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ECONOMIC VS. BIOLOGICAL GOALS IN TECHNOLOGY ADOPTION

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Abstract

Producers can benefit both economically and environmentally from proper goal setting and technology choice in irrigated cotton production. Efficiencies gained from adopting technology and management goals are addressed by analyzing differences in precision farming and whole-field farming technology with respect to yields, net present value of returns above nitrogen and water costs (NPVR), and nitrogen application levels under both a yield and profit maximizing management goal.

Currently, agronomic recommendations for producers only consider yield maximization as a goal. Because yield maximization is not necessarily consistent with profit maximization, errors in application recommendations may be compounded under precision farming practices where decisions are made on smaller subunits of the field. Results suggest that profit maximization as a goal outperforms yield maximization in terms of NPVR regardless of technology choice. This indicates profit maximizing management goals with no technology return more NPVR than precision farming technology under a yield maximizing management strategy. However, precision farming increases NPVR by $20.87/acre as compared to whole-field farming when maximizing profit, indicating that maximizing profits under precision farming is the most profitable scenario.

Introduction

Technology adoption is becoming more prevalent in the agricultural industry with the availability of Global Positioning Systems (GPS) in both livestock and crop production. Environmental and economic efficiencies can be gained from improved information which in turn fosters better management of inputs in current production systems. Technology adoption is an important step towards addressing current agricultural issues. Today U.S. farmers are facing record high costs of production; foreign tariffs over five times the U.S. tariff, foreign subsidies nine times greater than in the United States, and the fifth straight year of record low prices. To combat this situation, The Farm Security Rural Investment Act of 2002 was developed, allocating record levels of spending in conservation and environmental programs (United States Department of Agriculture). Precision farming technology in crop production has the potential to address both the economic and environmental concerns the agricultural industry is facing.

Precision farming, by definition, 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 is also called site-specific management because of the ability to account for the changing conditions within fields (Atherton et al., 1999). In crop production, GPS interfaces with satellites to collect, analyze, and distribute inputs across a field (English, Roberts, and Sleigh, 2000). Precision farming technology has the potential to minimize over or under application of inputs, decrease costs of production, and increase profitability for producers. Management zones can be identified and micromanaged for increased returns to the producer. This is in contrast to traditional whole-field farming methods where the field is treated as one homogeneous unit and managed based on average characteristics of the field. Given that fields vary both spatially and temporally, traditional management practices may not be optimal (Intarapapong, Hite, and Hudson, 2002).

In theory, input costs are combined with biological production functions to arrive at the profit maximizing level of input application. However, agronomic recommendations only consider yield maximization as a goal. Because yield maximization is not necessarily consistent with profit maximization, errors in application recommendations may be compounded under precision agriculture practices where decisions are made on smaller subunits of the field. Therefore, this paper attempts to determine the efficiencies gained from adopting technology and management goals by addressing differences in precision farming and whole-field farming with respect to yields, net present value of returns above nitrogen and water costs (NPVR), and nitrogen application levels under both a yield and profit maximizing management goal.

Cotton was the commodity chosen for the study due to the importance cotton production commands in the state of Texas. In the United States, Texas cotton has the highest commodity value at approximately \$436 million for cotton lint (National Agricultural Statistics Service). Cotton lint yields in Texas have averaged approximately 537 lbs/acre over the last three years (National Agricultural Statistics Service). Cotton is also unique in that it adapts to poor soils and uses fertilizers efficiently (National Cotton Council). Of the approximately 5.6 million acres of cotton planted annually in Texas, approximately 705,000 acres are planted in the Southern High Plains (SHP) region (National Agricultural Statistics Service). The SHP is a semi-arid region, which encompasses 21.9 million acres, located in the northwestern portion of the state. Within Texas, the SHP is the largest cotton production area. For these reasons, data used for the study was collected from the SHP of Texas.

Materials and Methods

The data for cotton was collected in Lamesa, Texas over two years. A Global Positioning System (GPS) was used to identify the latitude and longitude of twenty-one locations in the field. Cotton lint yield was then measured in lbs/acre at each of these GPS locations. Two water levels were used, one at 50% evapotranspiration (ET) and the other at 75% ET. Altitude was measured for each location as well as for residual nitrate-nitrogen in the soil. The residual nitrate-nitrogen was measured in increments of 12 inches, up to 48 inches of the soil profile. Nitrogen was applied at three different rates including 0, 80, and 120 lbs/acre. Sand, clay, and silt content in the soil were also measured. A cotton stripper equipped with sensors and GPS was used to harvest the cotton.

After the data was gathered for each of the 21 locations in the field, a production function and nitrogen-residual carryover function were estimated and used in conjunction with optimization procedures for maximizing yield and maximizing profit under both precision and whole-field farming scenarios. In the experiment, 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, sand, silt, irrigation water, and year. The residual nitrogen function, which estimated the residual nitrogen from 0 to 12 inches of soil depth at the end of the season, was found to be a linear function of nitrogen applied, irrigation water, residual nitrate-nitrogen from 0 to 12 inches of soil depth, and year.

Yield was measured in lbs/acre and was defined as Y. Total nitrogen available for crop growth was measured in lbs/acre and was defined as NT. Altitude was measured in feet above a reference point in the field and was defined as ALT. Sand and silt were measured as a percentage of the soil content. They were defined as SAND and SILT, respectively. Irrigation water was introduced as a dummy variable that represented two irrigation water levels, 50% ET and 75% ET. Irrigation water was defined as W, with 0 representing 50% ET and 1 representing 75% ET. Year of the experiment was introduced as a dummy variable as well, with 0 representing Year #1 and 1 representing Year #2, and was defined as YEAR. Residual nitrate-nitrogen from 0 to 12 inches of soil depth at the end of the season was measured in lbs/acre and was defined as NR_{t+1}. Nitrogen applied was the amount of nitrogen applied during the season in lbs/acre and was defined as NA. Residual nitrate-nitrogen from 0 to 12 inches of soil depth was measured in lbs/acre at the beginning of the season was defined as NR_t. The functions estimated for yield and residual nitrate-nitrogen at the end of the season with their parameter estimates and associated t-values are shown in equations (1) and (2), respectively.

Eq. [1]
$$Y = \underset{(6.64)}{516.7237} - \underset{(-2.48)}{0.1011*NT*NT} + \underset{(2.95)}{.2618*NT*ALT*SAND} - \underset{(-2.27)}{46.8968*NT*SILT} + \underset{(4.26)}{0.1488*ALT*W} + \underset{(0.69)}{20.4874*YEAR}; \qquad R^2 = 0.494$$

Eq. [2]
$$NR_{t+1} = \underset{(5.63)}{53.3405} + \underset{(1.22)}{0.0805*NA*W} + \underset{(1.62)}{0.2083*NR_t} - \underset{(-6.25)}{37.3192*YEAR}; \qquad R^2 = 0.530$$

The R-squared was 0.494 for the yield model and 0.530 for the residual model. This indicates that 49.4% of the variation in irrigated cotton yield was explained by NT*NT, NT*ALT*SAND, NT*SILT, ALT*W, and YEAR. NA*W, NR_t, and YEAR account for 53.0% of the variation in NR_{t+1}. The functions include several interaction terms that model the biological nature of the field. The models were estimated using the Generalized Linear Model procedure (GLM) in SAS (SAS, 1982). The results were then used to formulate optimization models in General Algebraic Modeling System (GAMS), to determine optimal input application decision rules. To determine the profit maximizing level of nitrogen application, the marginal physical product of nitrogen was set equal to the price of nitrogen divided by the price of cotton. To determine the yield maximizing level of nitrogen application, the change in cotton yield with respect to change in total nitrogen available for plant uptake was set equal to zero. Using the nitrogen application levels recommended, yield and profits above nitrogen and water costs were determined. A dynamic optimization model with an inter-temporal nitrate-nitrogen carry-over function was introduced to answer these questions over both time and space. The structure of the optimization models are as follows:

Eq. [3] $$MaxNPV = \sum_{t=0}^{n} (PC_t \times Y_t(NT_t) - (PN_t \times NA_t)) / (1+r)^t$$

subject to:

Eq. [4] $$NT_t = NA_t + NR_t$$

Eq. [5] $$NR_{t+1} = f_t(NA_t, NR_t)$$

Eq. [6] $$NR_0 = NR(0)$$

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

Eq.[7] $$MaxYield = \sum_{t=0}^{n} Y_t(NT_t)/t$$

subject to:

Eq. [8] $$NT_t = NA_t + NR_t$$

Eq. [9] $$NR_{t+1} = f_t(NA_t, NR_t)$$

Eq. [10] $$NR_0 = NR(0)$$

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

Where, NPV was 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 was the price of cotton in year t; Y_t was the cotton yield function in year t; PN_t was the price of the input in year t; NA_t was the amount of input applied in year t; r was the discount rate; NT_t was the total amount of input available for crop growth in year t; NR_t was the residual amount of input already available in the soil in year t; and NR_0 was the initial residual amount of input available in the soil at the beginning of the planning horizon.

Equations (3) and (7) were the objective functions, or performance measures of the optimization models. Equations (4) and (8) were the equality constraints that add the amount of input applied and residual input to obtain the total amount of input available for cotton growth in any given year. These equations were used in the objective function to calculate cotton yield. Equations (5) and (9) were the equations that updated residual input annually, which were necessary for equations (4) and (8), respectively. These were the equations of motion because they updated the input residual at time t+1 depending on residual input at time t and input application at time t. Equations (6) and (10) were the initial input residual conditions, which represented the residual level at the beginning of the planning horizon. Non-negativity constraints were also specified for input application, residual, and total amount of input.

Precision farming technologies are typically adopted in stages making it difficult to determine the precise costs of investing in or using this technology (Isik, Khanna, and Winter-Nelson, 2001). This study analyzed the efficiencies gained from improved technology. This was done by optimizing nitrogen application under precision farming management practices and whole-field farming management practices. This allowed for quantification of the changes in optimal nitrogen, yield, and net present value of returns above nitrogen and water costs (NPVR) under different technologies. This study allowed the management effect to be quantified as well. Under precision farming management, we were able to compare yield, nitrogen application, and NPVR under the goal of yield maximization and profit maximization.

Results

Several price scenarios were used to analyze the researchable problem. Input and output prices were varied, however, the results were not particularly sensitive to the prices. Therefore, a representative price scenario where the price of cotton was \$0.50/lb, nitrogen costs were \$0.30/lb, and water costs were \$3.50 acre-inch was used. To determine the optimal profit-maximizing yield at each location, the optimal nitrogen application was determined and then placed into the forecasted yield equation. Under the precision farming scenario, nitrogen application was optimized for each location with the characteristics of each location in the field. Under the whole-field farming scenario, nitrogen application was optimized under average location characteristics and then the optimal nitrogen application was entered back into the estimated yield equation for each location in the field. The nitrogen residual was updated throughout the 5-year planning horizon assumed using the estimated nitrogen carryover function. A 5-year planning horizon was chosen because most banks lend on 5 to 7 year equipment loans and soil testing must be re-done by the fifth year to appropriately account for residual nitrogen.

Several scenarios were analyzed to quantify the differences in maximizing yields and profits under the different management practices. The scenarios discussed in the following subsections include: (1) yield maximizing under precision and whole-field farming (2) profit maximizing under precision and whole-field farming, and (3) yield verses profit maximizing under precision farming.

Yield Maximizing Strategies

Precision and whole-field farming yields under a yield maximizing management goal were as large as or larger under precision farming technologies for every location in the field (Table 1). On the average, yields were 3.11% higher when the new technology was used. Precision farming yields were as high as 13.91% higher in location #20 and were equivalent to whole-field farming in locations #5 and #13. The average yield for precision farming was 795.4 lbs/acre and 771.99 lbs/acre under whole-field farming. On average, precision farming increased NPVR by 7.01% when maximizing yields, ranging from a 0.77% decrease in profits under precision farming in location #14 to an increase of 27.6% in location #20. The average NPVR under the yield maximizing precision farming scenario was $1427.64 and $1339.17 under whole-field farming for the 5-year planning horizon. Precision farming used 19.6% less nitrogen on average, using as much as 8.58% more in location #14 than whole-field farming and as much as 50.77% less in location #20. While nitrogen application increases in some locations, prior work by Intarapapong, Hite, and Hudson has shown that nitrogen run-off actually decreases with precision agriculture.

Profit Maximizing Strategies

Under the goal of profit maximization, precision farming generated more yield in some locations and less yield in other locations for an average of 1.24% more yield, as shown in Table 2. On the extremes, precision farming generated 1.10% less yield in location #18 and 5.25% more in location #14. Average yield for precision farming was 786.13 lbs/acre and 776.19 lbs/acre under whole-field farming practices when maximizing NPVR.

NPVR for both technologies were compared when maximizing profits as well. As expected, precision farming outperformed whole-field farming in every location with an average increase in NPVR of 1.36% across locations in the field. Precision farming was the most responsive in location #16 where NPVR improved 4.44%. Average NPVR was $1456.23 under precision farming and $1435.36 for whole-field farming when maximizing NPVR over the 5-year planning horizon. Precision farming used 8.84% more nitrogen than whole-field farming when maximizing profit. In location #14 as much as 84.8% more nitrogen was applied to maximize profits and 57.40% less under precision farming in location #20.

Yield verses Profit Maximizing under Precision Farming

When simply comparing the two management goals of yield maximization and profit maximization under precision farming, yields decreased by 1.18% on average when maximizing profits (Table 3). NPVR increased in every location when maximizing profits for an average increase of 2.02% over maximizing yields. The nitrogen application level decreased at every location in the field when precision farming was used under the profit maximization scenario and averaged a 33.85% decrease. Thus, following a management program of maximizing profit instead of yield does not have a large impact on profits or yield (although profits are higher and yield is lower), but does have a significant impact on the level of nitrogen application.

Summary and Conclusions

In summary, on average, yields and NPVR increased under precision farming regardless of the management goal as compared to whole-field farming methods. However, average optimal nitrogen application rates increased when using precision farming practices under a profit maximization scenario and decreased when using a yield maximization scenario as compared to whole-field farming.

When profits were maximized under precision farming technology, 33.85% less nitrogen application was necessary than when maximizing yields. This has important environmental implications. Yields decreased on average and profits increased on average when precision farming technology was used under the profit maximization scenario as opposed to the yield maximization scenario.

When determining whether or not to implement this new technology, under the profit-maximizing goal for precision farming, a producer would have $20.87/acre from which they must collect and analyze data and apply the optimal application. This was the amount per acre that precision farming exceeded whole-field farming when maximizing profits. The producer would gain $28.59/acre from managing for profits as opposed to managing for yields under precision farming, indicating that whole-field farming under a profit-maximizing scenario is better than precision farming under a yield maximizing scenario with respect to NPVR by $7.72/acre. This is an important point. These results suggest that the power of precision farming lies in its ability to allow profit-maximizing strategies to be employed at smaller subunits of the field. If one is simply going to maximize yields, it is probably more profitable to not employ precision farming and just manage the whole field on the basis of average characteristics. Nevertheless, the most profitable combination is to use precision farming practices with the management goal of maximizing NPVR.

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Table 1. Comparison of technological effect (precision farming and whole-field farming) with respect to yield maximization.

SPOT	**Yield % Change**	**Profit% Change**	**Applied N% Change**
1	0.37%	1.74%	-9.70%
2	2.19%	6.07%	-21.25%
3	1.40%	4.34%	-17.71%
4	0.34%	1.50%	-8.32%
5	0.00%	-0.50%	3.63%
6	0.97%	3.50%	-16.53%
7	0.96%	3.04%	-13.20%
8	0.38%	1.82%	-10.20%
9	1.42%	5.16%	-22.53%
10	3.46%	9.10%	-28.03%
11	2.12%	7.15%	-29.57%
12	0.56%	2.24%	-15.10%
13	0.00%	-0.47%	4.07%
14	0.06%	-0.77%	8.58%
15	0.04%	-0.48%	5.65%
16	11.68%	22.02%	-38.29%
17	8.15%	17.24%	-46.23%
18	7.08%	15.05%	-41.58%
19	7.66%	15.69%	-38.10%
20	13.91%	27.60%	-50.77%
21	2.48%	6.24%	-26.29%
Average	**3.11%**	**7.01%**	**-19.60%**

Table 2. Comparison of technological effect (precision farming and whole-field farming) with respect to net present value of returns to nitrogen and water maximization.

SPOT	Yield % Change	Profit% Change	Applied N% Change
1	2.28%	0.67%	31.52%
2	-0.22%	0.01%	-3.60%
3	0.47%	0.04%	7.12%
4	2.36%	0.71%	32.03%
5	4.82%	2.11%	59.05%
6	1.12%	0.20%	17.92%
7	1.02%	0.17%	14.86%
8	2.26%	0.65%	31.65%
9	0.46%	0.04%	7.09%
10	-0.83%	0.24%	-15.31%
11	-0.05%	0.00%	-0.99%
12	1.34%	0.29%	26.13%
13	3.98%	1.80%	55.70%
14	5.25%	2.43%	84.80%
15	5.17%	2.48%	83.36%
16	0.08%	4.44%	-42.65%
17	-1.06%	2.22%	-49.84%
18	-1.10%	2.21%	-45.45%
19	-0.92%	2.11%	-38.94%
20	0.13%	5.67%	-57.40%
21	-0.54%	0.08%	-11.45%
Average	**1.24%**	**1.36%**	**8.84%**

Table 3. Comparison of Precision Farming with respect to yield, profit, and nitrogen application under different management goals.

SPOT	Yield Change	Profit Change	Applied N Change
1	-1.25%	1.97%	-28.97%
2	-1.28%	2.59%	-34.68%
3	-1.28%	2.39%	-33.09%
4	-1.24%	2.07%	-29.14%
5	-1.19%	1.99%	-26.44%
6	-1.32%	2.21%	-33.30%
7	-1.27%	2.53%	-32.99%
8	-1.26%	1.95%	-29.14%
9	-1.29%	1.70%	-29.79%
10	-1.32%	2.58%	-37.29%
11	-1.39%	1.73%	-34.87%
12	-1.08%	1.41%	-30.52%
13	-0.98%	1.58%	-26.13%
14	-0.98%	1.44%	-25.29%
15	-1.02%	1.17%	-24.43%
16	-0.99%	2.67%	-38.89%
17	-1.18%	2.14%	-49.67%
18	-1.15%	2.11%	-44.32%
19	-1.07%	2.42%	-41.50%
20	-1.15%	1.92%	-44.49%
21	-1.08%	1.90%	-35.90%
Average	**-1.18%**	**2.02%**	**-33.85%**