Economic Impacts of Precision Farming in Irrigated Cotton Production

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ABSTRACT

Spatial optimal nitrogen fertilizer application levels and net revenues in irrigated cotton production were derived. Results indicate that precision farming can improve the profitability, and potentially reduce the environmental damages associated with nitrogen fertilizer use in irrigated cotton production.

KEY WORDS: precision farming, agricultural profitability, environmental impact

Increased use of fertilizers, pesticides, and other chemicals has contributed to the enhancement of agricultural productivity in recent decades. Currently, production agriculture is facing challenges, such as increasing costs of production, shortage of irrigation water, and increased public concern on the impacts of agricultural production on the environment. To survive in the highly competitive world market of agricultural commodities, agricultural producers must produce high quality products at low prices, while employing environmentally friendly practices. One way to accomplish these objectives is to adopt precision farming technology.

Traditionally, optimal fertilizer use in agriculture has assumed spatial and temporal field homogeneity with respect to soil fertility, soil moisture, pest populations, and crop characteristics. That is, decision rules for optimal fertilizer use do not account for field heterogeneity. Precision farming, precision agriculture, or site-specific management recognizes the variability of such factors within fields and seeks to optimize variable input use under these conditions. Robert et al. (1995) states that precision farming for site-specific management is an advanced information technology based agricultural management system designed to identify, analyze, and manage site-soil spatial and temporal variability within fields for optimum profitability, sustainability, and protection of the environment. The development of precision farming practices is closely related to several new technologies that have been utilized in agricultural production in recent years. These new technologies involve the use of microcomputers, microprocessor based control systems, satellite positioning technologies, and different kinds of sensors. With the support of these technologies, spatial soil testing, variable rate application of fertilizers, variable rate spraying, and yield mapping are becoming available.

The primary objective of this study was to evaluate the economic implications of precision farming practices with respect to nitrogen fertilizer use in irrigated cotton production in the Southern High Plains of Texas (SHPT), as compared to conventional whole-field farming practices. In particular, a dynamic optimization model that introduces an inter-temporal nitrate-nitrogen carry-over function is used to derive and evaluate optimal nitrogen application rates, yield, and the net present value of returns for a 10-year planning horizon.

The SHPT is a semi-arid region located in the northwestern portion of Texas. It encompasses approximately 22 million acres in 42 counties. Cotton is the most important crop produced in the areas in terms of both acreage and crop value. Annual cotton plantings vary between 2.6 and 3.3 million acres in a 25-county region within the SHPT, with approximately 50 percent of these acres being irrigated (Yu et al. 1999). The soil types in the SHPT include: hard lands, composed of fine-textured clays and clay loams, which represent 54% of the area; mixed lands, composed of medium-textured loams and loamy sands, which represent 23% of the area; and sandy lands, composed of coarse-textured sand, which also represents 23% of the area.

MATERIALS AND METHODS

Contemporary studies have shown that both nitrogen and phosphorous fertilizer application and residual fertility have positive impacts on cotton yields (Segarra et al. 1989, Carter et al. 1974, Onken and Sunderman 1972, Yu et al. 2000). Westerman and Kurtz (1972) discussed nitrogen residual in the soil in relation to soil types. They found that total nitrogen (nitrogen application plus nitrogen residual) is higher in heavy soils as compared to sandy soils. They also found that two-thirds of the nitrogen residual is in the top 10 centimeters of the soil.

The research discussed in this manuscript combines new technologies to address the impacts of nitrogen fertilizer application and nitrogen residual on irrigated cotton production under different levels of initial soil fertility, and soil and location characteristics in the long run. A dynamic optimization model is developed to evaluate the relationship between the optimal decision rules for nitrogen application and nitrogen residual, and other soil and location properties. In this model cotton yield is a function of total nitrogen available. Total nitrogen available is equal to applied nitrogen plus nitrogen residual in the soil at a given time. Nitrogen residual at a given time is a function of previous nitrogen application and previous levels of nitrogen residual. Specifically, the structure of the optimization model used is:

$$\text{Max } Z = \sum_{t=0}^{n} \{[P_t \cdot Y_t(NT_t, W_t, X_1, X_2, \ldots, X_n) - CP_t \cdot NA_t - CW_t \cdot W_t]\cdot(1+r)^{-t}\} \quad (1)$$

Subject to:

$$NT_t = NA_t + NR_t, \quad (2)$$

$$NR_{t+1} = f_t[NA_t, NR_t], \quad (3)$$

$$NR_0 = NR(0), \quad (4)$$

and NA_t, $NR_t \geq 0$ for all t.

Where Z is the per-acre net present value of returns to risk, management, overhead, and all other cotton production inputs except for nitrogen and irrigation water in \$/acre; n is the length of the decision-maker's planning horizon in years; P_t is the price of cotton in year t (\$/lb.); Y_t is the cotton yield function in year t (lbs./acre); NT_t is the total nitrogen available to the crop in year t (lbs./acre); W_t is irrigation water applied in year t (inches);

X_1, X_2, …, X_n are other variables that influence the crop yield; CP_t is the price of nitrogen in year t ($/lb.); NA_t is nitrogen applied in year t (lbs./acre); CW_t is price of irrigation water in year t ($/acre inch); NR_t is nitrogen residual in year t (lbs./acre); and r is the discount rate.

Equation (1) is the objective function, or performance measure, of the optimization model. Equation (2) is an equality constraint that adds the applied nitrogen to the nitrogen residual at time t, and it used in equation (1) to calculate the cotton yield at time t. Equation (3) is the equation of motion that updates nitrogen residual. Equation (4) is the initial condition on the level of nitrogen residual at the beginning of the planning horizon.

The primary source of data for this study was from an experiment conducted at the Texas Agricultural Experiment Station in Lamesa, Texas, in 1998. The experiment originally included 104 field locations, but only 100 locations were considered in the analysis because of missing data. At each location, the nitrogen residual level in the soil at a depth of 0 to 90 centimeters was measured on June 3, 1998. Using MapInfo, a desktop mapping software that provides a mapping technique for calculating and displaying the trends of data that vary over geographic space (Vertical Mapper Manual), the pre-season nitrogen residual levels in the 100 locations are shown in Figure 1. The nitrogen residual levels in the top soil at a depth of 0 to 90 centimeters ranged from 0 to 283.14 pounds per acre at the beginning of the season.

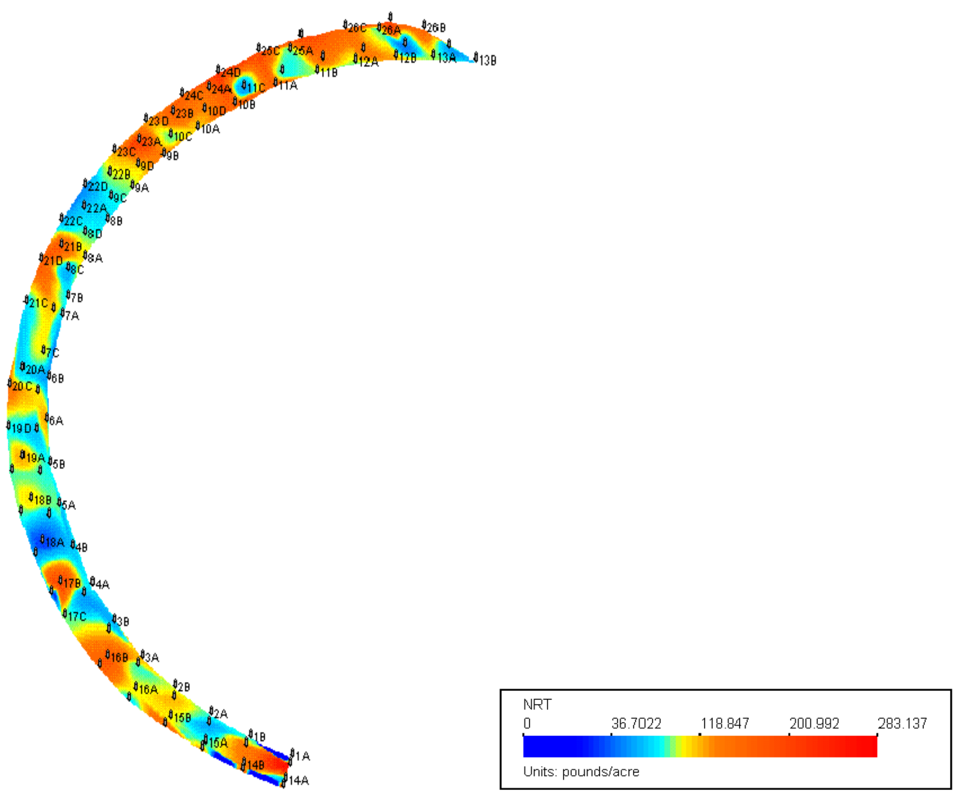

Figure 1. NO_3-N Pre-Season Residual Map from 0 to 90 Centimeters of Soil Depth, Lamesa, Texas, 1998.

The entire experimental field was treated equally, except for irrigation water, which was applied at two different levels of evapotranspiration (ET), 50% ET and 75% ET, and three different rates of nitrogen fertilizer (0, 80, and 120 pounds per acre). Other production inputs, such as pesticides, phosphorus fertilizer, and herbicides, were applied at the same rates across the experiment.

At the end of the growing season, a cotton stripper equipped with sensors and a Global Position System (GPS) was used to harvest the cotton. The yield data were downloaded into a computer and analyzed using MapInfo. Figure 2 shows the cotton lint yields in the 100 field locations, which ranged from 392.63 pounds per acre to 1086.67 pounds per acre. Notice that the inner portion of the field had relatively lower yields, as compared to the outer portion. This is likely explained by the lower water application level (50% ET) in this portion of the field.

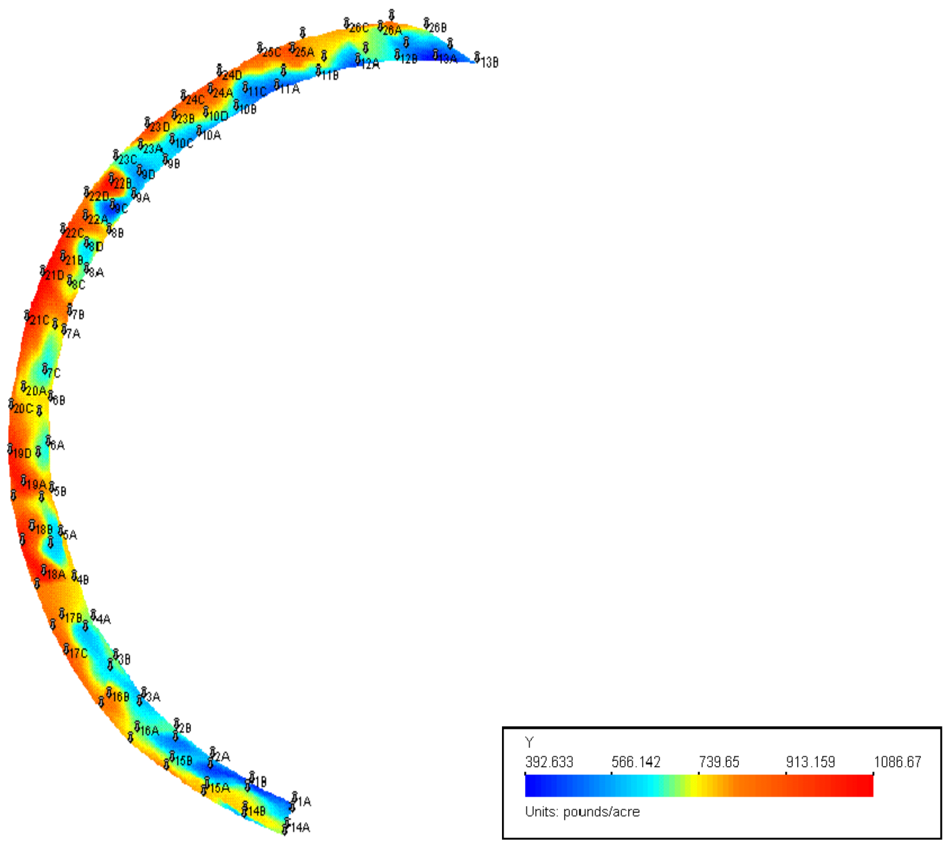

Figure 2. Spatial Cotton Yield Map, Lamesa, Texas, 1998.

The nitrogen residual level at a depth of 0 to 90 centimeters was measured again at each of the 100 locations on November 19, 1998, after the cotton was harvested. Post-harvest nitrogen residual levels ranged from 19.01 pounds per acre to 407.67 pounds per acre (Figure 3).

RESULTS

The cotton yield production function was estimated using GLM (General Linear Models) procedures (SAS 1982), assuming several functional forms including the double logarithmic, semi-logarithmic, Mistscherlich-Spillman, quadratic, and cubic. The quadratic functional form was found to best fit the data and provide economically sound results. The estimated cotton yield production function used in the analysis is:

$$\underset{(3.06)}{Y = 257.40} \underset{(9.66)}{+5.05*10^{-1}*NT*W*SD} \underset{(-8.33)}{-7.03*10^{-5}*NT*NT*ELEV*CL} \underset{(3.67)}{+28.03*PN} \qquad (5)$$

$$R^2 = 0.5321$$

Where Y is cotton lint yield in lbs./acre; NT is total nitrogen available to the crop (lbs./acre), which equals the nitrogen applied (NA) during the cotton growing season plus the nitrogen residual (NR) in the soil at the beginning of the season; W is the water available to the crop at either 50% or 75% ET; SD and CL represent the sand and clay percentage in the soil; ELEV is the elevation of the location in feet and; PN is the number of plants per acre. The numbers in parenthesis below the parameter estimates in equation (5) are *t*-values, which indicate that the terms NT*W*SD, and NT^2 *ELEV*CL were significant at the 0.0001 level; the PN term is statistically significant at the 0.0005 level; and the intercept term is statistically significant at 0.005 level.

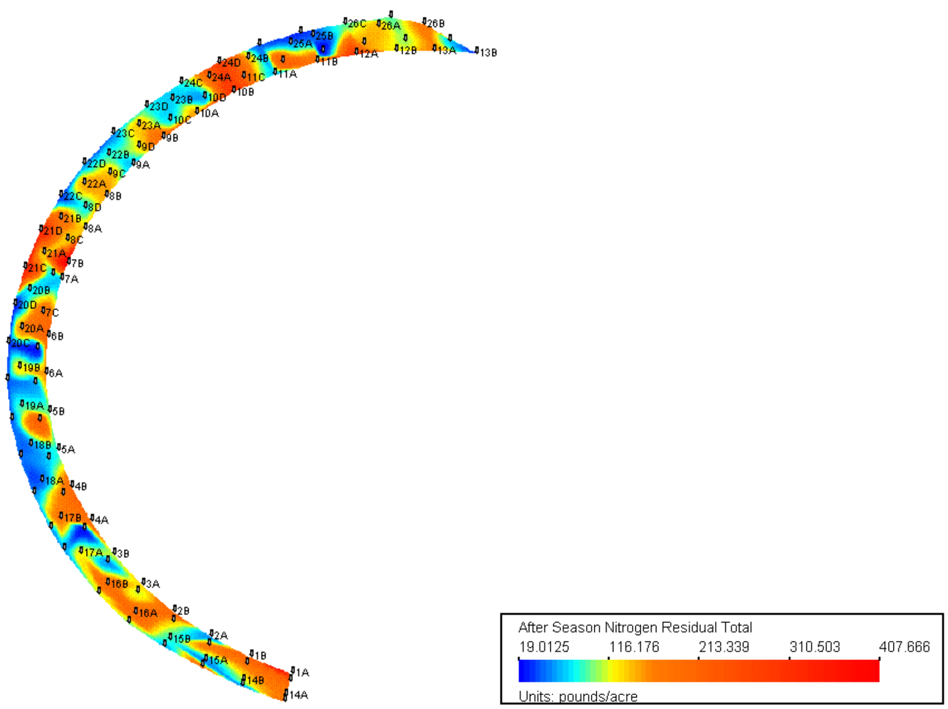

Figure 3. NO_3-N After-Season Residual Map from 0 to 90 Centimeters of Soil Depth, Lamesa, Texas, 1998.

The estimated production function suggests that there are significant interaction effects among nitrogen fertilizer, water, elevation, and soil properties (including the available clay and sand percentage in the soil) in explaining cotton yields. The R^2 value indicates that 53.21% of the variation in the observed cotton lint yields was explained by the independent variables included in the regression.

Based on the information of pre-season and post-season nitrogen residual (NR_t and NR_{t+1}) in the soil, and the nitrogen application level (NA_t) during the cotton growing season, the nitrogen carry-over function was estimated to be:

$$NR_{t+1} = \underset{(0.30)}{4.28} + \underset{(4.21)}{4.74*10^{-1}}\, NA_t + \underset{(3.01)}{4.17*10^{-1}}\, NR_t \tag{6}$$
$$R^2 = 0.2932.$$

Where the variables NR and NA are defined as before and the *t*-values are reported in parenthesis. All the parameters in equation (6), except the intercept term are statistically significant at the 0.05 level. The R^2 value indicates that 29.32% of the variation in the observed post-season nitrogen residual can be explained by the nitrogen application level during the cotton growing season and pre-season nitrogen residual level.

The dynamic optimization model was solved under two scenarios. The first scenario represents the optimality conditions under the precision input application technology. This was done to mimic possible scenarios of fertility that could be faced under precision farming practices within fields. That is, under precision farming practices, optimal input decision rules according to spatial differences within fields would be desired. For this scenario, 100 optimization models were built for the 100 locations within the field with their associated pre-season nitrogen residual levels, and soil and location characteristics (elevation, and the available sand and clay percentage in the soil).

The second scenario represents the optimality conditions under conventional input application technology, i.e., whole-field farming. For this scenario, because water was applied at only two different levels (50% ET and 75% ET) in the experiment, water was introduced as a dummy variable in the mathematical model. In order to mimic possible scenarios of fertility that could be faced under whole-field farming practices, the 100 locations were separated into two groups (50 locations for each group), according to their water application levels. Average initial nitrogen residual level, and average soil and location characteristics were calculated for each group and used in the optimization model.

The optimization model given by equations (1) through (4) was solved for all combinations of the following conditions: (1) a ten-year planning horizon, (2) a 5% discount rate (r = 0.05), (3) a water price of \$2.68/inch, (4) a cotton lint price of \$0.60/lb., (5) a nitrogen fertilizer price of \$0.30/lb., and (6) 100 locations with their corresponding initial nitrogen residual levels for precision farming practices, and the two ET groups described above with average initial nitrogen residual levels for whole-field farming practices.

As expected, the optimal decision rules for applying nitrogen fertilizer varied across periods in the planning horizon for a given nitrogen and cotton price combination at the different levels of nitrogen residual and soil and location characteristics. However, because a stable optimal decision rule is desirable to simplify management, an additional constraint of equating nitrogen applications across time periods within the planning horizon was introduced for each given nitrogen and cotton price combination and initial nitrogen soil fertility.

Solutions to the 102 optimization models (100 models for scenario one [precision farming practices], and 2 models for scenario two [whole-field farming practices]) were obtained using GAMS (General Algebraic Mathematical System), and are presented in Tables 1 and 2. These two tables list total optimal levels of nitrogen applications, total per-acre net present value of returns above nitrogen and water costs, and the tenth year after-season nitrogen residual level for each location for the ten-year planning horizon assumed for the evaluation of both precision farming practices and whole-field farming practices. Also, a comparison of the revenue and crop yield change associated with the two farming practices at each location is presented in Tables 1 and 2.

Table 1. A Comparison of Precision Farming and Whole-Field Farming Scenarios under 50% ET.

		Precision-Farming Practices					Whole-Field Farming Practices					Difference			
Number	PLOT	Total Revenue	Total Yield	Total NA	NR10	TFP	Total Revenue	Total Yield	Total NA	NR10	TFP	Revenue Change	Yield Change	TFP Change	NR10 Change
1	1A	3125.53	6945.56	454.24	44.24	15.29	3125.27	6951.78	466.98	45.27	14.89	0.0082%	-0.0896%	0.40	-1.03
2	1B	3223.90	7172.54	503.77	48.26	14.24	3221.77	7148.55	466.98	45.27	15.31	0.0661%	0.3356%	-1.07	2.99
3	2A	3105.08	6907.49	458.83	44.61	15.05	3104.97	6911.37	466.98	45.27	14.80	0.0035%	-0.0562%	0.25	-0.66
4	2B	3147.80	6997.32	466.19	45.21	15.01	3147.80	6997.74	466.98	45.27	14.99	0.0000%	-0.0060%	0.02	-0.06
5	2C	3147.51	7017.51	500.34	47.98	14.03	3145.73	6997.39	466.98	45.27	14.98	0.0566%	0.2876%	-0.96	2.71
6	2D	3185.77	7100.39	512.18	48.94	13.86	3182.55	7070.92	466.98	45.27	15.14	0.1009%	0.4167%	-1.28	3.67
7	3A	3012.92	6658.12	338.87	34.87	19.65	2982.34	6665.68	466.98	45.28	14.27	1.0252%	-0.1135%	5.37	-10.40
8	3B	3267.61	7315.79	604.17	56.41	12.11	3242.11	7193.93	466.98	45.27	15.41	0.7865%	1.6940%	-3.30	11.14
9	3C	3114.56	6926.71	459.27	44.64	15.08	3114.46	6930.43	466.98	45.27	14.84	0.0031%	-0.0537%	0.24	-0.63
10	3D	3276.02	7314.79	571.08	53.73	12.81	3260.18	7228.55	466.98	45.27	15.48	0.4858%	1.1930%	-2.67	8.45
11	4A	3083.21	6846.84	426.88	42.01	16.04	3080.31	6860.83	466.98	45.27	14.69	0.0940%	-0.2039%	1.35	-3.26
12	4B	3177.70	7084.91	514.83	49.16	13.76	3174.21	7053.44	466.98	45.27	15.10	0.1099%	0.4462%	-1.34	3.89
13	4C	3152.12	7016.56	482.51	46.53	14.54	3151.72	7007.94	466.98	45.27	15.01	0.0127%	0.1229%	-0.47	1.26
14	4D	3097.47	6870.22	418.71	41.35	16.41	3093.53	6887.80	466.98	45.27	14.75	0.1273%	-0.2554%	1.66	-3.92
15	5A	3292.24	7340.59	558.86	52.74	13.13	3279.89	7266.14	466.98	45.28	15.56	0.3765%	1.0245%	-2.42	7.46
16	5B	3297.82	7369.63	592.29	55.45	12.44	3276.09	7259.51	466.98	45.27	15.55	0.6633%	1.5168%	-3.10	10.18
17	5C	3275.45	7328.85	597.26	55.85	12.27	3251.45	7213.93	466.98	45.27	15.45	0.7382%	1.5931%	-3.18	10.58
18	5D	3448.97	7766.38	758.09	68.91	10.24	3352.63	7419.08	466.98	45.27	15.89	2.8737%	4.6812%	-5.64	23.64
19	6A	3700.20	8368.33	937.11	83.46	8.93	3499.16	7700.29	466.98	45.28	16.49	5.7453%	8.6755%	-7.56	38.18
20	6B	3278.67	7346.56	617.84	57.52	11.89	3247.89	7207.67	466.98	45.27	15.43	0.9479%	1.9269%	-3.54	12.25
21	6C	3068.12	6811.33	419.31	41.40	16.24	3064.13	6827.15	466.98	45.27	14.62	0.1300%	-0.2317%	1.62	-3.87
22	6D	3051.42	6759.77	387.04	38.78	17.47	3040.23	6779.07	466.98	45.27	14.52	0.3682%	-0.2847%	2.95	-6.49
23	7A	3290.97	7371.52	621.19	57.79	11.87	3259.90	7228.66	466.98	45.27	15.48	0.9531%	1.9763%	-3.61	12.52
24	7B	3090.20	6850.20	408.26	40.50	16.78	3083.95	6867.88	466.98	45.27	14.71	0.2028%	-0.2574%	2.07	-4.77
25	7C	3376.63	7559.69	650.43	60.17	11.62	3334.76	7375.03	466.98	45.28	15.79	1.2554%	2.5040%	-4.17	14.90
26	7D	3711.83	8428.23	998.08	88.40	8.44	3459.98	7635.12	466.98	45.27	16.35	7.2790%	10.3877%	-7.91	43.13
27	8A	3465.98	7806.40	773.26	70.15	10.10	3366.31	7440.38	466.98	45.27	15.93	2.9610%	4.9194%	-5.84	24.87
28	8B	3253.24	7262.43	559.54	52.79	12.98	3240.60	7188.98	466.98	45.27	15.39	0.3902%	1.0217%	-2.42	7.52
29	8C	3188.14	7104.86	511.36	48.87	13.89	3185.02	7076.00	466.98	45.27	15.15	0.0979%	0.4078%	-1.26	3.60
30	8D	3398.72	7640.85	715.68	65.47	10.68	3326.27	7363.83	466.98	45.27	15.77	2.1783%	3.7619%	-5.09	20.20
31	9A	3310.52	7403.86	609.65	56.86	12.14	3283.91	7273.70	466.98	45.27	15.58	0.8102%	1.7894%	-3.43	11.59
32	9B	3041.16	6726.68	360.73	36.65	18.65	3020.66	6742.74	466.98	45.28	14.44	0.6788%	-0.2382%	4.21	-8.63
33	9C	3170.96	7056.91	488.91	47.05	14.43	3170.19	7043.99	466.98	45.27	15.08	0.0240%	0.1834%	-0.65	1.78
34	9D	2993.00	6610.89	328.96	34.07	20.10	2955.14	6605.85	466.98	45.27	14.15	1.2809%	0.0764%	5.95	-11.21
35	10A	3078.81	6815.01	383.60	38.51	17.77	3066.17	6834.40	466.98	45.28	14.64	0.4121%	-0.2837%	3.13	-6.77
36	10B	3105.75	6881.70	406.81	40.39	16.92	3099.39	6901.22	466.98	45.28	14.78	0.2053%	-0.2830%	2.14	-4.89
37	10C	3061.11	6779.66	386.59	38.75	17.54	3049.76	6799.42	466.98	45.28	14.56	0.3723%	-0.2907%	2.98	-6.53
38	10D	2929.05	6458.29	285.08	30.50	22.65	2863.28	6420.67	466.98	45.27	13.75	2.2971%	0.5859%	8.90	-14.77
39	11A	2964.18	6537.95	295.95	31.39	22.09	2905.97	6513.51	466.98	45.28	13.95	2.0028%	0.3752%	8.14	-13.89
40	11B	3133.88	6962.79	454.35	44.25	15.32	3133.63	6968.98	466.98	45.27	14.92	0.0081%	-0.0889%	0.40	-1.03
41	11C	2846.37	6256.84	223.56	25.50	27.99	2708.39	6096.40	466.98	45.27	13.05	5.0948%	2.6316%	14.93	-19.77
42	11D	3115.09	6930.13	464.30	45.05	14.93	3115.08	6931.47	466.98	45.27	14.84	0.0004%	-0.0194%	0.08	-0.22
43	12A	3124.82	6950.67	464.45	45.07	14.97	3124.81	6951.93	466.98	45.27	14.89	0.0003%	-0.0181%	0.08	-0.21
44	12B	2962.14	6540.79	314.65	32.91	20.79	2918.46	6532.77	466.98	45.28	13.99	1.4967%	0.1227%	6.80	-12.37
45	12C	2932.02	6456.98	266.09	28.96	24.27	2844.85	6388.85	466.98	45.28	13.68	3.0641%	1.0664%	10.58	-16.31
46	12D	3009.41	6650.73	336.57	34.69	19.76	2978.43	6659.79	466.98	45.28	14.26	1.0402%	-0.1360%	5.50	-10.59
47	13A	3127.30	6948.52	452.17	44.07	15.37	3126.94	6955.47	466.98	45.27	14.89	0.0116%	-0.0999%	0.47	-1.20
48	13B	3059.53	6801.36	430.34	42.29	15.80	3057.17	6814.34	466.98	45.27	14.59	0.0774%	-0.1905%	1.21	-2.98
49	13C	3152.03	7013.57	478.26	46.19	14.66	3151.82	7007.42	466.98	45.27	15.01	0.0067%	0.0878%	-0.34	0.92
50	13D	3056.25	6787.15	418.30	41.32	16.23	3052.08	6802.74	466.98	45.27	14.57	0.1368%	-0.2291%	1.66	-3.95
Average		3169.58	7057.22	493.34	47.41	15.38	3138.43	6980.02	466.98	45.27	14.95	0.9812%	1.0476%	0.44	2.14

Table 2. A Comparison of Precision Farming and Whole-Field Farming Scenarios under 75% ET.

		Precision-Farming Practices					Whole-Field Farming Practices					Difference			
Number	PLOT	Total Revenue	Total Yield	Total NA	NR10	TFP	Total Revenue	Total Yield	Total NA	NR10	TFP	Revenue Change	Yield Change	TFP Change	NR10 Change
51	14A	3794.05	8640.43	791.22	71.60	10.92	3790.00	8656.34	841.69	75.70	10.28	0.1068%	-0.1837%	-10.28	-75.70
52	14B	4260.92	9732.97	1055.80	93.09	9.22	4203.61	9507.67	841.69	75.70	11.30	1.3632%	2.3697%	-11.30	-75.70
53	14D	3996.01	9099.31	880.60	78.86	10.33	3993.76	9075.47	841.69	75.70	10.78	0.0561%	0.2627%	-10.78	-75.70
54	15A	4007.47	9140.50	906.95	81.00	10.08	4001.18	9096.44	841.69	75.70	10.81	0.1574%	0.4844%	-10.81	-75.70
55	15B	3690.76	8362.82	669.68	61.74	12.49	3638.75	8345.95	841.69	75.71	9.92	1.4294%	0.2021%	-9.92	-75.71
56	15C	4007.39	9098.49	836.79	75.31	10.87	4007.35	9100.89	841.69	75.70	10.81	0.0010%	-0.0264%	-10.81	-75.70
57	15D	4006.72	9102.32	845.14	75.98	10.77	4006.70	9100.57	841.69	75.70	10.81	0.0005%	0.0193%	-10.81	-75.70
58	16B	3948.75	8943.12	769.33	69.83	11.62	3940.11	8964.39	841.69	75.71	10.65	0.2194%	-0.2373%	-10.65	-75.71
59	16C	3657.18	8314.84	700.74	64.25	11.87	3621.12	8305.81	841.69	75.70	9.87	0.9958%	0.1087%	-9.87	-75.70
60	16D	3833.80	8694.40	745.16	67.87	11.67	3818.46	8713.43	841.69	75.71	10.35	0.4018%	-0.2184%	-10.35	-75.71
61	17A	3549.86	8047.83	610.66	56.94	13.18	3437.88	7922.29	841.69	75.70	9.41	3.2572%	1.5847%	-9.41	-75.70
62	17B	3731.21	8465.23	706.55	64.73	11.98	3699.10	8466.36	841.69	75.70	10.06	0.8680%	-0.0133%	-10.06	-75.70
63	17C	3804.41	8662.61	785.64	71.15	11.03	3799.09	8677.52	841.69	75.70	10.31	0.1400%	-0.1718%	-10.31	-75.70
64	17D	4218.01	9647.62	1041.60	91.93	9.26	4163.81	9442.62	841.69	75.70	11.22	1.3018%	2.1711%	-11.22	-75.70
65	18A	3922.39	8974.16	915.87	81.72	9.80	3914.58	8923.63	841.69	75.70	10.60	0.1994%	0.5662%	-10.60	-75.70
66	18B	3979.95	9037.48	827.74	74.57	10.92	3979.64	9043.90	841.69	75.70	10.74	0.0078%	-0.0710%	-10.74	-75.70
67	18C	3858.63	8765.58	774.76	70.26	11.31	3850.78	8781.07	841.69	75.70	10.43	0.2040%	-0.1764%	-10.43	-75.70
68	18D	4183.80	9522.96	952.56	84.70	10.00	4165.83	9431.41	841.69	75.70	11.21	0.4314%	0.9707%	-11.21	-75.70
69	19A	4011.64	9131.76	873.42	78.28	10.46	4010.04	9113.43	841.69	75.70	10.83	0.0399%	0.2012%	-10.83	-75.70
70	19B	4083.53	9312.84	942.47	83.88	9.88	4069.13	9234.12	841.69	75.70	10.97	0.3538%	0.8525%	-10.97	-75.70
71	19C	4318.93	9865.67	1074.60	94.61	9.18	4248.77	9607.65	841.69	75.70	11.41	1.6513%	2.6855%	-11.41	-75.70
72	19D	3905.64	8878.18	812.94	73.37	10.92	3904.33	8889.79	841.69	75.70	10.56	0.0335%	-0.1305%	-10.56	-75.70
73	20A	4582.87	10484.25	1218.90	106.33	8.60	4414.09	9953.09	841.69	75.70	11.83	3.8235%	5.3366%	-11.83	-75.70
74	20B	4485.16	10253.62	1169.30	102.31	8.77	4357.95	9828.51	841.69	75.70	11.68	2.9191%	4.3253%	-11.68	-75.70
75	20C	3804.58	8621.23	718.55	65.71	12.00	3778.01	8629.78	841.69	75.71	10.25	0.7035%	-0.0990%	-10.25	-75.71
76	20D	4053.70	9251.47	939.99	83.68	9.84	4040.04	9175.95	841.69	75.70	10.90	0.3381%	0.8230%	-10.90	-75.70
77	21A	4304.57	9784.03	984.65	87.31	9.94	4275.63	9651.19	841.69	75.71	11.47	0.6769%	1.3763%	-11.47	-75.71
78	21B	4068.96	9241.58	870.46	78.04	10.62	4067.70	9224.25	841.69	75.71	10.96	0.0310%	0.1878%	-10.96	-75.71
79	21C	3865.85	8806.80	824.99	74.34	10.68	3865.41	8813.82	841.69	75.70	10.47	0.0114%	-0.0796%	-10.47	-75.70
80	21D	4278.08	9731.92	994.16	88.09	9.79	4248.02	9587.84	841.69	75.71	11.39	0.7075%	1.5026%	-11.39	-75.71
81	22A	3581.52	8164.48	710.87	65.07	11.49	3553.31	8167.42	841.69	75.70	9.70	0.7941%	-0.0360%	-9.70	-75.70
82	22B	4185.63	9562.44	1023.00	90.43	9.35	4143.54	9385.83	841.69	75.70	11.15	1.0156%	1.8817%	-11.15	-75.70
83	22C	4072.67	9302.79	958.42	85.18	9.71	4053.38	9207.89	841.69	75.70	10.94	0.4758%	1.0307%	-10.94	-75.70
84	22D	4194.47	9638.94	1124.20	98.64	8.57	4103.64	9316.33	841.69	75.70	11.07	2.2133%	3.4629%	-11.07	-75.70
85	23A	4322.63	9853.54	1048.00	92.46	9.40	4268.19	9635.78	841.69	75.70	11.45	1.2755%	2.2599%	-11.45	-75.70
86	23B	4071.06	9269.10	914.50	81.62	10.14	4063.54	9216.78	841.69	75.70	10.95	0.1850%	0.5676%	-10.95	-75.70
87	23C	4014.81	9154.19	919.45	82.02	9.96	4006.90	9097.48	841.69	75.71	10.81	0.1972%	0.6235%	-10.81	-75.71
88	23D	3872.93	8833.76	856.78	76.93	10.31	3872.61	8825.61	841.69	75.70	10.49	0.0083%	0.0924%	-10.49	-75.70
89	24A	3584.25	8120.49	622.84	57.93	13.04	3497.05	8054.65	841.69	75.71	9.57	2.4935%	0.8174%	-9.57	-75.71
90	24B	3580.23	8107.09	599.98	56.09	13.51	3477.37	8033.04	841.69	75.71	9.54	2.9579%	0.9218%	-9.54	-75.71
91	24C	3693.89	8360.46	642.09	59.50	13.02	3623.99	8329.76	841.69	75.71	9.90	1.9290%	0.3685%	-9.90	-75.71
92	24D	4293.69	9746.43	958.35	85.19	10.17	4275.23	9643.77	841.69	75.71	11.46	0.4317%	1.0646%	-11.46	-75.71
93	25A	3557.44	8075.08	641.75	59.47	12.58	3487.07	8030.04	841.69	75.70	9.54	2.0180%	0.5608%	-9.54	-75.70
94	25B	3850.58	8771.81	826.81	74.49	10.61	3850.25	8778.58	841.69	75.70	10.43	0.0084%	-0.0771%	-10.43	-75.70
95	25C	3791.03	8593.04	708.42	64.89	12.13	3762.84	8611.19	841.69	75.71	10.23	0.7492%	-0.2108%	-10.23	-75.71
96	25D	4304.37	9798.72	1019.80	90.17	9.61	4264.74	9620.87	841.69	75.71	11.43	0.9291%	1.8486%	-11.43	-75.71
97	26A	3503.20	7946.14	606.41	56.60	13.10	3399.79	7848.77	841.69	75.70	9.33	3.0417%	1.2406%	-9.33	-75.70
98	26B	4004.62	9104.11	858.05	77.03	10.61	4004.21	9095.05	841.69	75.70	10.81	0.0102%	0.0996%	-10.81	-75.70
99	26C	4154.56	9461.01	959.12	85.24	9.86	4136.48	9361.92	841.69	75.71	11.12	0.4371%	1.0584%	-11.12	-75.71
100	26D	3955.26	8968.38	791.10	71.60	11.34	3951.35	8988.42	841.69	75.71	10.68	0.0990%	-0.2230%	-10.68	-75.71
Average		3976.07	9048.96	860.62	77.24	10.73	3942.13	8970.29	841.69	75.70	10.66	0.8740%	0.8395%	-10.66	-75.70

Economic Implications

The optimal spatial nitrogen application rates for the assumed ten-year planning horizon under precision farming are depicted in Figure 4. These rates range from 20.59 pounds per acre to 122.76 pounds per acre per year. There is no clear relation between the optimal nitrogen application map (Figure 4) and the pre-season nitrogen residual map (Figure 1). Under conventional whole-field farming practices, the optimal nitrogen application rates are 46.70 pounds per acre per year for the 50% ET water application, and 84.17 pounds per acre per year for the 75% ET water application scenario.

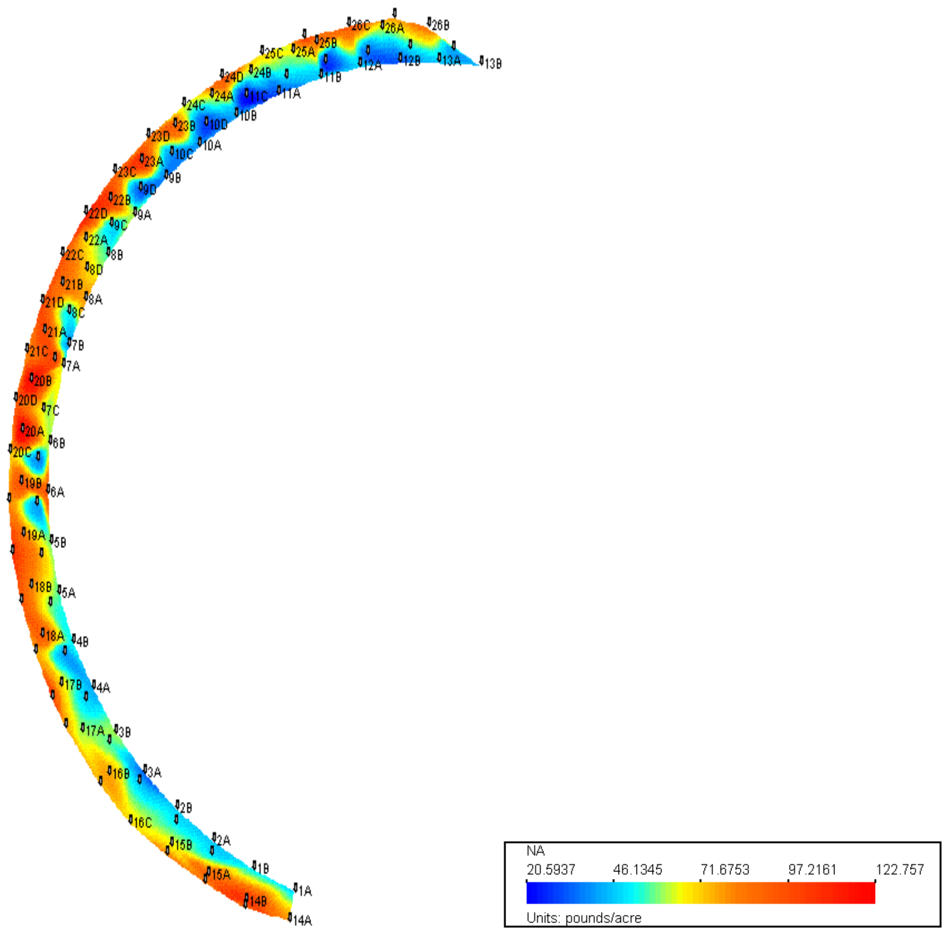

Figure 4. Optimal Levels of Spatial Nitrogen Application Map on a Per-Acre and Per-Year Basis for a Ten-Year Planning Horizon, Lamesa, Texas, 1998.

Tables 1 and 2 list the total cotton lint yields under the two nitrogen application technologies. Under precision farming practices, cotton yield ranged from 6,176.88 to 8,428.23 pounds per acre under 50% ET and 7,946.14 to 10,526.62 pounds per acre under 75% ET over a ten-year planning horizon. Under whole-field farming practices, total cotton yield ranged from 6,029.95 to 7,700.29 pounds per acre under 50% ET, and 7,848.77 to 9,995.83 pounds per acre under 75% ET over a ten-year planning horizon.

By comparing the yield difference at each field location under the two technologies, it was found that the average total yield for the ten-year planning horizon would increase by 1.11%, from 6,980.02 pounds per acre with conventional whole-field to 7,057.22 pounds per acre with precision farming under the 50% ET scenario. Under the 75% ET scenario, total yield would increase by 0.88%, from 8,970.29 pounds per acre (conventional whole-field farming practices) to 9,048.96 pounds per acre (precision farming practices). The yield percentage difference from precision farming ranged from a decrease of 0.29% (Location 10C) to an increase of 10.39% (Location 7D) under 50% ET, and from a decrease of 0.24% (Location 16B) to an increase of 5.34% (Location 20A) under 75% ET (Figure 5). 72% of the field locations show a yield increase, and 28% of the field locations show a yield decrease.

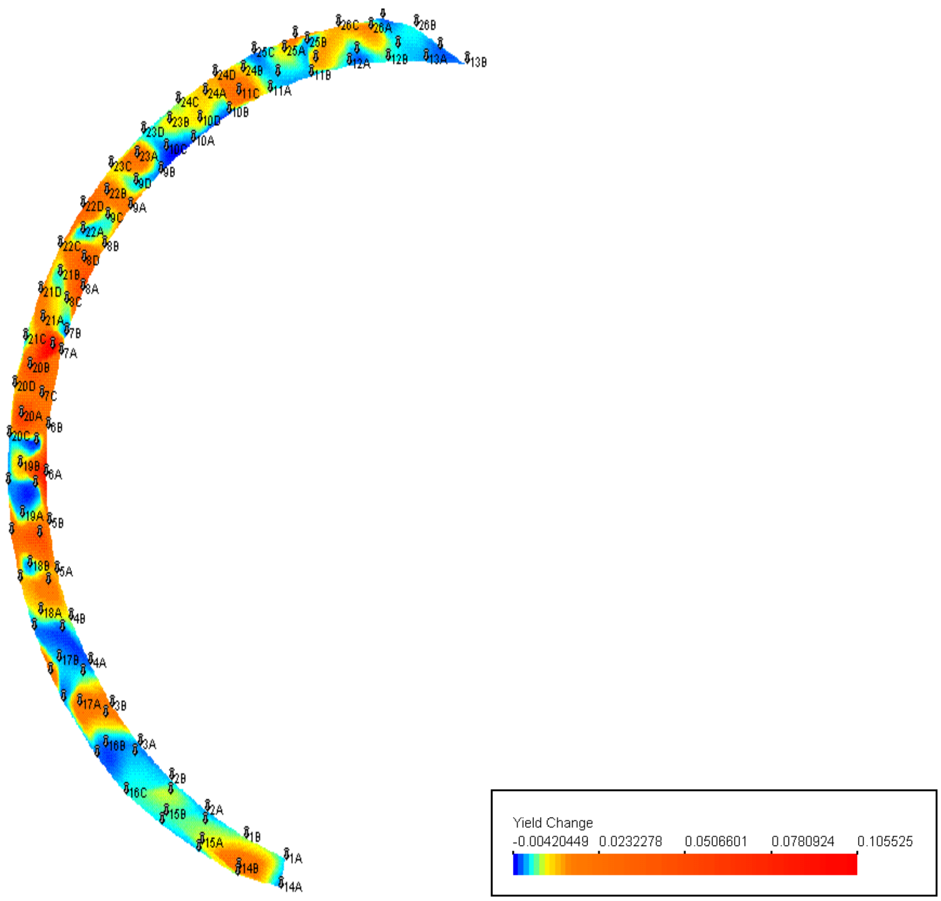

Figure 5. Yield Change for a Ten-Year Optimization Model (Precision Farming and Conventional Whole-Field Farming), Lamesa, Texas, 1998.

Net revenues above nitrogen fertilizer and water costs were also calculated under the two technologies (Tables 1 and 2). Spatial net revenue levels for the ten-year planning horizon ranged from $2,846.37 per acre (Location 11C) to $3,711.83 per acre (Location 7D) under 50% ET, and from $3,503.20 per acre (Location 26A) to $4,582.97 per acre (Location 20A) under 75% ET (Figure 6). The outer side of the field shows higher net revenues than in the inside of the circle. This is a direct result of higher levels of irrigation water applied on the outer locations. Under conventional whole-field farming, spatial net revenue levels for the ten-year planning horizon ranged from $2,708.39 per acre (Location 11C) to $3,499.16 per acre (Location 6A) under 50% ET, and from $3,399.79 per acre (Location 26A) to $4,414.09 per acre (Location 20A) under 75% ET.

In summary, the average net revenue during the ten-year planning horizon would be improved by 0.99%, from $3,138.43 per acre under conventional farming to $3,169.58 per acre under precision farming practices at 50% ET; and by 0.86%, from $3,942.13 per acre under conventional whole-field farming practices to $3,976.07 per acre under precision farming practices at 75% ET. The percentage change in net revenue above nitrogen fertilizer and water at each location in the field is shown in Figure 7. Change ranged from an increase of 0.00% (location 2B) to an increase of 7.28% (location 7D) under 50% ET, and from an increase of 0.0005% (location 15D) to an increase 3.82% (location 20A) under 75% ET. Note, however, that at every location in the field an increase in net revenue would be expected from the adoption of precision farming practices. A summary comparison of the previously discussed results is presented in Table 3.

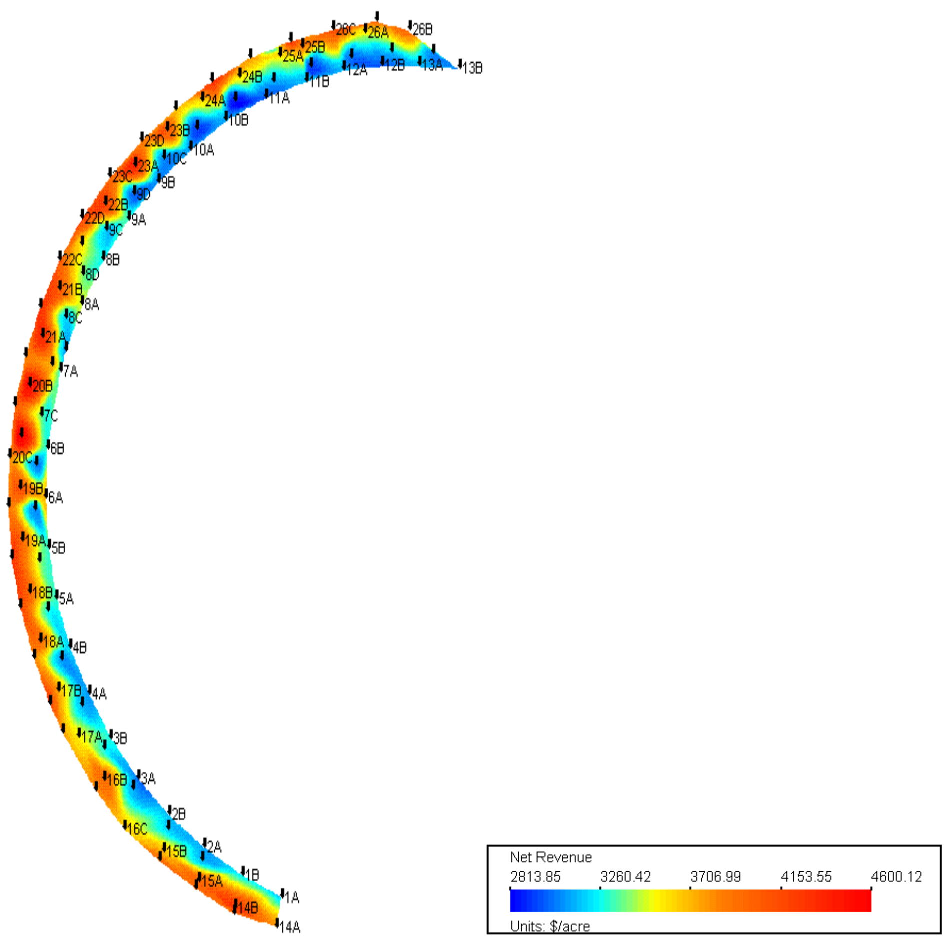

Figure 6. Spatial Net Revenue Above Nitrogen and Water Costs for a Ten-Year Optimization Model For Precision Farming Practices, Lamesa, Texas, 1998.

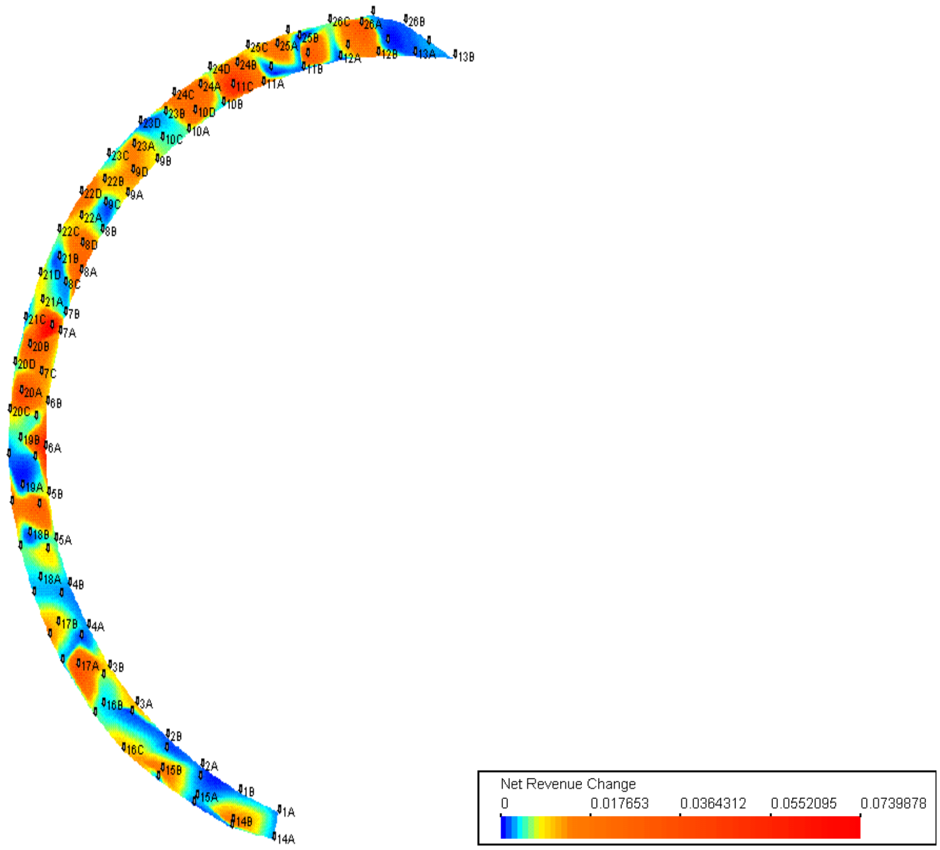

Figure 7. Spatial Net Revenue Change to Nitrogen Use (Precision Farming and Conventional Whole-Field Farming), Lamesa, Texas, 1998.

Table 3. Comparison of Precision Farming Practices and Conventional Whole-Field Farming Practices in Irrigated Cotton Production at Lamesa, Texas, 1998.

Applied Water Level		Precision Farming	Whole-Field Farming	Change
50% ET	Average Nitrogen Applied (lbs./a.)	49.33	46.70	5.33%
	Average Lint Yield (lbs./a.)	7057.22	6980.02	1.11%
	Average Net Revenue above Nitrogen and Water Costs ($/acre)	3169.58	3138.43	0.99%
75% ET	Average Nitrogen Applied (lbs./a.)	86.06	84.17	2.20%
	Average Lint Yield (lbs./a.)	9048.96	8970.28	0.88%
	Average Net Revenue above Nitrogen and Water Costs ($/acre)	3976.07	3942.13	0.86%

Productivity of Precision Farming verses Whole-Field Farming

Productivity, in its broadest sense, refers to the efficiency of a production process. In economics, it is commonly expressed as *total factor productivity* (TFP), which is the ratio of total output to total inputs used in the production process. TFP can be measured in an index form (Ahearn et al. 1998). If the ratio is increasing, this implies that productivity has improved, i.e., more output can be obtained from a given level of inputs.

Tables 1 and 2 also contain the TFP at each location in the field under the two nitrogen application technologies being evaluated. At 50% ET, the TFP change from whole-field to precision farming ranges from a decrease of 7.91 units (Location 7D) to an increase of 14.93 units (Location 11C). On the average, at 50% ET, precision farming increases TFP by 0.44 units. This means that precision farming practices increase cotton yield by an additional 0.44 pounds per acre for every pound of nitrogen fertilizer use, compared to whole-field farming practices. At the same time, precision farming builds up the average nitrogen residual level in the soil at the end of the tenth growing season by an average amount of 2.14 pounds per acre.

Table 2 shows that at 75% ET, the TFP change from whole-field to precision farming ranges from a decrease of 3.22 units (Location 20A) to an increase of 3.97 units (Location 24B). On the average, precision farming increases TFP by 0.07 units. That is, precision farming increases cotton yield by an additional 0.07 pounds per acre for every pound of nitrogen fertilizer use, as compared to whole-field farming practices. Also, at 75% ET, precision farming practices build up the average nitrogen residual level in the soil at the end of the tenth growing season by an additional 1.54 pounds per acre.

Tables 1 and 2 also show that there is an opposite relationship between the changes in TFP and the changes in the nitrogen residual level in the soil after the tenth season. If TFP increases, nitrogen residual level decreases, and vice versa. Both Tables 1 and 2 show that there are some locations in the field in which precision farming practices result in a lower TFP.

Under whole-field farming the average nitrogen residual levels at the end of the tenth season are 45.27 pounds per acre under 50% ET and 75.70 pounds per acre under 75% ET. Under precision farming practices, nitrogen residual levels are quite different depending on the location, perhaps due to the soil and location characteristics. Under dynamic optimization, if there is potential to increase net revenues in the future at a given location, precision farming practices would build up the nitrogen residual levels in that location. Because extra nitrogen fertilizer is applied to build up the after-season nitrogen residual levels, it is expected that TFP will decrease in that location. If future net revenues are not likely to increase in a given location, precision farming practices will lower their nitrogen residual levels, and TFP is expected to increase at those locations.

In short, precision farming practices can not only improve productivity, i.e., nitrogen use efficiency, but can also help to build up nitrogen residual in the soil at the end of the cotton growing season and improve the distribution of nitrogen residual levels across locations in the field.

CONCLUSIONS AND DISCUSSION

Overall, this analysis revealed that precision spatial utilization of nitrogen fertilizer, as compared to conventional whole-field farming, would result in an increase in crop yield, net revenue, and productivity on a per acre basis. This study found that nitrogen fertilizer could be used more efficiently, implying higher yields, net revenue, and output per unit of input used under precision farming practices, as compared to conventional whole-field farming practices. More importantly, it was found that precision farming practices would either build up or lower nitrogen residual levels at the end of the growing season, according to the net revenue potential of different locations.

This can improve yields, net revenue and input use efficiency, and have the potential to decrease the negative environmental impacts of agricultural production.

Net revenues do not show a sufficient increase as a result of adopting precision farming practices. This is partially explained by the fact that the experimental field did not have much variability on its initial soil nitrogen residual levels, and other spatial and soil properties. Future studies should be conducted to evaluate the relationship between the net revenue and the degree of variability in these factors. It is important to point out, however, that precision farming can effectively be used to determine "measurement zones" within fields where the benefits of precision farming would be sufficient.

Also, because of information limitations, this study only considered variable costs associated with the use of nitrogen fertilizer and water application and did not consider the fixed costs associated with the adoption of precision farming practices. For precision farming to be profitable in the future, this technology should also be used to control the variable application of other inputs, including seed, phosphorus fertilizer, potassium fertilizer, pesticide, herbicide, and other inputs. The application of multiple inputs could help to lower the average fixed costs of precision farming. Future studies should incorporate more variable inputs and consider the fixed costs of precision farming.

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