.17	2721.18	958.06	51.03	2708.87	957.34	55.86	0.45%	0.08%	-8.64%
92a	4.99	2684.36	953.23	61.39	2701.12	954.95	55.86	-0.62%	-0.18%	9.90%
93a	6.23	2720.77	956.50	48.66	2695.56	953.24	55.86	0.94%	0.34%	-12.89%
94a	1.37	2682.59	952.11	60.54	2698.49	954.14	55.86	-0.59%	-0.21%	8.37%
95a	2.28	2722.46	962.51	57.50	2694.79	953.00	55.86	1.03%	1.00%	2.93%
96a	5.66	2637.03	931.74	50.37	2721.52	961.24	55.86	-3.10%	-3.07%	-9.83%
97a	2.20	2595.49	921.34	54.26	2618.84	929.58	55.86	-0.89%	-0.89%	-2.86%
98a	1.07	2575.93	915.83	55.12	2589.66	920.58	55.86	-0.53%	-0.52%	-1.32%
99a	0.58	2555.26	903.93	46.28	2573.04	915.46	55.86	-0.69%	-1.26%	-17.15%
100a	6.67	2488.27	889.99	56.94	2519.21	898.86	55.86	-1.23%	-0.99%	1.94%
WFnaive	**4.66**	**2649.10**	**938.88**	**55.86**						
AVERAGE		**2649.68**	**939.12**	**55.95**	**2646.03**	**937.96**	**55.86**	**0.1984%**	**0.1649%**	**0.1564%**
VARIANCE		**22847.38**	**2184.74**	**61.51**	**24158.02**	**2296.85**	**0.00**			

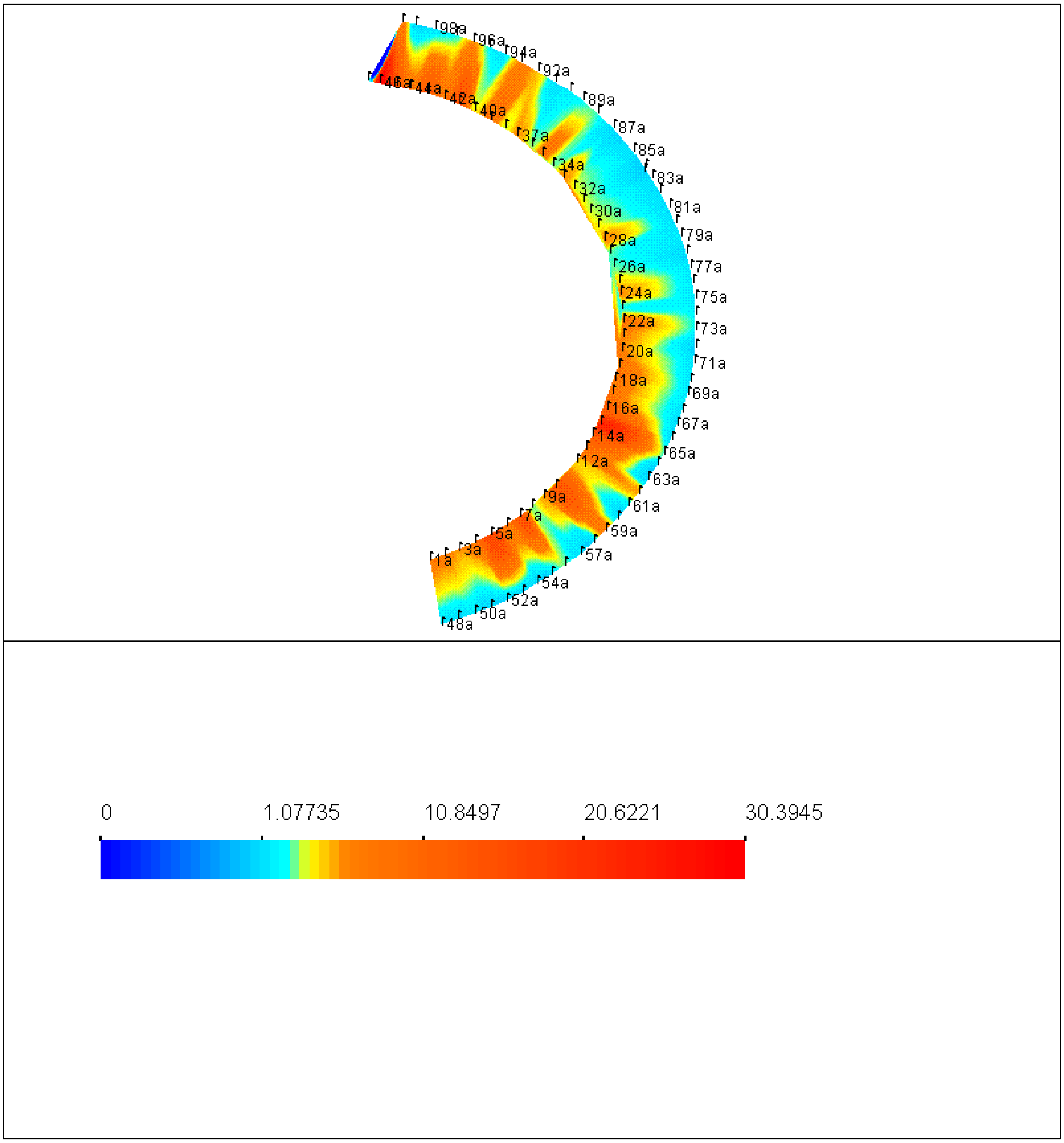

Figure 1. NO3-N Pre-Season Residual Map from 0 to 12 Inches of Soil Depth, Lamesa, Texas.

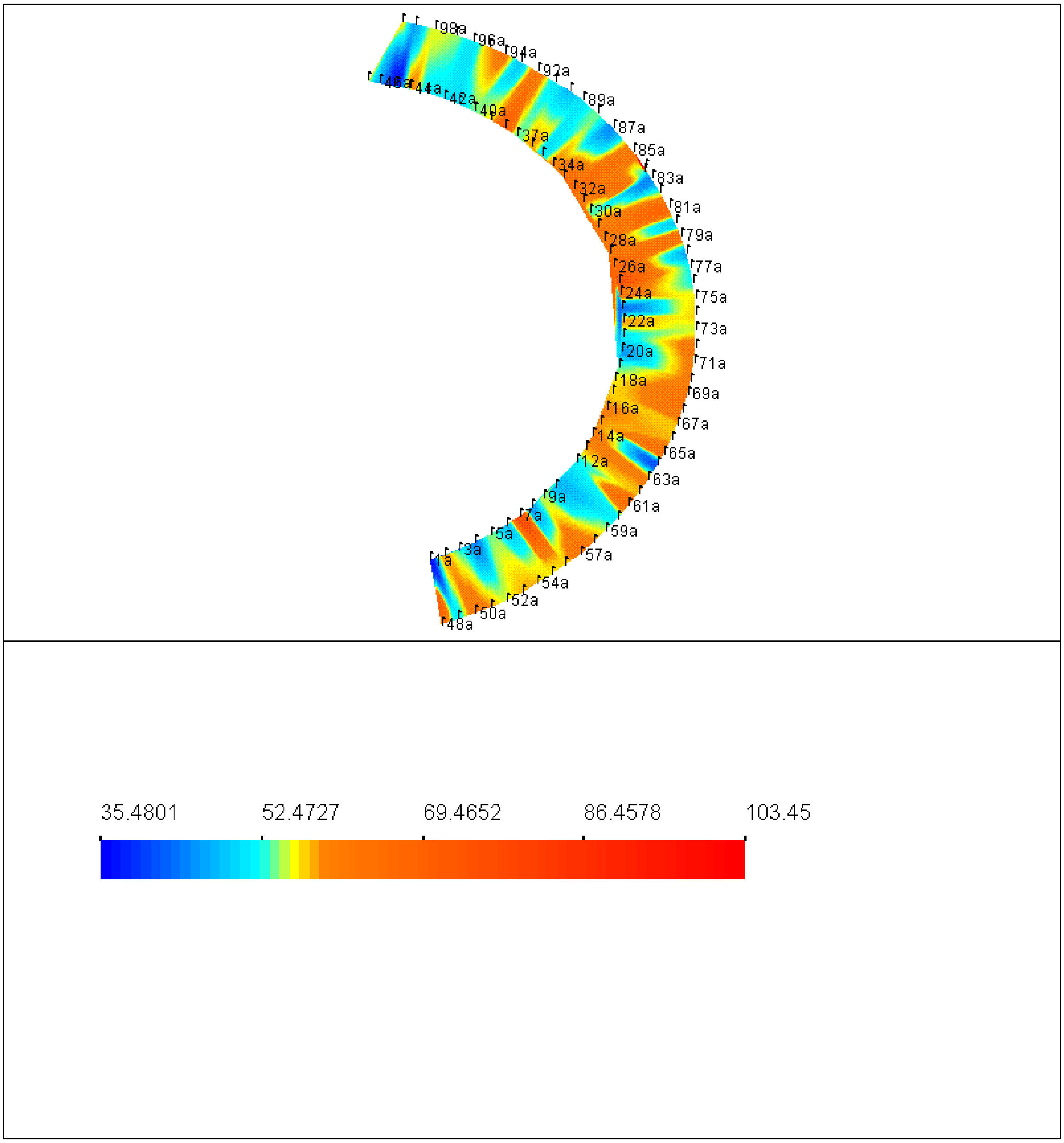

Figure 2. Optimal Levels of Spatial Nitrogen Application Map for Precision Farming Practices on a Per-Year Basis for a Ten-Year Planning Horizon, Lamesa, Texas.

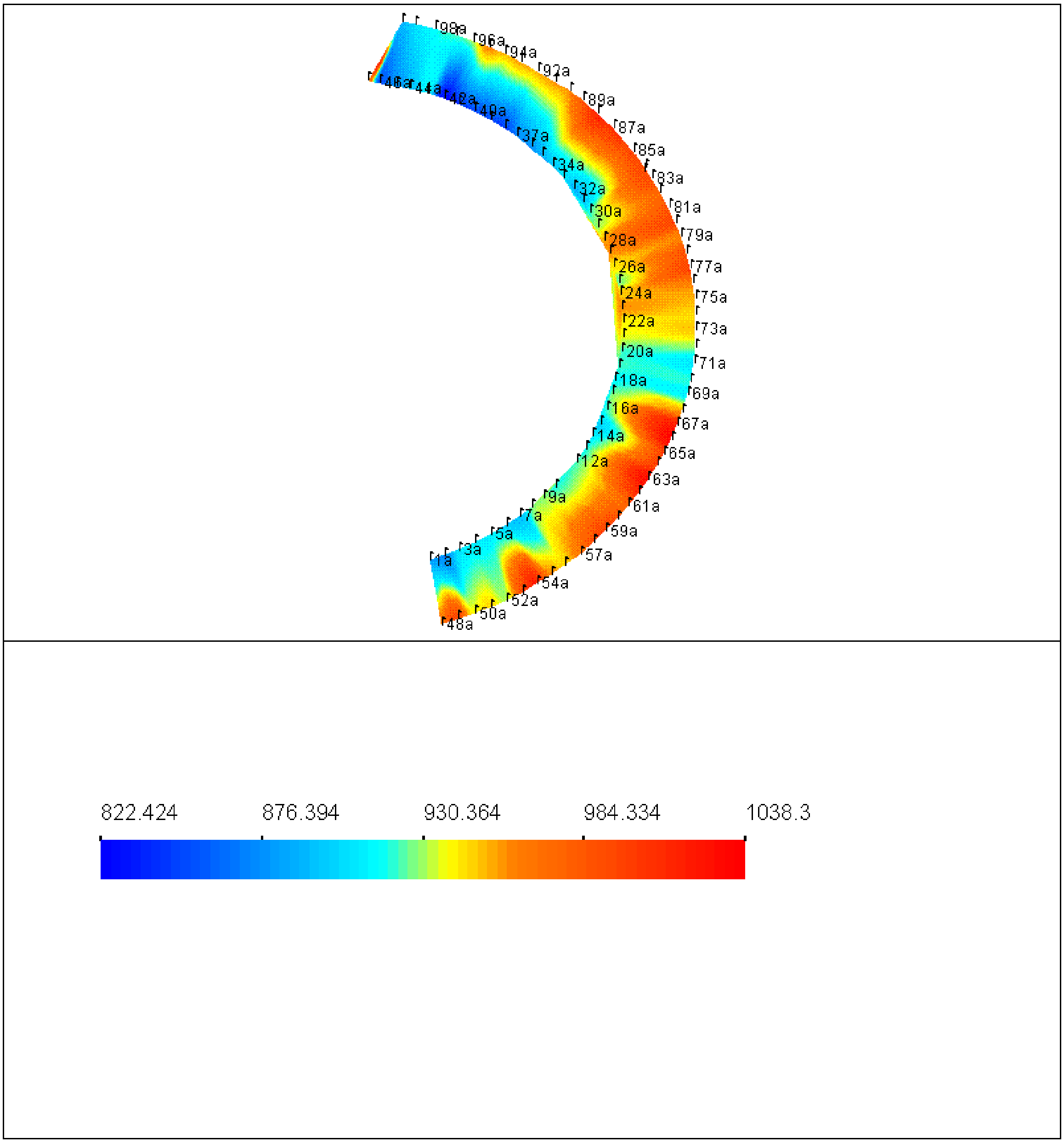

Figure 3. Spatial Cotton Yield Map for Precision Farming Practices, Lamesa, Texas.

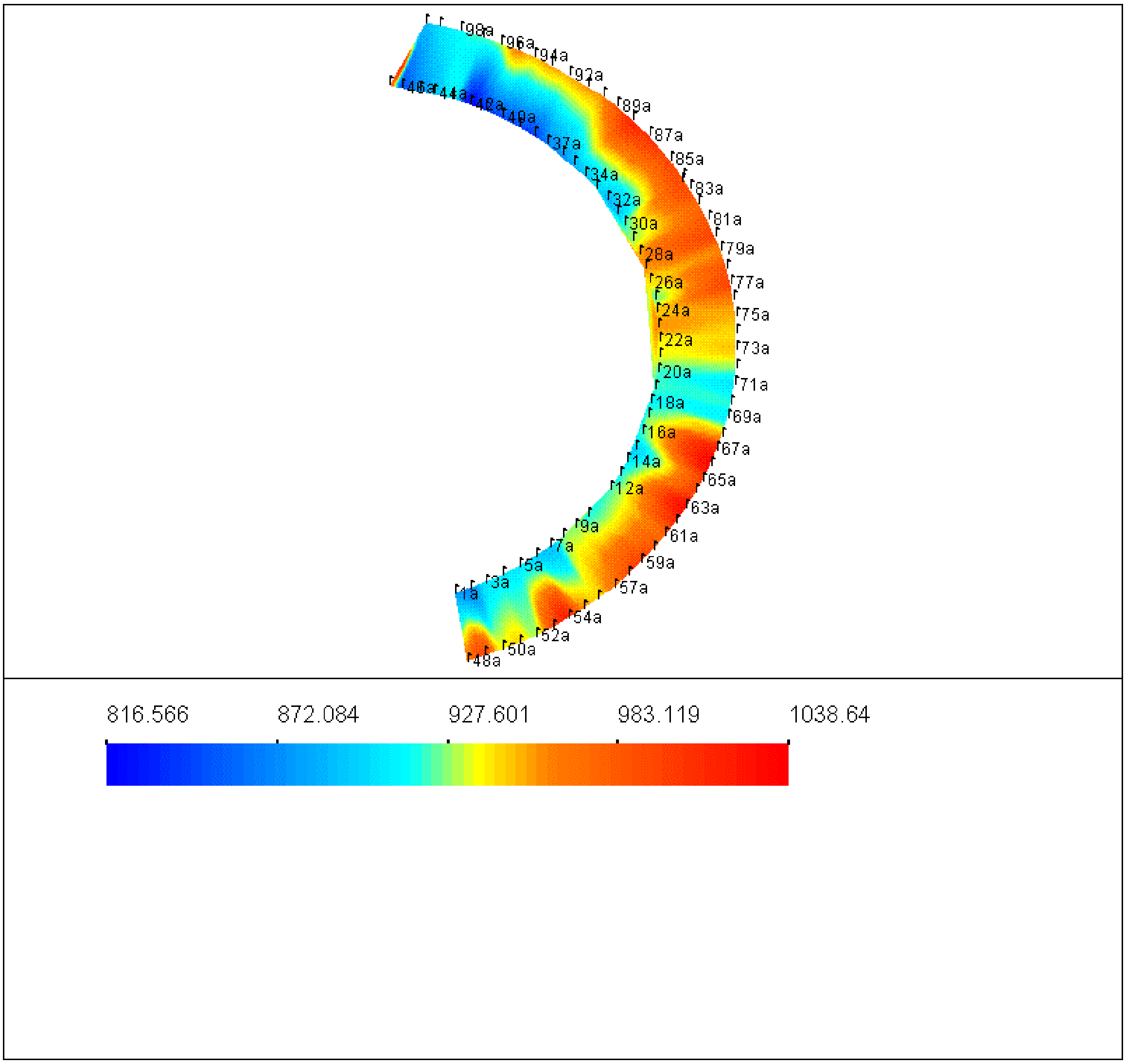

Figure 4. Spatial Cotton Yield Map for Whole-Field Farming Practices, Lamesa, Texas.

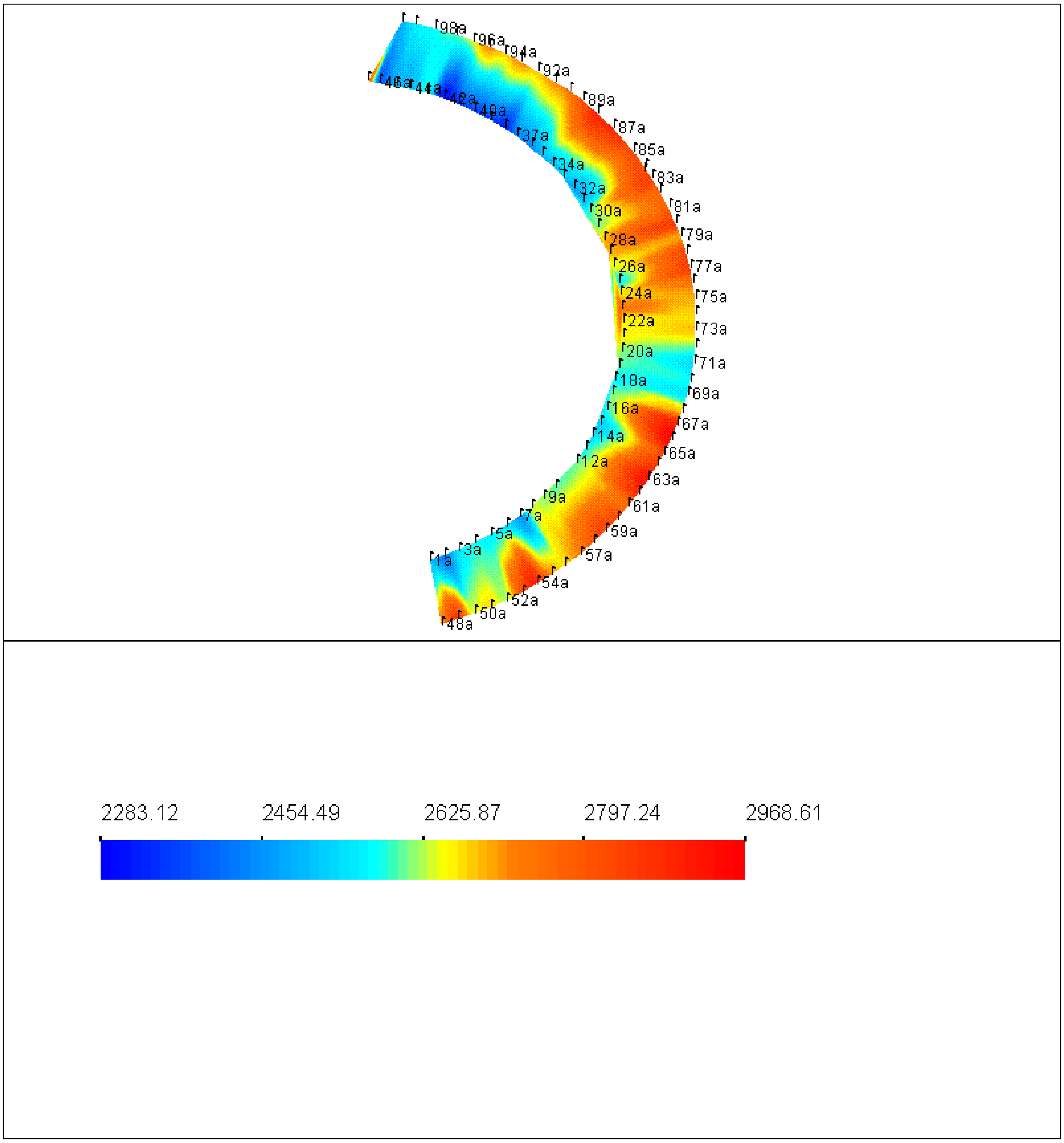

Figure 5. Spatial Net Revenue Above Nitrogen and Water Costs for a Ten-Year Optimization Model for Precision Farming Practices, Lamesa, Texas.

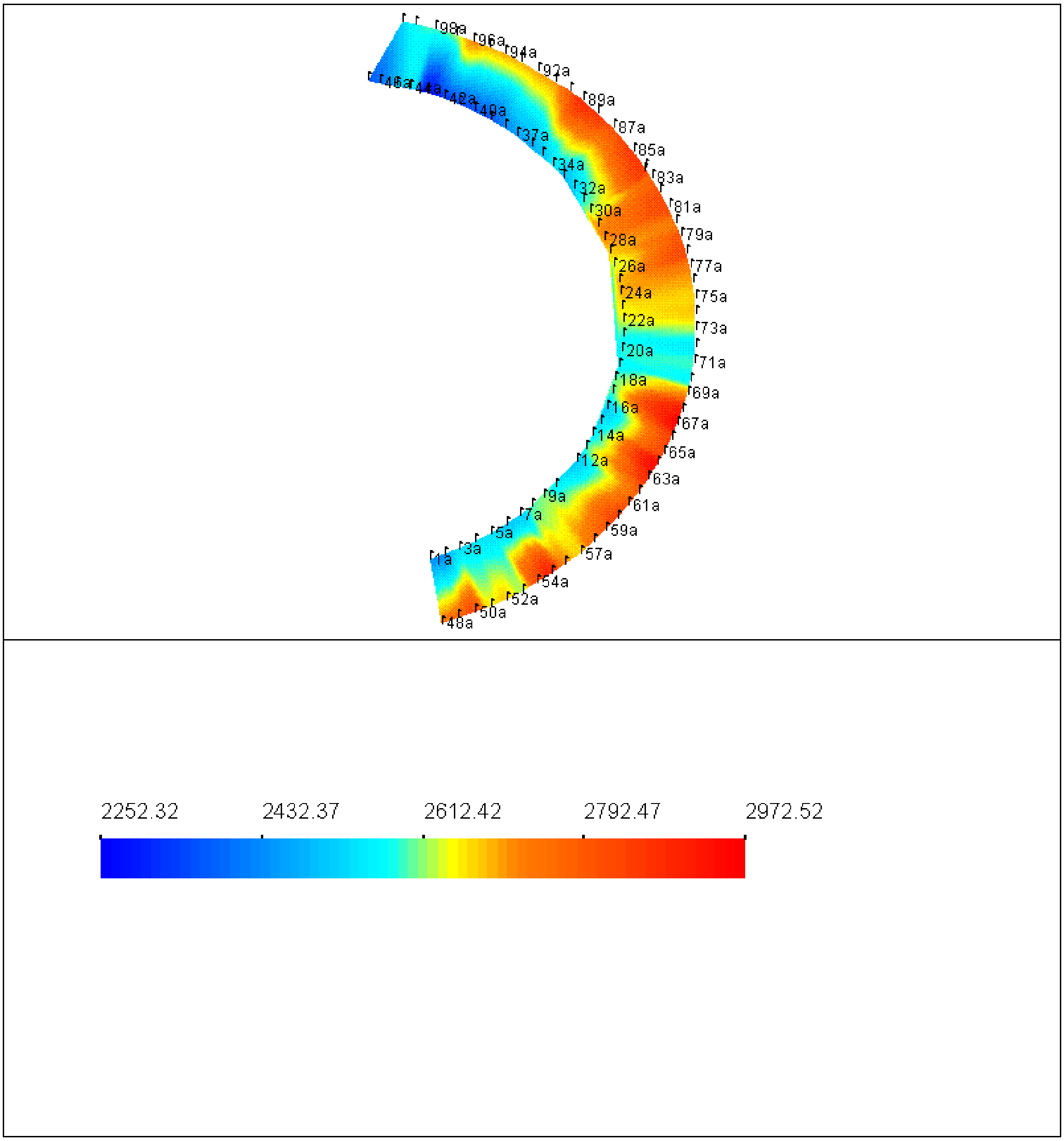

Figure 6. Spatial Net Revenue Above Nitrogen and Water Costs for a Ten-Year Optimization Model for Whole-Field Farming Practices, Lamesa, Texas.

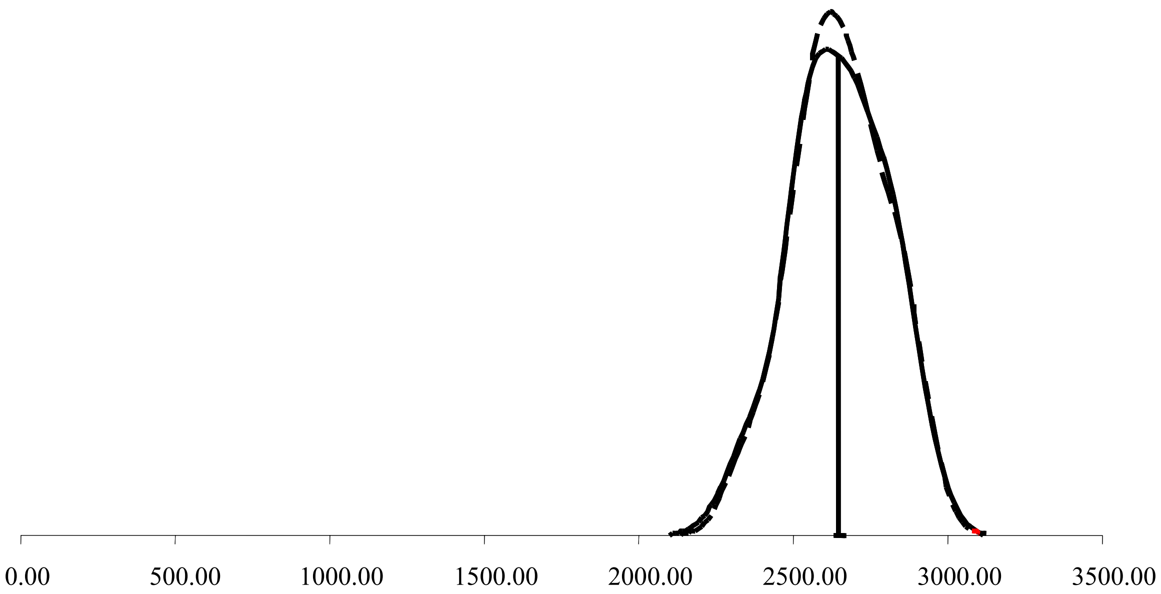

Figure 7. Probability Density Function for Cotton Net Revenues Above Nitrogen and Water Costs.

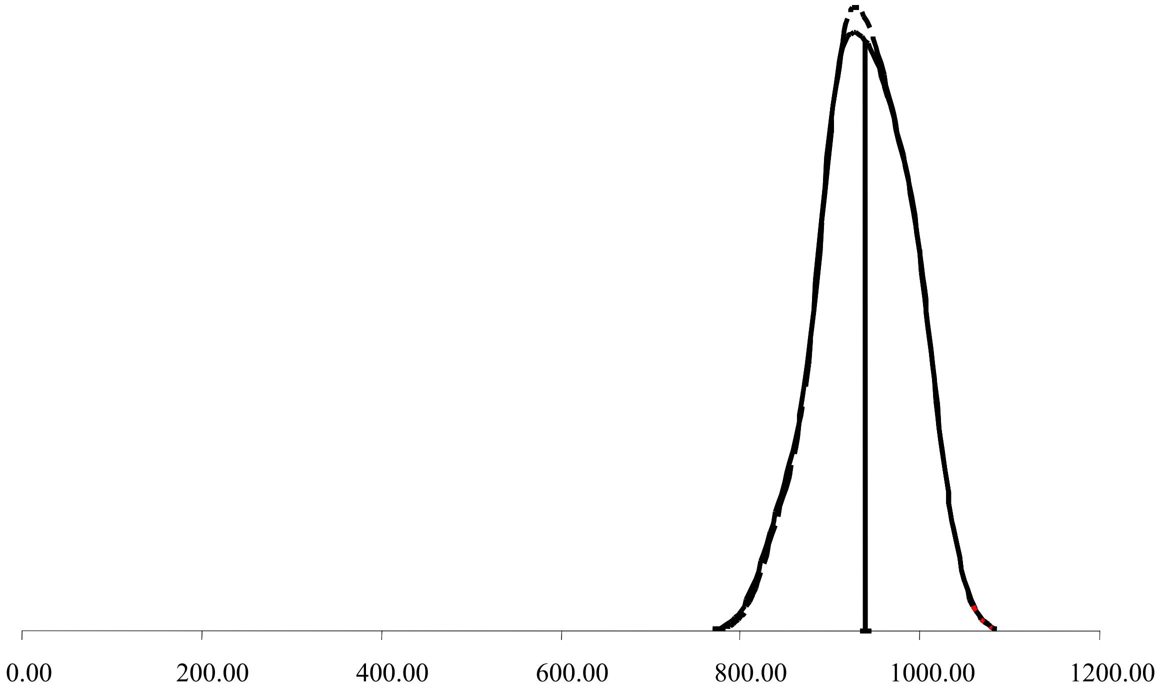

Figure 8. Probability Density Function for Cotton Yields.

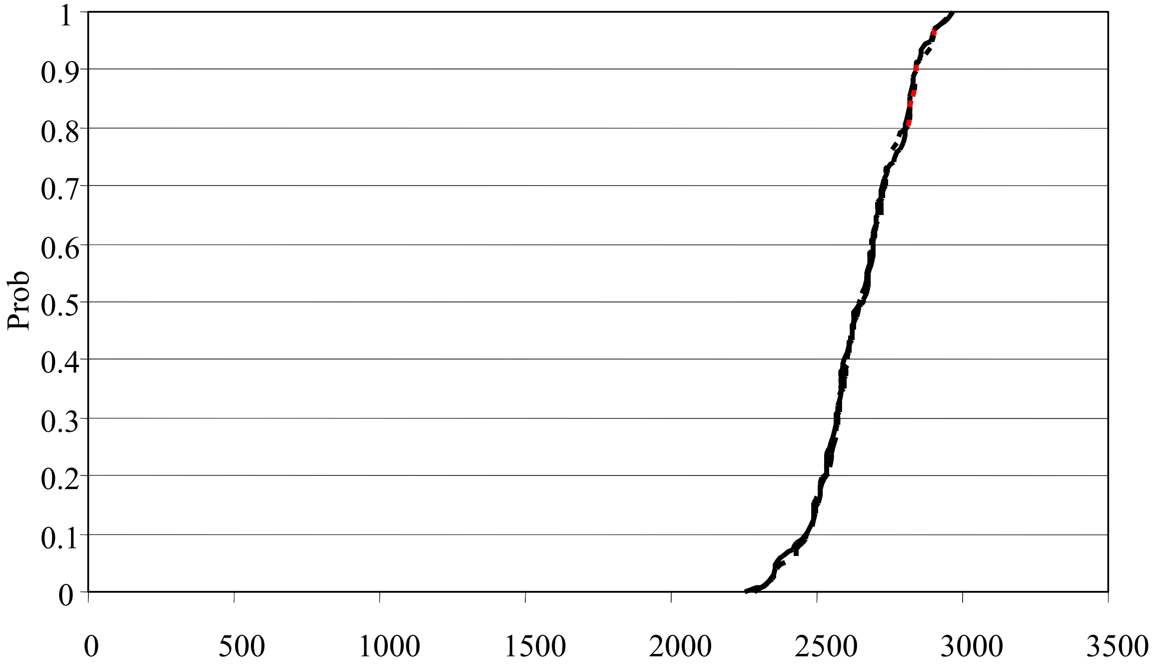

Figure 9. Cumulative Density Function for Cotton Net Revenues Above Nitrogen and Water Costs.